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ARTS

SYNERGY OF 2D AND 3D ANIMATION IN MOTION DESIGN

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СИНЕРГІЯ 2D ТА 3D АНІМАЦІЇ В МОУШН ДИЗАЙНІ

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Abstract

The paper explores the interaction of 2D and 3D animation in modern motion design, analyzes their functional and visual features, identifies the advantages and limitations of each approach, and justifies the feasibility of combining them. It is established that the synergy of two-dimensional and three-dimensional animation provides a balance between production speed and visual expressiveness, increasing the effectiveness of visual communication. Practical aspects of the application of combined solutions in various areas of digital design are considered.

Анотація

У роботі досліджено взаємодію 2D та 3D анімації в сучасному motion design, проаналізовано їхні функціональні та візуальні особливості, визначено переваги й обмеження кожного підходу та обґрунтовано доцільність їх поєднання. Встановлено, що синергія двовимірної і тривимірної анімації забезпечує баланс між швидкістю виробництва та візуальною виразністю, підвищуючи ефективність візуальної комунікації. Розглянуто практичні аспекти застосування комбінованих рішень у різних сферах цифрового дизайну.

Keywords: motion design, 2D animation, 3D animation, visual communication, synergy, digital design, animation design, UX/UI, multimedia content, visual culture.

Ключові слова: motion design, 2D-анімація, 3D-анімація, візуальна комунікація, синергія, цифровий дизайн, анімаційний дизайн, UX/UI, мультимедійний контент, візуальна культура.

Постановка проблеми та аналіз основних досліджень. Сучасний розвиток цифрового середовища зумовлює суттєві трансформації у сфері візуальної комунікації, в межах якої особливого значення набуває motion design як інтегративний напрям, що поєднує графічний дизайн, анімацію та аудіовізуальні технології. У сучасній креативній індустрії він активно застосовується у рекламних кампаніях, цифрових інтерфейсах, соціальних медіа та мультимедійних продуктах, забезпечуючи не лише естетичну виразність, а й ефективну передачу інформації.

Аналіз наукових досліджень свідчить, що motion design розглядається як важливий компонент сучасного медіа-арту та чинник формування візуальної культури цифрового суспільства. У працях таких авторів як В. Олійник, К. Марашовська, Д. Нормана (Don A. Norman), а також Р.

Маєра (Richard E. Mayer), досліджуються різні аспекти розвитку анімації, вплив цифрових технологій, а також окремі види анімаційних технік, зокрема 2D та 3D [2;3;7;10]. Водночас більшість досліджень має фрагментарний характер і зосереджується або на технічних, або на художніх аспектах, що не дає цілісного розуміння їх взаємодії. Питання комплексного поєднання різних типів анімації у межах motion design залишається недостатньо опрацьованим і потребує подальшого дослідження.

Мета роботи. Метою дослідження є аналіз особливостей 2D та 3D анімації у структурі сучасного motion design, визначення їх функціональних характеристик, а також обґрунтування доцільності їх синергії як ефективного підходу до створення візуального контенту та підвищення ефективності візуальної комунікації.

Виклад основного матеріалу. Сучасний розвиток цифрового середовища спричинив суттєві зміни у способах візуальної комунікації, серед яких особливого значення набуває motion design як інтегративний напрям, що поєднує графічний дизайн, анімацію та аудіовізуальні технології. У межах сучасної креативної індустрії motion design використовується у рекламних кампаніях, цифрових інтерфейсах, соціальних медіа та мультимедійних продуктах, забезпечуючи не лише естетичну привабливість, а й ефективну передачу інформації. Дослідження українських науковців підтверджують, що моушн-дизайн виступає важливим компонентом сучасного медіа-арту та відіграє значну роль у формуванні візуальної культури цифрового суспільства.

У структурі motion design особливе місце займають різні типи анімації, серед яких найбільш поширеними є двовимірна (2D) та тривимірна (3D) анімація. Вони формують основу більшості сучасних візуальних продуктів і застосовуються у широкому спектрі завдань – від пояснювальної графіки до складних візуальних ефектів. Як зазначається у наукових роботах, motion design охоплює різні види анімації, включаючи 2D-векторну, 3D-комп'ютерну анімацію та візуальні ефекти, що розширює можливості створення комплексних візуальних рішень.

Аналіз сучасних досліджень свідчить про те, що 2D та 3D анімація мають принципово різні технічні та художні характеристики. Зокрема, 2D-анімація вирізняється відносною простотою виробництва, меншою ресурсозатратністю та високою ефективністю у візуалізації інформації, особливо у сфері цифрових інтерфейсів та мобільних застосунків. Водночас 3D-анімація забезпечує можливість створення просторових сцен, високий рівень деталізації та реалістичності, що значно розширює потенціал візуального впливу на глядача. Дослідження також підтверджують, що розвиток анімації як мистецької та технологічної практики супроводжується інтеграцією різних стилів і підходів, що сприяє переходу до нових форм аудіовізуального вираження.

Разом із тим, у сучасній науковій та практичній площині спостерігається певна фрагментарність у дослідженні анімації: більшість робіт зосереджені або на технічних аспектах створення 2D чи 3D графіки, або на аналізі окремих видів анімації як самостійних явищ. Наприклад, окремі дослідження присвячені комунікативному потенціалу анімаційних форм, зокрема stop-motion, як ефективного засобу передачі інформації у сучасному дизайні, тоді як інші розглядають вплив новітніх технологій, зокрема штучного інтелекту, на процес створення анімаційного контенту. Водночас питання комплексного поєднання різних типів анімації в єдиній системі motion design залишається недостатньо опрацьованим.

Окрему увагу привертає тенденція до змішування різних візуальних підходів, яка стає характерною ознакою сучасного дизайну. У контексті

розвитку цифрових технологій спостерігається перехід від використання окремих анімаційних технік до їх інтеграції, що дозволяє досягати більш гнучких та адаптивних візуальних рішень. Зростання популярності відеоконтенту, інтерактивних медіа та соціальних платформ додатково стимулює пошук нових підходів до створення анімації, що поєднує швидкість виробництва та високий рівень візуальної виразності.

Необхідність дослідження синергії 2D та 3D анімації як комплексного підходу до створення motion design продуктів є актуальною. Поєднання цих двох типів анімації дозволяє не лише компенсувати обмеження кожного з них окремо, але й формувати нові принципи побудови візуального контенту, що відповідають вимогам сучасного цифрового середовища. У цьому контексті особливого значення набуває аналіз взаємодії 2D та 3D анімації, їх функціональних можливостей та впливу на ефективність візуальної комунікації, що логічно зумовлює необхідність подальшого дослідження даного питання та розгляду специфіки кожного з підходів і особливостей їх поєднання у сучасному motion design.

У сучасній практиці візуальної комунікації 2D анімація зберігає стійкі позиції завдяки своїй універсальності та ефективності у швидкому виробництві контенту. Її використання особливо поширене у цифрових інтерфейсах, рекламних матеріалах та соціальних мережах, де ключовими факторами виступають швидкість створення, адаптивність та легкість сприйняття. Як зазначає американський науковець та дизайнер Дон Норман, у своїй книзі «The Design of Everyday Things» [7] пояснюючи те, що спрощена візуальна мова 2D-анімації дозволяє фокусувати увагу користувача на змісті повідомлення, мінімізуючи когнітивне навантаження та забезпечуючи ефективну комунікацію в умовах обмеженого часу сприйняття. Крім того, використання 2D-анімації значно оптимізує виробничі процеси, що є критично важливим у контексті сучасного контентного середовища, де швидкість оновлення матеріалів безпосередньо впливає на конкурентоспроможність продукту.

Водночас 3D анімація демонструє інші переваги, пов'язані з можливістю створення складних просторових сцен, високим рівнем деталізації та реалістичністю зображення. У межах сучасного motion design 3D-технології активно застосовуються у рекламі, продуктової візуалізації, кіноіндустрії та інтерактивних середовищах. Згідно з науковими публікаціями, використання тривимірної графіки дозволяє формувати більш глибокий емоційний зв'язок із аудиторією за рахунок ефекту присутності та візуальної переконливості [2]. Разом із тим, створення 3D-контенту потребує значно більших технічних ресурсів, часу та спеціалізованих знань, що ускладнює його використання в умовах швидкого виробництва.

Порівняльний аналіз дозволяє виявити ключові відмінності між 2D та 3D анімацією, які визна-

чають їх функціональну роль у motion design. Зокрема, 2D-анімація характеризується високою швидкістю створення та гнучкістю у адаптації під різні платформи, що робить її ефективним інструментом для масового контенту. Натомість 3D-анімація забезпечує вищий рівень візуальної складності та здатність передавати об'єм, матеріальність і фізичні властивості об'єктів, що є важливим у випадках, коли необхідно досягти максимального рівня залучення глядача. Завдяки цьому спостерігається своєрідний баланс між продуктивністю та візуальною виразністю, де кожен із підходів реалізує різні аспекти комунікативного потенціалу анімації.

Окремої уваги заслуговує питання сприйняття анімаційного контенту користувачами. Дослідження у сфері візуальної комунікації свідчать, що спрощені форми та умовна графіка, характерні для 2D-анімації, сприяють швидкому розпізнаванню образів та ефективному засвоєнню інформації, тоді як 3D-анімація, завдяки своїй реалістичності, здатна формувати більш емоційно насичений досвід взаємодії [3]. Це свідчить про те, що вибір між 2D та 3D не є виключно технічним рішенням, а визначається цілями комунікації та особливостями цільової аудиторії.

Разом із тим, у процесі аналізу виявляється, що протиставлення 2D та 3D анімації є умовним і не повною мірою відображає сучасні тенденції розвитку motion design. У реальних проєктах дедалі частіше спостерігається комбінування різних технік, що дозволяє досягти оптимального результату з урахуванням як естетичних, так і виробничих вимог. Зокрема, використання 2D-графіки для створення базових композицій у поєднанні з 3D-елементами для акцентування ключових об'єктів дозволяє зберегти швидкість виробництва, одночасно підвищуючи візуальну привабливість продукту.

Такий підхід свідчить про формування нової парадигми у motion design, у межах якої 2D та 3D анімація розглядаються не як альтернативні, а як взаємодоповнюючі інструменти. Відповідно, актуальним стає питання дослідження їх синергії, що передбачає не лише технічне поєднання різних типів анімації, але й переосмислення принципів побудови візуального контенту. Це, у свою чергу, зумовлює необхідність більш детального розгляду механізмів інтеграції 2D та 3D анімації у сучасному motion design та визначення їхнього впливу на ефективність візуальної комунікації, що логічно переводить дослідження до аналізу синергійних підходів як ключового етапу розвитку анімаційного дизайну.

Проведений аналіз особливостей 2D та 3D анімації дозволяє перейти до розгляду їхньої взаємодії як цілісного підходу в межах сучасного motion design, де ключовим стає не протиставлення, а інтеграція різних візуальних стратегій. У цьому контексті синергія 2D і 3D анімації постає як закономірний етап еволюції цифрового дизайну, обумовлений потребою поєднання високої візуальної виразності з ефективністю виробничих процесів. Як зазначається у сучасних дослідженнях цифрового

дизайну, інтеграція різних візуальних технологій є характерною ознакою розвитку медіасередовища та сприяє формуванню нових форматів аудіовізуальної комунікації [1].

Сучасні дизайн-практики демонструють тенденцію до формування гібридних візуальних рішень, у яких двовимірна та тривимірна графіка функціонують у межах єдиного композиційного середовища. Така інтеграція не є механічним поєднанням різних технік, а передбачає їх узгодження на рівні стилістики, просторової організації та комунікативної функції. Зокрема, 2D-анімація часто використовується як базовий інструмент структурування композиції, формування ритму та подачі інформації, тоді як 3D-елементи виконують роль акцентів, підсилюючи візуальну глибину та емоційний вплив. Подібний підхід корелює з дослідженнями візуальної комунікації, де підкреслюється важливість поєднання різних рівнів візуальної складності для підвищення ефективності сприйняття [5].

У межах синергійного підходу відбувається переосмислення ролі кожного з типів анімації. 2D перестає виконувати виключно допоміжну функцію спрощеної візуалізації, а набуває значення активного елементу композиції, що задає логіку сприйняття. Водночас 3D анімація використовується не лише для досягнення реалістичності, а як засіб формування візуальних акцентів, просторової ієрархії та динамічних ефектів. Такий підхід відповідає сучасним тенденціям розвитку motion design, у яких акцент зміщується від окремих технік до комплексних візуальних систем [4].

Важливим аспектом синергії є також оптимізація виробничого процесу. Поєднання 2D та 3D анімації дозволяє раціонально розподіляти ресурси, використовуючи більш складні тривимірні рішення лише там, де це обґрунтовано з точки зору візуального ефекту. Це сприяє зменшенню часу виробництва без втрати якості кінцевого продукту, що є особливо актуальним у контексті швидкого темпу створення цифрового контенту. У дослідженнях з цифрового виробництва контенту підкреслюється, що комбінування різних технологій є одним із ключових факторів підвищення ефективності креативних процесів [9].

Окремо слід відзначити вплив синергії 2D та 3D анімації на користувацьке сприйняття. Комбінування умовної графіки з просторовими елементами дозволяє одночасно активізувати раціональні та емоційні механізми обробки інформації. З одного боку, 2D-компоненти сприяють швидкому зчитуванню змісту, з іншого – 3D-елементи підсилюють візуальне залучення та формують ефект присутності. Подібні висновки узгоджуються автором Richard E. Mayer у книзі «Multimedia Learning» де зазначається, що поєднання різних типів візуального представлення інформації підвищує рівень її засвоєння [10].

У сучасному motion design синергія 2D та 3D анімації проявляється у різних формах, зокрема у поєднанні векторної графіки з тривимірними сце-

нами, інтеграції 3D-об'єктів у 2D-інтерфейси, а також у використанні гібридних стилів, що поєднують плоску та об'ємну естетику. Розвиток програмного забезпечення, такого як системи композитингу та 3D-моделювання, сприяє спрощенню процесів інтеграції, роблячи їх доступними для ширшого кола дизайнерів. Це підтверджує загальну тенденцію до уніфікації інструментів та підходів у сучасному цифровому дизайні [1].

Синергія 2D та 3D анімації виступає також як ефективна стратегія створення сучасного візуального контенту, що дозволяє поєднати переваги різних підходів та мінімізувати їхні обмеження. Її застосування сприяє формуванню нових принципів організації анімаційного простору, орієнтованих на гнучкість, адаптивність та високу комунікативну ефективність, що обумовлює доцільність подальшого розгляду практичних аспектів використання даного підходу у різних сферах motion design.

Подальший розвиток дослідження синергії 2D та 3D анімації доцільно розглядати крізь призму її практичного застосування у сучасному motion design, де інтеграція різних візуальних підходів набуває не лише теоретичного, але й прикладного значення. Аналіз актуальних дизайн-практик свідчить про те, що комбінування 2D і 3D анімації активно використовується у різних сферах цифрового середовища, забезпечуючи гнучкість, адаптивність та підвищену ефективність візуальної комунікації.

Однією з ключових сфер застосування синергійного підходу є рекламний та бренд-дизайн, у межах якого анімація виконує функцію не лише візуального оформлення, але й засобу формування емоційного зв'язку з аудиторією. У сучасних рекламних відео та digital-кампаніях спостерігається тенденція до використання 2D-графіки для передачі інформаційного змісту у поєднанні з 3D-елементами, що створюють ефект глибини та підсилюють візуальну привабливість. Такий підхід дозволяє досягати балансу між швидкістю виробництва контенту та його естетичною виразністю, що є критично важливим у динамічному медіасередовищі.

У сфері цифрових інтерфейсів та UX/UI-дизайну синергія 2D та 3D анімації проявляється у створенні інтерактивних елементів, які поєднують простоту сприйняття з візуальною глибиною. Зокрема, 2D-анімація використовується для забезпечення зрозумілої навігації та швидкого зчитування інформації, тоді як 3D-компоненти додають відчуття просторовості та підвищують рівень залучення користувача. У результаті формується більш інтуїтивний і водночас емоційно насичений досвід взаємодії з цифровим продуктом.

Значного поширення синергія 2D та 3D анімації набула у сфері контенту для соціальних мереж, де особливо важливими є швидкість виробництва та здатність привернути увагу користувача в умовах інформаційного перевантаження. Використання комбінованих анімаційних рішень дозволяє створювати динамічний контент, що поєднує зрозумілість 2D-графіки з візуальною привабливістю 3D-ефектів. Це сприяє підвищенню ефективності

комунікації та залученості аудиторії, що підтверджується сучасними дослідженнями цифрового маркетингу та візуального контенту [8].

Окремим напрямом є застосування синергії у пояснювальній анімації та освітньому контенті, де важливим є не лише естетичний аспект, але й ефективність передачі інформації. Поєднання 2D та 3D дозволяє одночасно використовувати умовні графічні образи для спрощення складних понять і тривимірні моделі для демонстрації процесів або об'єктів у просторі. Такий підхід підвищує рівень розуміння матеріалу та сприяє кращому засвоєнню інформації.

У межах сучасної практики також спостерігається тенденція до використання синергії 2D та 3D у створенні гібридних візуальних стилів, що поєднують елементи плоского дизайну з об'ємною графікою. Це проявляється у використанні 3D-об'єктів у 2D-середовищі, накладанні векторної графіки на тривимірні сцени, а також у створенні композицій, де межа між двовимірним і тривимірним простором є умовною. Подібні рішення дозволяють формувати унікальну візуальну ідентичність продукту та виділяти його серед конкурентів.

Аналіз практичного застосування синергії 2D та 3D анімації свідчить про те, що її використання є не випадковим, а зумовленим конкретними функціональними та комунікативними завданнями. Зокрема, комбінування різних типів анімації дозволяє оптимізувати процес створення контенту, підвищити його візуальну якість та адаптувати до різних платформ і форматів [6]. У цьому контексті синергія виступає як ефективний інструмент, що забезпечує гнучкість дизайнерських рішень та відповідає вимогам сучасного цифрового середовища.

Практичне застосування синергії 2D та 3D анімації підтверджує її значний потенціал у різних сферах motion design, що дозволяє розглядати її як один із ключових напрямів розвитку сучасної візуальної комунікації. Це, у свою чергу, зумовлює необхідність узагальнення отриманих результатів та формулювання висновків щодо ефективності даного підходу та перспектив його подальшого використання.

Висновок. Проведене дослідження особливостей 2D та 3D анімації у структурі сучасного motion design дозволяє зробити висновок про доцільність їх комплексного розгляду як взаємодоповнюючих інструментів візуальної комунікації. Встановлено, що кожен із підходів має власні функціональні переваги: 2D-анімація забезпечує швидкість виробництва, простоту сприйняття та ефективність у передачі інформації, тоді як 3D-анімація сприяє формуванню глибини, візуальної виразності та емоційного впливу.

У результаті порівняльного аналізу виявлено, що використання 2D та 3D анімації як окремих підходів не завжди дозволяє досягти оптимального балансу між продуктивністю та якістю візуального контенту. Це зумовлює необхідність їх інтеграції у межах єдиної дизайнерської системи. Синергія 2D і 3D анімації розглядається як ефективна стратегія,

що дозволяє поєднувати переваги різних технологій, компенсуючи їхні обмеження.

Аналіз сучасних практик motion design підтверджує, що комбінування двовимірних і тривимірних елементів сприяє підвищенню ефективності візуальної комунікації, покращенню користувацького досвіду та оптимізації процесів створення контенту. Використання гібридних підходів дозволяє формувати більш адаптивні, динамічні та конкурентоспроможні дизайнерські рішення, що відповідають вимогам цифрового середовища.

Встановлено, що синергія 2D та 3D анімації впливає не лише на естетичні характеристики візуального продукту, але й на його функціональні параметри, зокрема швидкість виробництва, гнучкість адаптації та ефективність сприйняття інформації. Це дозволяє розглядати її як один із ключових чинників розвитку сучасного motion design.

Отримані результати свідчать про те, що подальший розвиток анімаційного дизайну пов'язаний із поглибленням інтеграції різних технологій, удосконаленням інструментів їх поєднання та пошуком нових форм візуальної виразності. Перспективними напрямками подальших досліджень є вивчення впливу автоматизованих та генеративних технологій на процес створення анімації, а також аналіз ефективності синергійних підходів у різних сферах цифрового дизайну.

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BIOLOGICAL SCIENCES

DENDROFLORA OF NAKHCHIVAN: BOTANICAL AND GEOGRAPHIC ANALYSIS OF RELICT, ENDEMIC, AND RARE SPECIES IN FOREST AND SHRUB VEGETATION

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NAXÇIVANIN DENDROFLORASI, MEŞƏ VƏ KOLLUQ BİTKİLİYİ: RELİKT, ENDEM VƏ NADİR NÖVLƏRİN BOTANİKİ-COĞRAFİ ANALİZİ

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Abstract

The present study provides a comprehensive botanical and geographic analysis of relict, endemic, and rare species within the dendroflora of the Nakhchivan Autonomous Republic (Republic of Azerbaijan), with a particular focus on forest and shrub vegetation. The conducted studies revealed that the vegetation of the Nakhchivan Autonomous Republic is classified into one forest vegetation type, three forest formation classes, fourteen forest formation groups, one shrub vegetation type, two shrub formation classes, and nine shrub formation groups. In forest and shrub vegetation, relict species such as *Carpinus betulus* L., *Mespilus germanica* L., *Juglans regia* L., *Cerasus incana* (Pall.) Spach. (*C. mahaleb* L.), *Salix alba* L., *Acer hyrcanum* Fisch. et C.A. Mey., *A. velutinum* Boiss., *Tilia begoniifolia* Stev., *Pyrus salicifolia* Pall., *Sorbus boissieri* C.K. Schneid., *Ulmus glabra* Huds., *Punica granatum* L., *Ficus carica* L., and *Celtis caucasica* Willd. are among the dominant species.

In the dendroflora of the Nakhchivan Autonomous Republic, three relict tree and shrub species belonging to three genera and three families—*Punica granatum* L., *Gleditsia caspia* Desf., and *Ficus carica* L.—are considered rare taxa, representing remnants of the subtropical Poltava flora that have persisted to the present day. In the study area, a total of 16 species belonging to 14 genera and 12 families of the temperate deciduous Turgay flora have been identified. Among them, *Pinus kochiana* Klotzsch ex K.Koch and *Vitis vinifera* L. (*V. sylvestris* C.C. Gmel.) are considered rare species.

Based on the results of the research, *Pyrus salicifolia* Pall. and *Amygdalus fenzliana* (Fritsch.) Lipsky. are assigned to the xerothermic relicts of the Tertiary period in Nakhchivan, taking into account the ecogeographical analysis of their distribution in Nakhchivan and other regions of the Republic of Azerbaijan, as well as their biological characteristics. In the dendroflora of Nakhchivan, a total of 21 species belonging to 19 genera and 16 families have been identified as Tertiary relicts, while 38 rare species belonging to 23 genera and 15 families have been recorded. In addition, five species belonging to five genera and five families are classified as both relict and rare taxa.

A total of 13 endemic tree, shrub, and subshrub species belonging to 9 genera and 8 families have been recorded. Among them, 5 species are rare, while 2 species are both rare and relict. Taking into account the soil-climatic conditions and ecogeographical characteristics, the relict species were analyzed according to historical groups, and the Batabat forest massif was identified as a mesothermic relict area. In contrast, the areas around Mount Qaragush in the Sharur District, as well as the surroundings of the Alinja River in the direction of the villages of Lakitagh and Boyahmadli in the Julfa District, were identified as xerothermic relict areas.

Considering the sharply continental climate of Nakhchivan, characterized by very cold winters and hot summers, as well as global climate change—particularly drought—and increasing anthropogenic impacts, it can be predicted that significant threats may arise in the future for a number of relict, rare, and endemic species.

Xülasə

Aparılan tədqiqatlar nəticəsində Naxçıvan Muxtar Respublikasının (Azərbaycan Respublikası) bitkiliyində 1 meşə bitkiliyi tipi, 3 meşə formasiya sinfi, 14 meşə formasiya qrupu, 1 kolluq bitkiliyi tipi, 2 kolluq formasiya sinfi, 9 kolluq formasiya qrupu müəyyən edilmişdir.

Meşə və kolluq bitkiliyində *Carpinus betulus* L., *Mespilus germanica* L., *Juglans regia* L., *Cerasus incana* (Pall.) Spach. (C.mahaleb L.), *Salix alba* L., *Acer hyrcanum* Fisch. et C.A.Mey., *A. velutinum* Boiss., *Tilia begoniifolia* Stev., *Pyrus salicifolia* Pall., ***Sorbus boissieri* C.K. Scheid.**, *Ulmus glabra* Huds., *Punica granatum* L., *Ficus carica* L., *Celtis caucasica* Willd. reliktləri dominant növlər sırasındadırlar.

Naxçıvan dendroflorasında subtropik Poltav florasından dövrümüzə qədər qalmış 3 fəsiləyə, 3 cinsə aid 3 relikt ağac və kol növlərinin (*Punica granatum* L., *Gleditsia caspia* Desf. və *Ficus carica* L.) hər biri nadir bitkilərdir.

Ərazidə mülayim, yarpağını tökən Turqay florasına aid 12 fəsiləyə, 14 cinsə, daxil olan 16 növ müəyyən edilmişdir. Bunlardan *Pinus kochiana* Klotzsh ex. K.Koch. və *Vitis vinifera* L. (*V.sylvestris* C.C.Gmel.) nadir növlərdir.

Tədqiqatlar nəticəsində *Pyrus salicifolia* Pall. və *Amygdalus fenzliana* (Fritsch.) Lipsky. növlərinin Naxçıvanda, Azərbaycan Respublikasının digər ərazilərində areallarının ekocoğrafi analizi və bioloji xüsusiyyətləri nəzərə alınaraq III dövrün kserotermik reliktlərinə aid edilmişdir.

Naxçıvan dendroflorasında ümumilikdə III dövrün reliktlərinə aid 16 fəsiləyə, 19 cinsə aid 21 növ, 15 fəsiləyə, 23 cinsə aid 38 nadir növ yayılmışdır. 5 fəsiləyə 5 cinsə aid 5 növ isə həm relikt, həm də nadir bitkilərdir.

8 fəsiləyə, 9 cinsə aid 13 növ endem ağac, kol və kolcuqlar yayılmışdır. Bunlardan 5 növü nadir, 2 növü isə nadir olmaqla yanaşı həm də relikt bitkilərdir.

Torpaq- iqlim şəraiti, ekocoğrafi xüsusiyyətləri nəzərə alınaraq, relikt növlər tarixi qruplar üzrə təhlil ediləndən sonra Batabat meşə massivi mezotermik relikt ərazi, Şərur rayonu Qaraquş dağı, Culfa rayonun Ləkitağ kəndi, Boyəhmədli kəndləri istiqamətində Əlinəcə çayının ətrafı kserotermik relikt ərazi hesab edilmişdir.

Naxçıvanın qışı çox soyuq, yayı isti kəskin kontinental iqlimini, global iqlim dəyişiklikləri, xüsusilə quraqlığı və artmaqda olan antropogen təsirləri nəzərə alsaq, bir sıra relikt, nadir və endem növlər üçün gələcəkdə böyük təhlükələr yarana biləcəyini proqnozlaşdırma bilirik.

Keywords: Nakhchivan, Batabat, Qaragush, Poltava flora, Turgay flora, relict species, rare species, endemic species, distribution area, Red Book

Açar sözlər: Naxçıvan, Batabat, Qaraquş, Poltav florası, Turqay florası, relikt növ, nadir, endem, areal, qırmızı kitab .

Giriş

İndiki dövrümüzdə təbii proseslərlə və iqlim dəyişiklikləri ilə yanaşı insanın ətraf mühitə mənfi təsirləri əhəmiyyətli amilə çevrilmişdir. Nəticədə bir sıra bitkilik formasiyalarının, qruplarının təbii strukturlarının dəyişməsi, xüsusi ilə relikt və endem növlərin azalması, mövcudluğunun təhlükə altına düşməsi və yox olması riski yaranmışdır. Antropogen amillərin bitkiliyə və ayrı-ayrı növlərə mənfi təsiri daha çox gəriyə dönməz prosesdir.

İqlim dəyişiklikləri və digər təbii hadisələr bitkilərə təsir etdiyi kimi, bitkilər də iqlimə reaksiya verir, təsir edirlər [31,33]. Qlobal istiləşmə və iqlim dəyişiklikləri bitkilərin daha hündürüklərə və enliklərə miqrasiyasına, növlərin, populyasiyaların paylanması və arealların parçalanmasına səbəb olacaqdır [34].

Antropogen təsirlər və iqlim dəyişiklikləri meşələrin yuxarı sərhəddinin aşağı düşməsinə, torpaq eroziyasının sürətlənməsinə və global miqyasda gedən aridləşmə prosesinə təsir göstərir.

Bütün bunlar meşə örtüyünün çox az olduğu Naxçıvanın meşə və kolluq bitkiliyi tədqiq etmək, relikt, nadir və endem növlərini müəyyən etmək, müasir vəziyyətini təhlil edərək, gələcək üçün proqnozlar hazırlamağı zəruri edir.

Ətraf mühit amillərinə daha həssas olan relikt, endem və nadir bitkilərin müxtəlif ekoloji şəraitlərdə öyrənilməsi dünyada botanik və ekoloqların prioritet tədqiqat istiqamətlərindən biridir.

Tang C.Q., Matsui T., Ohashi H. və başqaları Şərqi Asiyada relikt bitki növləri üçün uzunmüddətli sabit yaşayış yerlərinin müəyyən edilməsini öyrənmişlər. Tədqiqatlar 133 relikt cins üzərində aparılmışdır. Onlardan 98%-i oduncaqlı, 2%-i ot, 93 cins Şərqi Asiya endemiki, digər 40 cins isə Şərqi Asiya ilə dünyanın digər hissələri arasında disjunkt paylanmalara malik cinslərdir. Belə nəticəyə gəlmişlər ki, 2070-ci ilə qədər relikt növlərin yüksək zənginliyi ilə potensial əlverişli ərazilər azalacaq, Çinin cənub-qərbindəki və Vyetnamın şimalındakı ərazilər uzun-

müddətli iqlim baxımından sabit sığınacaq kimi qalacaqdır [38].

Plamen Glogov Bolqarıstanın Sofya bölgəsindəki Lozenska dağının relikt florasında 48 cins və 35 fəsiləyə aid 61 relikt növ yayıldığını göstərmişlər. Lozenskanın florasının 7,4%-ni (823 növ) və Bolqarıstan florasındakı relikt növlərin 17,6%-ni (347 növ) təşkil edir [35].

Xürrəm Şahzadə və b. Mərkəzi Çinin Qinling dağlarında və Şərqi Asiyanın ona bitişik ərazilərində *Dipteronia sinensis* növünün misalında geoloji və iqlim hadisələri təsirindən nəslə kəsilməkdə olan və relikt ağac növlərinin təkamül tarixini öyrənmişlər. Tədqiqat zamanı məlum olmuşdur ki, Şərqi Asiyada və Qinling dağlarının şərq və qərb tərəflərində *D. sinensis*-in iki genetik nəslə Pleistosen buz dövründən sonra əhəmiyyətli dərəcədə arelləri genişlənməmişdir [37].

Çindəki Qinling Dağları Şərqi Asiyada kritik biomüxtəlifliyin qaynar nöqtələrindən hesab olunur. Burada 337-dən çox relikt və nəslə kəsilməkdə olan növlər vardır [40].

Atəfəh Qorbanəlizadə, Hüseyn Əxani İranda Hirkanın III dövr relikt elementləri ilə zəngin meşələrin növ müxtəlifliyini, endemik və nadir bitkilərini öyrənmişlər. IUCN meyarlarına uyğun olaraq 30 növ təhlükə altında olan, 52 növ nəslə kəsilməkdə olan, 30 növ həssas və 81 növ isə ən az təhlükədə olanlardır. Hirkan meşə zonası Avro-Sibir regionu daxilində mühüm və unikal endemizm mərkəzidir. Hirkan meşələrində yayılmış *Parrotia persica* (DC.) C.A. Mey., *Quercus castaneifolia* C.A. Mey. *Alnus subcordata* C.A. Mey., *Acer velutinum* Boiss., *Pyrus boissieriana* Buhse, *Frangula grandifolia* (Fisch. & C.A. Mey.) növlər relikt bitkilərdir [32].

S. V. Saksonov və b. Volqa dağlarında aparılmış tədqiqatlar nəticəsində belə fikrə gəlmişlər ki, ayrı-ayrı relikt növlərin ekogeografi, bioekoloji xüsusiyyətlərini, ərazinin bitkiliyinin tarixi formalaşması ilə birlikdə öyrənmək məqsədəuyğundur [26].

Maqomadova R.S. və b. Qafqazın Rusiya hissəsinin kserofit florasını təhlil etmiş, burada 80 relikt növü olduğunu qeyd etmişlər. Yayılma sahəsi məhdud olan daha 8 növü üçüncü dövr reliktlərinə aid etmişlər. (*Pinus pallasiana*, *P. pitysua*, *Juniperus foetidissima*, *J. excelsa*, *J. isophylos*, *J. polycarpus*, *Ephedra equisetina*, *Celtis caucasica*) [25].

İ.S. Səfərov. və V.A. Olisaev Qafqaz florasında *Platanus orientalis* L., *Parrotia persica* C.A.Mey., *Punica granatum* L., *Juglans regia* L., *Buxus sempervirens* subsp. *hyrcana*, *Taxus baccata* L., *Castanea sativa* Mill., *Ficus carica* L., *Parrotia persica* C.A.Mey., *Danae racemosa* L. Moench., *Zelkova carpinifolia* (Pall) C.Koch., *Quercus castaneifolia* C.A.Mey., və s. relikt növlərinin olduğunu göstərmişlər [27. Səh.144-156].

V.C. Hacıyev qeyd edir ki, Böyük Qafqazda *Quercus*, *Tilia*, *Acer* və *Alnus* cinslərinin bir və ya iki növləri əsas meşə əmələgətiricilərdir. Yüksəklik artdıqca iri gövdəli meşələr get-gedə alçaq gövdəli, hətta park tipli meşələrə çevrilirlər. Belə meşələrdə *Quercus macranthera* Fisch., *Acer trautvetteri* Medw. növləri üstünlük təşkil edir [10. Səh. 29-36].

A.A. Bayramova Azərbaycanın Qərb rayonlarının

xüsusi qorunan ərazilərində 21 növ Azərbaycan, 47 növ Qafqaz endemi, 54 relikt növ olduğunu göstərmişdir. Müəllifin fikrincə bölgənin reliktləri Üçüncü dövr, Buzlaşma dövrü (pleystosen), Buzlaşmadan sonrakı (kserotermik) dövrün florasına aid olmaqla üç qrupa bölünür. 60-70 ildə antropogen amillərin təsiri ilə *Quercus macranthera*, *Acer trautvetteri*, *Betula pendula*, *B.litvinovii*, *Ulmus glabra*, *Padus avium*, *Laurocerasus officinalis* kimi reliktlərin təbii yayılma sahəsi azalmışdır [17].

C.Ə. Əliyev bioloji müxtəlifliyin qanunauyğunluqlarını tədqiq edərək qeyd edir ki, yer kürəsi biomüxtəlifliyinin yaranmasında iqlim amillərinin böyük rolu vardır. IV dövr buzlaşmaları Qafqazın biomüxtəlifliyinə də böyük təsir etmişdir. Buzlaşmalar Talış və Naxçıvan regionlarından yan keçmişdir. Talışda 3-cü dövrün relikt bitkiliyi (dəmirağac, şabalıdyarpaq palıd və s. ibarət Hirkan meşəsi) bu yerlərin buzlaşmaya məruz qalmamasının nəticəsidir [7. Səh. 53-55].

Naxçıvanın meşə örtüyünün az olmasına baxmayaraq, növ etibarı ilə zəngindir. A. İbrahimov qeyd edir ki, Naxçıvanda 3 şöbə, 3 sinif, 33 sıra, 45 fəsilə, 35 cinsə aid 299 növ, 8 variasiya və 2 forma ağac və kol bitkiləri vardır. Bunlardan 104 növü mədəni, 195 növü isə təbii florada yayılmışdır [11].

Ərazinin əsas və geniş meşə örtüyü Batabat yaylasındadır. M.Seyidov, T. Məmmədli və başqaları Naxçıvan Muxtar Respublikasının şimalında, Zəngəzur silsiləsinin cənub yamacında yerləşən Batabat yaylasında Biçənək aşırımından əraziyə daxil olan rütubətli hava axını səbəbindən nisbi rütubətin yüksək olduğunu qeyd edirlər. Bu amil zəngin bitki örtüyünün əmələ gəlməsinə səbəb olur. Belə ki, Batabat yaylasının florasında 58 fəsiləyə, 344 cinsə aid 968 bitki növünün olduğu müəyyən edilmişdir [28].

Material və metodlar.

Ərazinin təbii şəraiti: Təbii floranın tarixən formalaşmasında, meşə ekosistemlərinin yaranması, növ tərkibləri və davamlılığında ərazinin fiziki-coğrafi xüsusiyyətləri böyük rol oynayır. Odur ki, tədqiqat ərazisinin təbii şəraitini təhlil etmək, nəzərə almaq vacibdir.

Naxçıvanın özünəməxsus meşə və kolluq bitkiliyi ərazinin coğrafi vəziyyətindən, relyefindən, geoloji quruluşundan, dağ və çay sistemlərindən, torpaq və iqlim amillərindən, eyni zamanda tarixən baş vermiş tektonik hadisələrdən asılı olaraq milyon illər ərzində formalaşmışdır.

Fiziki-coğrafi xüsusiyyətləri, geoloji quruluşu, hidrocoğrafiyası: Azərbaycan Respublikası ərazisi şərti olaraq 5 böyük (Böyük Qafqaz, Kiçik Qafqaz, Kür-Araz ovalığı, Naxçıvan və Talış) və 20 yarım botaniki-coğrafi rayona bölünür. Naxçıvan Muxtar Respublikasının ərazisi Naxçıvan botaniki-coğrafi rayonunun "Naxçıvan dağlığı" və "Naxçıvan düzənliyi" yarım botaniki-coğrafi rayonlarını əhatə edir. Ölkənin Cənub Qərbində yerləşir. **Şəkil 1** və 2-də tədqiqat ərazisinin xəritəsi elektron mənbələrə istinadən verilmişdir [42,43].

Azərbaycan Respublikası ərazisi Alp-Himalay geosinklinalının bir hissəsi olub, Şərqi Avropa tavası ilə Afrika-Ərəbistan tavalarının toqquşduğu sərhəddə,

Qafqazın cənub-şərqində $39^{\circ} 24'$, $41^{\circ} 54'$ şimal en dairələri arasında və $44^{\circ} 46'$, $50^{\circ} 45'$ şərq uzunluğunda yerləşir.

Naxçıvanın dağlıq hissəsi Kiçik Qafqaz bir hissəsini təşkil edir. Kiçik Qafqaz dağ silsilələrinin ən yüksək zirvələri Zəngəzur silsiləsindədir (Qapıcıq 3906 m, Qazangöldağ 3814m və s.). Dərələyəz silsiləsinin hündür zirvələri Küküdağ (3210 m), Keçəldağdır (3115 m).

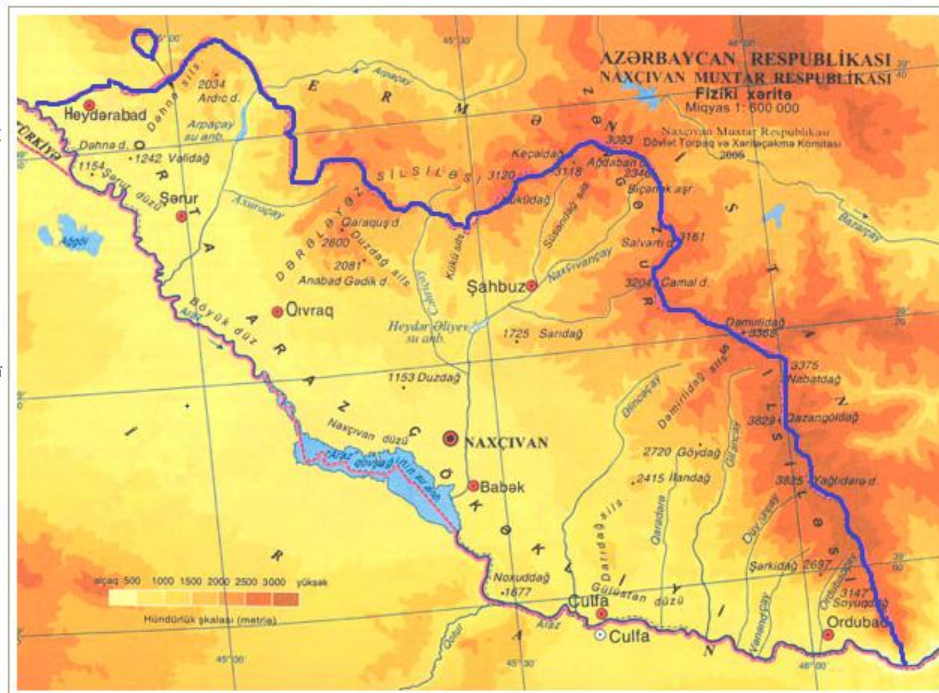
Naxçıvan çökəkliyinin əsas elementləri Arazın, Arpaçayın, Naxçıvançayın allüvial düzənlikləri, Əlincəçay, Gilançay, Ordubadçayın allüvial-prolüvial düzənlikləri, geniş sinklinal platolar (Düzdağ, Qıvrıq, Qarğalıq və s.), alçaqdağlıq massivlər (Vəlidəğ, Oğlanqala), çoxsaylı tirələr, kiçik sinklinal çökəklər,

platolar və dərələrdir (Nehrəm dərəsi və s.).

Naxçıvanda-Dərələyəz silsiləsində və Sədərək qalxmasında, Culfa rayonunun Araz çayı sahillərində, Alt Paleozoy çöküntüləri isə yalnız Tovuz rayonunda Zəyəmçay və Əsrəkçay hövzələrində çox kiçik sahələrdə vardır. Ölkə ərazində yeganə olaraq Tiras çöküntüləri Naxçıvanda Dərələyəz dağlarının cənub qərb hissəsində və Nehrəm dərəsində vardır. Təbəşir dövrü çöküntüləri Naxçıvanda Ordubad rayonunun cənub-şərq hissəsində geniş ərazilərdə vardır. Dördüncü dövrün allüvial-prolüvial və flüvio-qlyasial mənşəli çaqıl-daşı və qum qatlarından, lössəbənzər gilicələrdən ibarət kontinental çöküntüləri Naxçıvan çökəkliyində Arazyanı maili düzənlikdə vardır.



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Şəkil 1. Azərbaycan Respublikasının fiziki xəritəsi [42].

Şəkil 2. Tədqiqat ərazisi- Naxçıvan Muxtar Respublikasının fiziki xəritəsi [43].

Naxçıvanın ən iri çayı transmilli Araz çayıdır. Araz çayı Kürün ən böyük qoludur. Ümumi uzunluğu 1072 km-dir. Hövzəsinin sahəsi 101,9 min km²-dir. Mənbəyi Türkiyədə Bingöldağ silsiləsinin şimal yamacındadır (2990 m). Axura qolu qovuşandan sonra Araz Bəhramtəpə su qovşağının yaxınlığındakı təqribən 600 km məsafədə Ermənistan-Türkiyə, Azərbaycanın- Türkiyə və Azərbaycan-İran dövlət sərhədlərini təşkil edir. Çayın üzərində Naxçıvan MR və İran ərazisində Araz su qovşağı yaradılmışdır. Naxçıvan ərazisindən axan çaylar Şərqi Arpaçay, Naxçıvançay, Çanaqçıçay, Axuraçay (Qabaxlıçay), Cəhriçay, Əlincəçay, Qaradərəçay, Düylünçay, Vənəndçay, Əylisçay, Ordubadçay və Gənzəçay Kəməncaydır. Bu çayların əksəriyyəti az sulu və kiçik çaylardır. Regionun bütün çayları öz mənbələrini Zəngəzur və Dərələyəz silsilələrinin Araz baxan yamaclarından götürür. Yalnız öz mənbələrini Arpaçayı Vardenis, Qarabağ yaylalarının cənub yamacı və Dərələyəz silsiləsinin şimal yamaclarından götürür. Bu çaylar əsasən bulaqlardan və yağıntılardan formalaşır [6].

İqlimi: Azərbaycan Qafqazın cənub-şərqində, mülayim və subtropik iqlim qurşaqlarının qovuşduğu sahədə yerləşir. Böyük Qafqaz dağları şimaldan gələn soyuq, Kiçik Qafqaz dağları isə cənubdan gələn isti quru tropik hava axınlarının təsirini azaldır. Xəzər dənizi isə iqliminin mülayimləşməsinə təsir göstərir. Dünyada mövcud olan 7 iqlim qurşağından Azərbaycanda subtropik (ümumi ərazinin əksəriyyəti-65 %) və mülayim iqlim (Böyük Qafqaz dağlarının şimal-şərqində (ümumi ərazinin 35 %-i) qurşaqları vardır. Subtropik iqlim qurşağında yerləşən Naxçıvanda aşağıdakı iqlim tipləri vardır:

İqlim tipləri: Yarımsəhra və quru çöl iqlimi. Naxçıvanın Arazboyu düzənliklərini (1000 metrədən) əhatə edir. İllik yağıntı mümkün buxarlanmanın 15–50%-ni təşkil edir. Qışı soyuq, yayı qızdırıcıdır, bəzi günlər havanın temperaturu 42 °C-dən yuxarı olur.

Yayı quraq keçən soyuq iqlim. Naxçıvan MR-nın orta və yüksək dağlıq zonasını (1000–3000 m) əhatə edir. İllik yağıntı mümkün buxarlanmanın 50–dən 100%-ə qədərdir. Qışı soyuq və qarlı, yayı sərin.

Dağlıq tundra iqlimi. Naxçıvan MR-nın 3200 m-dən yüksək ərazilərindədir. Yağıntı mümkün buxarlanmadan 100–200% çox olur. Qış və yay soyuq keçir.

Temperatur. Azərbaycanda mütləq maksimum (+46 °C) və minimum (-32 °C) temperatur Naxçıvanda Culfa rayonunda müşahidə edilir. Temperaturun illik amplitudu Naxçıvanda 60 °C-dən çox olur (Kəskin kontinental iqlim tipidir). İlin ən soyuq ayı yanvardır. Yanvar ayında havanın orta aylıq temperaturu 2000 m yüksəklikdə –5–6 °C olur.

Atmosfer yağıntısı. Arazboyu ərazilərdə illik yağıntıların miqdarı 300 mm-dən azdır. Dağlarda yağıntılar 2600–2800 m. yüksəkliklərdə 2600–3000 m olur. Yağıntılı günlərin orta illik sayı Naxçıvan MR-nın Arazboyu düzənliklərində 60–70 gün, dağlıq ərazilərdə 90–110 gündür.

Havanın rütubətliyi. Naxçıvanda mütləq rütubət Azərbaycanın digər ərazilərinə nisbətən 1–1,5 mb azdır. Yanvarda düzənlik ərazilərdə ərazilərdə 4 mb,

dağlarda isə az olur.

Nisbi rütubət. Havanın orta illik nisbi rütubəti 55–65 %, yayda ən aşağı nisbi rütubətlik 35–50 % olur..

Günəş radiasiyası. Arazboyu düzənliklərində 2600–2800 saat, Orta dağlıq zonada 1900–2200 saat, yüksək dağlıq zonada (3000m) arıq 2200–2500 saat təşkil edir [1, 2].

Torpağı: Azərbaycanın torpaq örtüyünün 25 tipi, 60 yarım tip formaları vardır.

Naxçıvan ərazində hündürlüyə görə torpaqlar aşağıdakı kimi yayılmışdır:

1. Yarımsəhra, quru-çöl iqlimli düzənliklərində boz, boz-qonur, boz-çəmən torpaqlar.

2. Şoran torpaqlar Şərur və Ordubad düzənliklərində tala şəklində yayılıb.

3. 800 m-ə qədər dağətəyi və alçaq dağ çöllərində şabalıdı (boz-qəhvəyi) torpaqlar yayılmışdır. Şabalıdı torpaqlarda humusun miqdarı 2,5–3,5%-dir. Aşağıdan yuxarı getdikcə açıq şabalıdı, şabalıdı və tünd şabalıdı torpaqlar bir-birini əvəz edir.

4. 1800–2000 m-dən hündürlükdə subalp və alp çəmənliklərdə dağ-çəmən torpaqlarının ibtidai, torflu, çimli, yumşaq çimli yarım tipləri vardır.

5. Daha hündür dağ zirvələrinin əlverişsiz iqlimi torpaq əmələ gəlməsi prosesinə mənfi təsir göstərir. Dağlıq tundra iqlimi şəraitində (2000m-dən yüksəklikdə) dağ-çəmən torflu torpaqlar, dağ meşələri altında dağ-meşə torpaqları, yüksək qələvili torpaq tipləri mövcuddur [5].

Tədqiqatın obyekti: Ərazinin flora biomüxtəlifliyi əsasən Kiçik Qafqaz, Qədim, Bozqır və kserofit flora elementlərinə daxildir, zəngin növ müxtəlifliyinə malikdir. Bununla belə meşə sahələri olduqca azdır. Azərbaycanın 1021 min hektar meşə ərazilərinin 49%-i Böyük Qafqazın, 34%-i Kiçik Qafqazın, 15%-i Talış zonasının, cəmi 2%-i isə Aran zonası ilə birlikdə Naxçıvanın payına düşür [15].

Naxçıvan botaniki-coğrafi rayonunun “Naxçıvan düzənliyi” yarım botaniki-coğrafi rayonunun spesifik bitki örtüyü “Efemerli-yovşanlı və qışotlu səhralar”, “Xüştəkli-yovşanlı, xüştəkli və ləkəli-şorəngəli səhra və yarımsəhralar”, “Naxçıvan dağlığı” isə “Dağ-kserofit bitkiliyi”, “meşə, alp və subalp bitkiliyi ilə xarakterizə edilir. Naxçıvan florası Azərbaycanın ən zəngin floristik bölgəsidir. Burada 2700-dən çox ali sporlu bitki növü yayılmışdır [12.səh.12-13,]. Ərazidə təbii halda 200-ə yaxın oduncuqlu bitki növü müəyyən edilmişdir.

Tədqiqatın əsas obyekti Böyük Qafqazın Cənub yamaclarının (Azərbaycan Respublikası ərazisində) dendroflorasında olan relikt, nadir və endem növlər, meşə və kolluq bitkiliyidir.

Tədqiqatın metodları: E.M.Qurbanov Azərbaycan Respublikası meşə və kolluq bitkiliyini şərti olaraq 1 meşə bitkiliyi tipi, 7 formasiya sinfi, 34 formasiya qrupu və bir kolluq bitkilik tipi, 2 formasiya sinfi 9 formasiya qrupunda təsnif etmişdir [12 s.219-279]. Meşə və kolluq bitkiliyi bu təsnifata görə təhlil edilmişdir.

Reliktlərin geoloji dövrlər üzrə təsnifatı və ümumi siyahısı A.A.Qrossheyim [23], V.İ.Baranov [18. Səh.195-204] və A.N.Kriştofoviç [24.Səh.555-557], endem növlər A.M.Əsgərova [8] görə verilmişdir.

Cins və növlərin adları World Flora Online [41] informasiya sistemində görə verilmişdir. Tədqiq olunan nadir bitkilərin qırmızı siyahısı və statuslarının müəyyən edilməsində Azərbaycan Respublikasının Qırmızı Kitabından [4] və T.S.Məmmədov və başqalarının [14] əsərlərindən istifadə edilmişdir.

Nəticə və müzakirələr.

2019-cu ildə Naxçıvan meşələrində yayılmış və mədəni florada Turqay florasına aid *Juglans regia* L., *Salix alba* L., *Acer velutinum* Boiss., *Carpinus betulus* L., *Mespilus germanica* L., *Ulmus scabra* Mill., *Vitis sylvestris* C.C.Gmel. növləri üzərində fenoloji müşahidələr aparılmış, böyümə və inkişaf dinamikalarını öyrənilmişdir. Toxumları götürülərək Mərkəzi Nəbatat Bağında təcrübə sahəsində əkilmiş, ontogenezin müxtəlif dövr və mərhələləri tədqiq edilmişdir. Məlum olmuşdur ki, bu növlər Mərkəzi nəbatat Bağının yerləşdiyi Abşeronun quru subtropik iqlimində becərilmə və suvarma zamanı normal cücərir və böyüyüb, inkişaf edirlər.

2021-ci ilin iyun ayının II ongünlüyündə Şahbuz rayonunda Batabat meşə massivinin (Həsən Əliyev adına Zəngəzur Milli Parkı) Biçənək kəndi ətrafı (39°30'10" şm. e. 45°46'09" ş. u., d.s.h 1633 m), Naxçıvan çayın sahillərinə yaxın ərazilərdə meşənin qismən seyrəkləşdiyi, bəzi həşərat növlərinin süfrələrinin ağac və kol bitkilərinin yarpaqlarına ciddi zərər verdiyi aşkar edilmişdir. Belə bir hal 90-cı illərin sonu, 2000-ci illərin əvvəllərində də müşahidə edilmişdir. Lakin sonralar meşə özünü təbii bərpa etmişdir. Gəlinən nəticə budur ki, bu proses dövrü olaraq bir neçə on illikdən bir baş verir, antropogen təsirlərə nisbətən ekoloji amillərdən daha çox asılıdır.



Şəkil 3. *Juglans regia* L. Culfa rayonu, Bayəhmədli kəndi. D.s.h.1750m. 13.07.2021

Şərur rayonu Qaraquş dağında (39°30'41" şm. e. 45°15'33" ş. u., D.s.h.2600m.), Culfa rayonun Ərəfsə (39°17'31" şm. e. 45°47'05" ş. u., D.s.h.1600 m) Ləkitağ, Boyəhmədli (39°16'03" şm. e. 45°50'45" ş. u., 1750m.) kəndləri istiqamətində Əlincə çayın ətrafında

Meşənin yuxarı qurşağında, həmçinin Biçənək və Qışlaq kəndləri arasında quraqlıq, torpağın qeyri münbitliyi səbəbindən firqanoid- seyrək, əsasən kolluqlardan ibarət meşə bitkili yayılmışdır. Və şəraitə, xüsusilə quraqlığa qarşı uyğunlaşmaq üçün alçaqboylu olmaqla yanaşı, gövdə və budaqları daha çox odunlaşmış, yoğunlaşmış, bəzən iri tikanlarla örtülmüşdür. Burada *Crataegus* L., *Rosa* L., *Prunus* L., *Pyrus* L., *Juniperus* L.- cinslərinə daxil olan növlərin nümayəndələri üstünlük təşkil edir.

Biçənək və Qışlaq kəndləri arasındakı ərazinin bitkiliyi Culfa və Ordubad rayonlarının orta dağ qurşağı, həmçinin Xızı rayonunun firqanoid tipli bitkiliyi ilə oxşardır.

Eyni zamanda müşahidə edilmişdir ki, meşənin əsasını təşkil edən *Quercus macranthera* Fisch.et C.A. Mey. bol meyvələr (qozalar) gətirmişdir. Bəzi illərdə (2023) burada palıd ağaclarının demək olar ki, heç meyvə vermədiyi də müşahidə edilmişdir.

Sentyabrın III on günlüyü və oktyabrın I on günlüyündə Şərur, Sədərək, Şahbuz və Culfa rayonlarında meşə və kolluq bitkiliyinin, mədəni bitkiliyin tədqiqi zamanı *Corylus avellana* L. və *Juglans regia* L. relik növlərinin vegetasiyanı başa vurduğu, xəzan və meyvə vermənin sona çatdığı müşahidə edilmişdir. *Corylus avellana* L. və *Juglans regia* L. qoz ağaclarının bəzi yerlərdə seyrək, bir çox yerlərdə isə bol məhsul gətirdiyi müşahidə edilmişdir (Şəkil 3). Seyrək məhsul gətirən ərazilərdə çiçəkləmə dövründə hava şəraitinin kəskin dəyişməsi, hətta qar yağması müşahidə edilmişdir (Məsələn Şərur rayonunda).

firqanoid- seyrək, meşə və kolluq bitkiliyində *Rosa* L., *Prunus* L., *Salix* L., *Pyrus* L. cinsləri, *Pyrus salicifolia* Pall., *Amygdalus fenzliana* (Fritsch.) Lipsky növləri üstünlük təşkil edir (Şəkil 4). Xüsusilə *Pyrus salicifolia* Pall. geniş yayılmış və çoxlu forma müxtəlifliyi vardır.

Pyrus salicifolia Böyük Qafqazın Şimal Şərqində Xızı dağlarında da quraqlıq ərazilərdə, firqanoid tipli bitkilik ərazilərində geniş yayılmışdır.

Bu ərazilərin quraq iqlim şəraitini və ekocoğrafi xüsusiyyətlərini, quraqlıq sevən relikտ növlərini nəzərə alsaq, kserotermik relikտ ərazilər hesab edə bilərik.



Şəkil 4. *Pyrus salicifolia* Pall. Şərur r, Qaraquş dağı. d.s.h.2600m. (30.05.2024)

Batabat meşə massivinın (39°32'21" şm. e. 45°47'04" ş. u., D.s.h. 2134-2500 m) iqlim və torpaq şəraitinin bitkilər aləmi üçün əlverişli olduğunu, ekocoğrafi mövqeyini, dağların şimaldan gələn soyuq hava cərəyanlarının qarşısını kəsdiyini, tez-tez və sürətlə əsən küləklərin olmadığını, bulaqların çoxluğunu, Naxçıvan çayın burada bol sulu olmasını, Turqay florasından qalmış relikտ növlərlə zənginliyini nəzərə alsaq ərazini mezotermik relikտ ərazi hesab edə bilərik.

Aparılan tədqiqatlar nəticəsində Naxçıvanın Muxtar Respublikasının bitkiliyində 1 meşə bitkiliyi tipi, 3 meşə formasiya sinfi, 14 meşə formasiya qrupu, 1 kolluq bitkiliyi tipi, 2 kolluq formasiya sinfi, 9 kolluq formasiya qrupu müəyyən edilmişdir (**Cədvəl 1**).

Bəzi meşə bitkiliyi birliklərində relikտlərin də dominant növlər sırasında olduğu müəyyən edilmişdir :

1.Enliyarpaqlı dağ meşələri: Şahbuz, Culfa, Ordubad, Şərur.500-2200 m.*Carpinus betulus* L.,

Mespilus germanica L., *Rosa canina* L., *Juglans regia* L., *Cerasus incana*(Pall.), *Salix alba* L.

2. Yüksək dağ meşələri: Şahbuz, Culfa, Ordubad, Şərur.700-3000 m. *Carpinus betulus* L., *Acer hyrcanum* Fisch. et C.A.Mey., *Tilia begoniifolia* Stev., *Pyrus salicifolia* Pall., *Sorbus Ulmus glabra* Huds.,

3.Arid seyrək meşələr: Şahbuz, Culfa, Ordubad, Şərur, Babək, Kəngərli. 500-3200 m. *Punica qranatum* L., *Pyrus salicifolia* Pall., *Amygdalus fenzliana* (Fritsch.) Lipsky), *Ficus carica* L. *Celtis caucasica* Willd., *Acer velutinum* Boiss., *A.hyrcanum* Fish.ex.

Naxçıvanda enliyarpaq dağ meşə və yüksək dağ meşələri tipləri əsasən Şahbuz rayonu ərazisində olan Batabat yaylasındadır. Digər ərazilərdə Arid seyrək meşə tipləri mövcuddur.

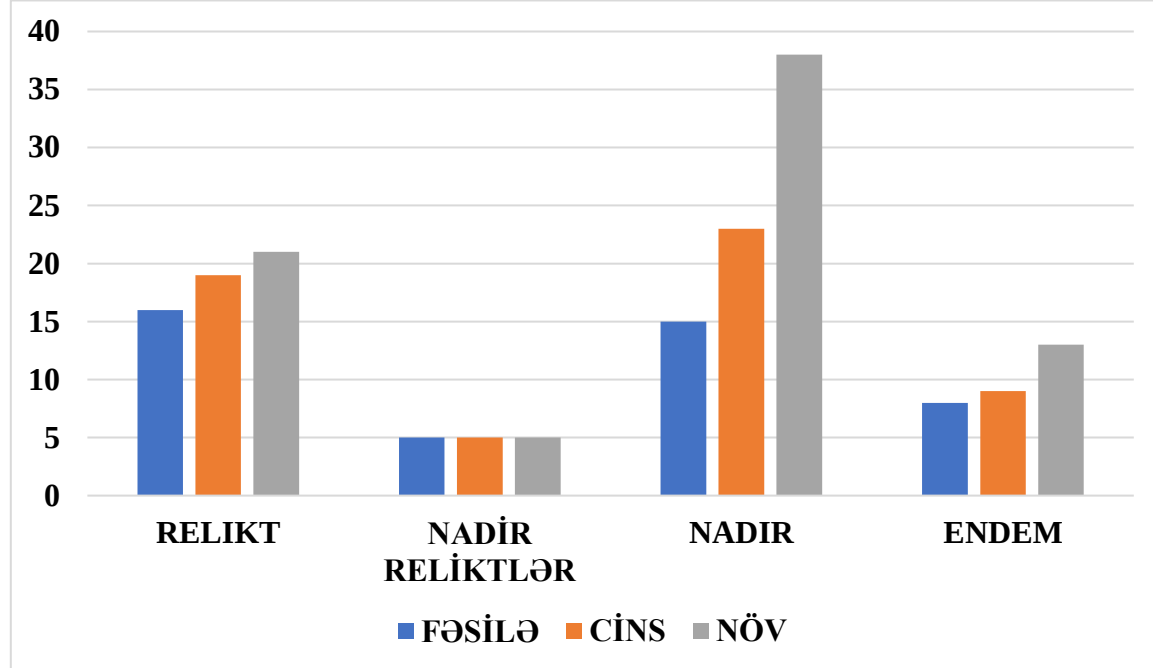
Naxçıvan meşə kolluq bitkiliyinin tarixi formalaşması Kiçik Qafqaz florasının, İran-Turan flora vilayətinin, Aralıq Dəniz ətrafı flora vilayətinin və Anadolu qırılma xəttindən şimal-şərqdə yayılan flora örtüyünün yerli torpaq-iqlim şəraiti və ekocoğrafi amillərin qarşılıqlı əlaqəsindən formalaşmışdır.

Naxçıvanın meşə (FOREST) və kolluq (SCHURBS) bitkiliyi.

Formasiya sinifləri	Formasiya qrupları	Dominant növlər	Areallar və hündürlük
Bitkilik Tipi: MEŞƏ (FOREST) BİTKİLİYİ			
1.Enliyarpaqlı dağ meşələr formasiya sinfi	(Carpineta), (Querceta) və (Carpineta-Crataegeta)	<i>Carpinus betulus</i> L., <i>Crataegus pentagyna</i> Waldst. et Kit, <i>Quercus macranthera</i> Fisch. Et C.A.Mey., <i>Mespilus germanica</i> L., <i>Rosa canina</i> L., <i>Juglans regia</i> L., <i>Cerasus incana</i> (Pall.), <i>Salix alba</i> L.	Şahbuz, Culfa, Ordubad, Şərur, Babək rayonları. 500-2200 m.
2.Yüksək dağ meşələri formasiya sinfi	(Carpineta-Quercetum), (Acereta-Carpinetum), (Acereta)	<i>Quercus macranthera</i> Fisch. Et C.A.Mey., <i>Carpinus betulus</i> L., <i>Crataegus pentagyna</i> Waldst. Et, Kit., <i>C. pallasii</i> Griseb., <i>Acer campestre</i> L., <i>A. hyrcanum</i> Fisch. et C.A.Mey., <i>Tilia begoniifolia</i> Stev., <i>Pyrus salicifolia</i> Pall., <i>Sorbus boissieri</i> C.K. Scheideid. , <i>Ulmus glabra</i> Huds.,	Şahbuz, Culfa, Ordubad, Şərur. 700-3000 m
3. Arid seyrək meşələr formasiya sinfi	(Junipereta), (Querceta), (Pyruta), (Amygdaleta), (Crataegeta), (Puniceta) və (Acereta), (Maleta-Pruneta)	<i>Pistacia mutica</i> Fisch. et C.A.Mey., <i>P. vera</i> L., <i>Punica granatum</i> L., <i>Juniperus foetidissima</i> Willd., <i>J. polycarpus</i> C.Koch., <i>Pyrus salicifolia</i> Pall., <i>Amygdalus fenzliana</i> (Fritsch.) Lipsky., <i>Crataegus meyeri</i> Pojark., <i>Acer ibericum</i> Bieb., <i>Ficus carica</i> L. <i>Celtis caucasica</i> Willd. <i>Acer velutinum</i> Boiss., <i>A.hyrcanum</i> Fish.ex, <i>Malus orientalis</i> Uglitzk., <i>Prunus divaricata</i> Ledeb.	Şahbuz, Culfa, Ordubad, Şərur, Babək, Kəngərli 500-3200 m.
Bitkilik Tipi: KOLLUQ (SCHURBS) BİTKİLİYİ			
1. Meşəaltı kolluqlar formasiya sinfi	(Crataegeta), (Tamariceta), (Elaeagneta), (Elaeagneta-Tamaricetum), (Rubueta) (Rubueta-Tamaricetum)	<i>Crataegus caucasica</i> C.Koch., <i>Tamarix ramosissima</i> Ledeb., <i>Tamarix hohenackeri</i> Bunge., <i>Elaeagnus augustifolia</i> L., <i>Berberis vulgaris</i> L., <i>Hippophae rhamnoides</i> L., <i>Rubus anatolicus</i> Foske ex Hausskn.	Şahbuz, Culfa, Ordubad, Şərur, Babək, Kəngərli, Sədərək 400-2800 m.
2. Kserofit kolluqlar formasiya sinfi	(Tamariceta-Rubuetum-Elaeagnosum), (Paliureta) və (Tamariceta)	<i>Elaeagnus augustifolia</i> L., <i>Rubus anatolicus</i> Foske ex Hausskn., <i>Tamarix ramosissima</i> Ledeb., <i>Paliurus spina-christi</i> Mill., <i>Rhamnus pallasii</i> Fisch. et C.A.Mey., <i>Rhamnus spathulifolia</i> Fisch.et C.A.Mey.,	Şahbuz, Culfa, Ordubad, Şərur, Babək, Kəngərli, Sədərək 300-2500 m

Tarixi geoloji dövrlərdə global genişmiqyaslı iqlim dəyişiklikləri bitkilərin miqrasiyasına, özlərinə uyğun sığınacaq yerlərində toplanmasına səbəb olmuşdur. Mövcud şəraitə uyğun növlər mübarizədən qalib çıxaraq məskulanlaşmış, daha çox əlverişli əlamətlərə malik bitkilər isə dominant növlər olmuşdur. Naxçıvanın təbii şəraiti burada əsasən dağlıq, quru, kontinental iqlimə uyğun kserotermik, kəskin isti və soyuqlara dözə bilən növlər üçün sığınacaq ola bilməmişdir.

Naxçıvanın meşə və kolluq bitkiliyinin bioloji xüsusiyyətlərini analiz edərək, burada və Azərbaycan Respublikasının digər ərazilərində arealların ekogeografi amillərinin təhlilini apararkən *Pyrus salicifolia* Pall. və *Amygdalus fenzliana* (Fritsch.) Lipsky. növlərini III dövrün Kserotermik reliktlərinə aid etmişik. Naxçıvan dendroflorasında ümumilikdə III dövrün reliktlərinə aid 16 fəsiləyə, 19 cinsə aid 21 növ, 15 fəsiləyə, 23 cinsə aid 38 nadir növ yayılmışdır. 5 fəsiləyə 5 cinsə aid 5 növ isə həm relik, həm də nadir bitkilərdir (**Şəkil 5.**).



Şəkil 5. Naxçıvan dendroflorasının relik, endem və nadir növləri.

III dövrün Poltav və Turqay florasına aid relik ağac və kol növləri Naxçıvanın meşə və kolluq bitkililiyinin qiymətli bitkilərindən olmaqla yanaşı, ekosistemlərin əsas elementlərindəndir. Kaynazoy erasının III dövrünün Paleosen və Eosen mərhələlərində iqlim isti və rütubətli olmuşdur. Bu dövrdə Poltav florası- əsasən həmişəyaşıl bitkilər üstünlük təşkil etmişdir. Üçüncü dövrün Oligosen mərhələsinin əvvəllərindən etibarən həmişəyaşıl Poltav florasını yarpaqlarını tökən Turqay florası əvəz etməyə başladı. Bu proses Avropadan başlayıb, şimala doğru getmişdir.

O cümlədən Aralıq dənizi ətrafını və Qafqazı da əhatə etmişdir. Turqay florasında *Fagus* L., *Ulmus* L., *Betula* L., *Quercus* L., *Juglans* L., *Pterocarya* Runth., *Acer* L., *Vitis* L., *Zelkova* Spch., və s. yarpağını tökən cinslər üstünlük təşkil etmişlər. Oligosenin ortalarında Turqay florası Asiyadan Yaponiyaya, Saxalindən Kazaxıstana, Urala, Avropada Şotlandiya, İngiltərəyə qədər yayılır və iynəyarpaqlıların areallarını sıxışdırırlar.

III dövrün sonları, IV dövrün əvvəllərindən etibarən buzlaşma ilə əlaqədar olaraq Avropa, Asiyada, Qafqazda, o cümlədən də indiki Azərbaycan ərazisində Oligosen dövründən geniş yayılmış Turqay florasının arealları kiçilməyə başlayır [24.s-552.].

E.V.Vulf "relik" anlayışına tarixi-coğrafi baxımından yanaşır. Onun fikrincə hər hansı növ az və ya çox qədim floranın relik arealının bir hissəsinə çevrildiyi vaxtdan relik bitki hesab edilir [19]. A.A.Qrossheyim isə hesab edirdi ki, yeni mövcud şəraitə yüksək polimorfizm dərəcəsinə malik qədim növlər adaptasiya oluna bilirdi [22].

A.L. Ebel qeyd edir ki, relik növlərin öyrənilməsi florogenez haqqında bir sıra fikirləri üzə çıxarmışdır ki, bunların əsasında "relik nəzəriyyəsi"-nin qəbul edilmiş bəzi müddəalarının tənqidi təhlilinə zərurət yaranmışdır [30]. "Reliktlərin filogenezinin tədqiqi təkamülün istiqamətləri, mövcud coğrafi -ekoloji şəraitdə tarixən flora əvəzedilmələrinin, vegetativ və

generativ orqanlarda baş vermiş dəyişikliklərin istiqamətləri və mexanizmlərinin izah edilməsində mühüm rol oynayır. Relikt bitkilər arealı müəyyənləşdirən amillərin global dəyişikliklərinə müxtəlif orqanların genetik potensialı, çevik reaksiya verə bilmək xüsusiyyətlərindən asılı olaraq, mövcud şəraitə uyğunlaşmışlar " [21] E.V.Vulf, A.A.Qrossheyim və A.L. Ebelin bu fikirləri, bizim nəzəri təhlillər əsasında gəldiyimiz qənaətlər ilə üst-üstə düşür.

Üçüncü dövr reliktləri- Pliosendən bu yana ciddi dəyişikliklər olmadan qorunub saxlanılan növlərdir.

III dövr reliktlərini tarixi və flora kompleksləri baxımından aşağıdakı qruplara bölmək olar:

1. III dövr subtropik həmişə yaşıl Poltav florası reliktləri (III dövr arktik flora qədər mezotermik reliktlər.).

2. III dövr arktik floranın yarpağını tökən mezotermik reliktləri-Turqay reliktləri.

3. III dövr kserotermik reliktlər.

Reliktlərin dövrümüzdə qədər gəlib çıxmalarını və yaşamlarını davam etdirmələrini iki mühüm kompleks amillərlə izah etmək olar.

Birinci amillər kompleksi növlərin özlərinə aiddir. Global dəyişikliklərə genetik potensial, çevik reaksiyadan asılı olaraq, mövcud şəraitə adaptasiya oluna bilmək. Buna bariz nümunə kimi III dövrün əvvəllərinə qədər hökm sürən tropik iqlim şəraitində yayılmış həmişəyaşıl bitki növlərinin bəzilərinin mülayim və soyuq iqlimə uyğunlaşmaq üçün yarpaqlarını tökən formalara keçid etməsidir. Relikt növlər olan *Parrotia persica* (DC.) C.A.Mey.-dəmir ağac, *Quercus monqolica* Fisch.ex Ledeb.-monqol palıdı və s. bitkilərdə qışda yarpaqlar qurular da, tökülməyərək budaqlarda qalırlar. Bu isə həmin növlərin çox güman ki tropik iqlimin hökmran olduğu, hələ differensasiya etmədiyi təbəşir dövründə və III dövrün əvvəllərində geniş yayılmış həmişəyaşıl Poltav florasının elementləri olduğunu söyləməyə əsas verir. Yarpaqların tökülməsi dendrofloranın təkamülündə yeni mərhələ

olub, soyuğa dözməyə imkan verən mühüm təkamül dəyişikliyi.

Digər dəyişikliklərə misal olaraq quraqlığa davamlılığa uyğunlaşmaq üçün kseromorf quruluşların meydana gəlməsini misal göstərmək olar. Məsələn *Quercus* L., *Juglans* L., *Carpinus* L. və s. relik cinslərdə kök sisteminin güclü inkişaf etməsi pilosen mərhələsinin sonu, IV dövrün əvvəllərində başlayan qlobal buzlaşma zamanı bu cinslərin soyuğa və quraqlığa dözməsinə imkan yaratmışdır. Tumurcuqların örtük pulcuqlarının sərtləşməsi, toxumları əhatə edən meyvələrin qalınlaşması, bəzən oduncaqlaşması (*Quercus* L., *Juglans* L., *Corylus* L., *Castanea* L. və s.), cücərtilərin epikatil-ləpə yarpaqlarının torpağın altında qalan tipdə olması, biokimyəvi tərkiblərin dəyişməsi, məsələn payızda müxtəlif orqanlarda, xüsusilə meyvələrdə şəkərin miqdarının artması-bütün bunlar soyuğa, quraqlığa və s. əlverişsiz ekoloji dəyişikliklərə adaptasiya etməyə imkan verən əhəmiyyətli təkamül dəyişiklikləridir.

İkinci mühüm amillər kompleksi relik arelların xüsusiyyətləri ilə əlaqədardır. Yəni müxtəlif tarixi geoloji dövrlərdə arelların qlobal kəskin ekoloji və coğrafi dəyişmələrin təsirindən kənarda qalmasıdır. III dövr reliktlərinin arelları buzlaşma dövründə buzlaşmaya məruz qalmayan ərazilərdir. Yəni əvvəldən orda olub, indiyə qədər məhv olmayıb, qalan növlərdir. Qərbi Qafqazın sahilboyu, Cənub-Şərqi Qafqazda Talışda, Kolxididə, Uzaq Şərqdə, Krımda, Şimali Amerikanın Sakit okean sahillərində relik arellar mövcuddur [16. s.221-222]. Göründüyü kimi relik arelların böyük əksəriyyəti dəniz və okean sahillərində və ya ona yaxın ərazilərdədir. Buradan iki nəticə çıxarmaq olar: Birincisi, böyük su hövzələri sahil ərazilərdə iqlimi kəskin dəyişməyə qoymur, nisbətən sabit saxlayır. Bu da suyun yüksək istilik tutumu ilə izah oluna bilər (Suyun xüsusi istilik tutumu. $c=4200 \text{ C/kq} \cdot \text{K}$).

Relikt arelları bitkilər üçün əlverişli edən amillərdən biri də duman və çəndir. Toros Dağları Yunanıstanın Rodos adasından başlayıb, Suriya sərhədlərinə qədər 2000 km-ə qədər uzanır. Bu dağların Türkiyənin Ağdəniz sahillərinə paralel olan ərazilərində çənli və dumanlı günlərin sayı çoxdur. Dənizin buxarlanmasından yaranan çən, duman dağlarda, xüsusilə dərələrə dolaraq uzun müddət qalır. Türkiyənin meşələrinin 25%-i Ağdəniz bölgəsində, xüsusilə Toros dağlarındadır. Ölkə florasında olan növlərin 1/3-i (3700-ə yaxın) endem, 20%-dən çoxu relik növlərdir və onların çoxu Toros dağlarındadır. Türkiyədə Mərmərə dənizinin ətrafı, Qara dənizin şərq və qərb sahillərinə yaxın meşələrdə də daha çox relik ağac və kol növləri vardır [36].

Güclü və tez-tez əsən küləklər relik ərazilər üçün xarakter deyil. Ümumiyyətlə bu cür küləklər buxarlanmanı həm torpaqdan, həm də yarpaqlardan sürətləndirir, torpağın üst münbit qatını sovurur. İstinin və soyuğun bitkiyə mənfi təsirini şiddətləndirir. Ontogenezin və morfogenezin yarpaqlama, çiçəkləmə, tozlanma, meyvəvermə və b. fazalarına mənfi təsir edir. Ağac və kolları cücərti, yuvenil və virqinil mərhələlərində müxtəlif istiqamətlərə tez-tez kəskin əyir, hündür ağacların gövdə və budaqlarını möhkəm

silkələyir, tarazlığını pozur, çatladır, qırır. Eyni zamanda ərazidə meteoroloji amilləri-temperaturu, nəmliyi, yağıntıları tez-tez dəyişir ki, bitkilər buna uyğunlaşmağa vaxt tapa bilmirlər. Küləklər bitkilərin tənəffüs proseni də təsir göstərir. Odur ki, küləklərin tez-tez və sürətlə əsdiyi Abşeron yarımadasında təbii ağac və kol növləri çox azdır.

Xızı rayonu ərazisində Böyük Qafqazın Cənub Qərb 800-1500 m yüksəkliklərdə quraqlıq, torpağın qeyri münbitliyi, xüsusilə küləklər səbəbindən firqanoid-seyrək, əsasən kolluqlardan ibarət meşə bitkiliyi üstünlük təşkil edir. Burada *Pyurus salicifolia* Pall., *Mespilus germanica* L., *Q.iberica* Stev. Ex Bieb., *Pyrus salicifolia*, *Prunus spinosa* L., *Quercus macranthera* Fisch.et C.A. Mey., *Salix alba* L., *Acer laetum* C.A. Mey., *Salix caprea* L. növləri yayılmışdır. Şəraitə, xüsusilə küləyə qarşı uyğunlaşmaq üçün alçaqboylu olmaqla yanaşı, gövdə və budaqları daha çox odunlaşmış, yoğunlaşmışdır, bəzən iri tikanlarla örtülmüşdür. Küləkləri nəzərə almasaq, quraqlıq və torpağın qeyri münbitliyi, temperaturun qışda çox aşağı, yayda da isti olması, nisbi rütubətin azlığı baxımdan ərazinin ekocoğrafi xüsusiyyətləri, eyni zamanda bitkiliyi Naxçıvanın Şərur, Culfa və Ordubad rayonlarının orta dağ qurşağı ərazilərinə oxşardır.

Arealı müəyyənləşdirən amillərdən biri də günün uzunluğu, işığın düşmə müddəti və düşmə bucağıdır. Ərazinin geoloji quruluşu və relyefi də bitki arellarının sərhədlərini müəyyənləşdirən əhəmiyyətli amillərdəndir. Məhz bu amil eyni ekoloji amillərə malik, yaxın ərazilərin fərqli flora örüyünə səbəb olur. Məsələn, Nax. MR-nın əsas meşə örtüyünün olduğu Batabat, ağac və kol bitkiləri bitməyən digər yaxın ərazilərdən iqlim amilləri ilə kəski fərqlənmir. Burada meşənin mövcudluğu ərazinin geoloji quruluşu, relyefi, su dövrünü, işığın düşmə müddəti (ışıqlı və kölgəlik vaxtların növbələşməsi) və digər amillərlə izah edilə bilər. Eyni zamanda, bəzən meşələrin sərhəddi seyrəkləşərək tədricən deyil, sanki kəsilmiş, xətt çəkilmiş kimi bitir. Eyni torpaq-iqlim şəraiti olan ərazinin meşə sahəsindən 5-10 m aralıda heç bir ağac və ya kola rast gəlinmir. Bunun əsas səbəblərindən biri də Günəş şüalarının düşmə xüsusiyyətləri, işıqlanma dərəcəsi, xüsusilə radiasiya amilləri ola bilər.

Müasir dövrümüzdə Azərbaycanın təbii florasında Poltav florasına aid 7 fəsiləyə, 8 cinsə aid 8 növ, Turqay florasının 16 fəsiləyə, 28 cinsə aid 38 növ, kserotermik reliktlərdən isə 3 fəsilə, 3 cinsə aid 4 növ ağac və kol bitkiləri yayılmışdır. Turqay florasından qalma relik bitkilərə əsasən Talışda, Kolxididə və Böyük Qafqazın Cənub yamaclarını əhatə edən meşələrdə daha çox təsadüf edilir [20].

Naxçıvan dendroflorasında subtropik Poltav florasından dövrümüzə qədər qalmış 3 fəsiləyə, 3 cinsə aid 3 relik ağac və kol növlərinin (*Punica granatum* L., *Gleditsia caspia* Desf. və *Ficus carica* L.) hər biri nadir bitkilərdir (**Cədvəl 2**).

Ərazidə mülayim, yarpağını tökən Turqay florasına aid 12 fəsiləyə, 14 cinsə, daxil olan 16 növ müəyyən edilmişdir. Bunlardan *Pinus kochiana* Klotzsh ex. K.Koch. və *Vitis vinifera* L. (*V.sylvestris* C.C.Gmel.) nadir növlərdir.

Pyrus salicifolia Pall. və *Amygdalus fenzliana* (Fritsch.) Lipsky. növləri III dövrün Kserotermik reliktləridir.

2023-cü ildə nəşr edilmiş “Azərbaycan Respublikasının Qırmızı Kitabı”nın üçüncü nəşrində nadir və nəslə kəsilmək təhlükəsində olan 460 flora növü, o cümlədən 383 ali, 15 ali sporlu, 6 mamır, 14 şibyə, 5 yosun və göbələk növü göstərilmişdir. Nadir ali bitkilərin 102 növü (27 %-i) ağac, kol, yarımkol və kolcuqlardır [4. Səh.10]. Ancaq 10 il əvvəl (2013 -cü ildə) nəşr edilmiş “Azərbaycan Respublikasının Qırmızı Kitabı”nın ikinci nəşrində 266 ali bitki növləri haqqında məlumat verilir [3].

Demək 10 ildə nadir və nəslə kəsilmək təhlükəsində olan ali bitkilər sırasına 117 növ (44%) əlavə edilmişdir ki, bu fakt təbii florada ümumən növlərin nə qədər təhlükə altına düşməsinə və tamam yoxa çıxması ehtimalının yüksək olduğunu göstərir.

Qafqazın təbii florasında 6350 növ [39], Azərbaycan florasında isə 4961 ali bitki növü yayılmışdır [12. Səh.214]. Ölkənin florasının zənginliyi (Qafqaz florasının 78%-dən çoxu) təbii, fiziki-coğrafi şəraiti, iqlim müxtəlifliyi ilə izah edilir. Ali bitkilərin 28 fəsiləyə daxil olan 75 cinsə aid 146 növü endem, 53 fəsiləyə daxil olan 191 cinsə aid 402 növü subendem bitkilərdir. Endemlərin çoxu Naxçıvan və Talış florasında mövcuddur [9. Səh.5-8].

Azərbaycanın florasında 48 fəsiləyə, 135 cinsə aid 435 ağac və kol növü yayılmışdır. Bunlardan 119 növ ağac, 316 növ isə kol bitkisidir. Ağac və kolların təxminən 16%-i, 70 dən çox növü endem bitkilərdir. Endemlərin əksəriyyəti relikt növlərdir (*Ficus carica* L., *Punica granatum* L., *Betula raddeana* Trautv., *Corylus colurna* L., *Pinus eldarica* Medw.) [29]. Relikt bitkilərdən *İlex hyrcana* Pojark., *Hedera pastuchowii* Woronow., *Albizzia julibrissin* Durazz., *Alnus subcordata* C.A.Mey., *A.barbata* C.A. Mey., *Quercus castaneifolia* C.A.Mey., *Fraxinus coriariifolia* Scheele., *Pinus eldarica* Medw. növləri subendemlərdir [8].

Tədqiqat ərazisində endem ağac və kol növləri də yayılmışdır. Azərbaycanın dendroflorasında olan endemik növlərin çoxu Orta Asiya elementi kimi Naxçıvan florasında rast gəlinir. Talışda təsadüf olunan endemiklər isə Hirkan mənşədirlər, yəni üçüncü dövrün reliktlərindəndir [13].

Naxçıvanın meşə və kolluq 8 fəsiləyə, 9 cinsə aid 13 növ endem ağac, kol və kolcuqlar yayılmışdır. Bunlardan 5 növü nadir, 2 növü isə nadir olmaqla yanaşı həm də relikt bitkilərdir.

Naxçıvanın meşə və kolluq bitkililiyinin relikt, nadir və endem növlərinin təbii bərpasına, areallarının sərhədinə qlobal iqlim dəyişiklikləri və antropogen amillər son dövrlərdə daha çox mənfi təsir göstərir.

Cədvəl 2.

Naxçıvan dendroflorasının relikt, nadir və endem növləri

RELİKT NÖVLƏR Family,Genus and Species.	NADİR NÖVLƏR IUCN -nin kateqoriya və kriteriyalarına görə milli qiymətləndirmə. National Status. Family,Genus and Species.	ENDEM NÖVLƏR Family,Genus and Species.
1	2	3
Poltav florasına aid relikt növlər.		
Punicaceae Horan.: <i>Punica granatum</i> L.	Punicaceae Horan.: <i>Punica granatum</i> L. VU B1ab(i, i, iii).	Punicaceae Horan.: <i>Punica granatum</i> L.
Fabaceae Lindl: <i>Gleditsia caspia</i> Desf.	Fabaceae Lindl: <i>Gleditsia caspia</i> Desf. VU A2abcde+3de.	
Moraceae Link. <i>Ficus carica</i> L.	Moraceae Link. <i>Ficus carica</i> L. NT	Moraceae Link. <i>Ficus carica</i> L.
Turqay florasına aid relikt növlər.		
Pinaceae Lindl.: <i>Pinus kociana</i> Klotzsh ex. K.Koch.	Pinaceae Lindl. <i>Pinus kociana</i> Klotzsh ex. K.Koch. NT	
Vitaceae Juss.: <i>Vitis vinifera</i> L. (<i>V.sylvestris</i> C.C.Gmel.)	Vitaceae Juss. <i>Vitis vinifera</i> L. (<i>V.sylvestris</i> C.C.Gmel.)LC	
Rosaceae Juss.- <i>Cerasus incana</i> (Pall.) Spach. (<i>C.mahaleb</i> L.), <i>Mespilus germanica</i> L., <i>Sorbus boissieri</i> C.K. Sechneid.	Rosaceae Juss.: <i>Rosa Azerbaijanica</i> Novopokr.et Rzazade. EN B1 ab(i,iii)+2b(ii,iii,v), <i>R.karjaginii</i> Sosn. NT. <i>R. nisami</i> Sosn. NT. <i>R.rapinii</i> Boiss. et. Balansa. VU D1. <i>R. sosnovskyi</i> Chrshan. EN B2ab(ii,iii,iv,v). <i>R.zangezura</i> P.Jar. VU B1 ab(ii)+2ab(ii,iii,iv). <i>Sorbus persica</i> Hedi. VU B1ab(ii,iii)+2ab(iii), <i>S.roopiana</i> Bordz. CR B2b(ii,iii), <i>S.subfusca</i> Boiss. VU D2. <i>Pyurus georgica</i> Kuthath. NT <i>P. salicifolia</i> Balb. NT., <i>P. Medvedevii</i> Rubtz. NT, <i>P.raddeana</i> Woronow. VU B1 ac(ii); C2a(i), <i>P.voronovii</i> Rubtz. VU B1ac(ii);	Rosaceae Juss.: <i>Rosa Azerbaijanica</i> Novopokr.et Rzazade. <i>R. gadjievii</i> Chrshan. et. İskenderov., <i>R.İssaevii</i> Gadzhieva,

	C2(i), <i>Cotoneaster saxatilis</i> Pojark. V U D2C. <i>pontica</i> K.Koch. EN A1 abc; B2ab (i,ii), <i>Prunus microcarpa</i> C.A.Mey. VU B1ab(i,ii), <i>P.nachichevanica</i> Kudr. NT	
Betulaceae S.F.Gray.: <i>Carpinus betulus</i> L.	Fabaceae Lindl.: <i>Astragalus caraganae</i> Fisch.et Mey.CR B1ab (i, ii, iii)c(i)+2ab(i, ii, iii)c(i). <i>A. achundovii</i> Grossh. EN B1 ab(ii,iii,iv), <i>A.karjaginii</i> Boriss: LC., <i>Colutea komarovii</i> Takht. CR B1ac(ii,iv); C2a(i), <i>Halimodendron halodendron</i> (Pall.)Druce. VU D2	Fabaceae Lindl.: <i>Astragalus caraganae</i> Fisch.et Mey <i>Crataegus eriantha</i> Pojark., <i>C.ferganensis</i> Pojark., <i>C. caucasica</i> C.Koch.
Juglandaceae A.Rich.: <i>Juglans regia</i> L.	Chenopodiaceae Vent.: <i>Salsola fugilis</i> İljin. VU D2.	Chenopodiaceae Vent.: <i>Salsola fugilis</i> İljin.
Salicaceae Lindl.: <i>Salix alba</i> L.	Lamiaceae Lindl.: <i>Thymus hyemalis</i> Lange. NT <i>T. kotschyanus</i> Boiss. Et. Hohen. NT	Lamiaceae Lindl.: <i>Thymus karjaginii</i> Grossh., <i>T.migricus</i> Klok.et.Shost.
Oleaceae Hoffmegg.et Link.: <i>Fraxinus excelsior</i> L.	Cupressaceae Rich. Ex Bartl .: <i>Juniperus foetidissima</i> Willd. NT	Hypericaceae Juss.: <i>Hypericum atropatanum</i> Rzazade
Cornaceae Dumort.: <i>Cor-nus mas</i> L.	Buxaceae Dumort.: <i>Buxus colchica</i> Pojark (<i>B.sempervirens</i> L.) VU D2	Plumbaginaceae Juss.: <i>Acantholimon tenuiflorum</i> Boiss.
Aceraceae Juss.: <i>Acer hyrcanum</i> , Fish.ex.C.A.Mey., <i>A. velutinum</i> Boiss.	Celastraceae R.Br .: <i>Euonymus velutinus</i> Fisch. et. C.A.Mey. VU A1ac; B1b(i,ii)	
Tiliaceae Juss.: <i>Tilia be-goniifolia</i> Stev.	Berberidaceae Juss .: <i>Berberis heteropoda</i> Schrenk. VU C2a(i); D2	
Rhamnaceae Juss.: <i>Rham-nus spathulifolia</i> Fisch.et C.A.Mey.	Thymelaeaceae Juss .: <i>Daphne kurdica</i> Bornm. VU D2	
Ulmaceae Mirb.: <i>Ulmus scabra</i> Mill. <i>U. glabra</i> Huds (U.elliptica C.koch).	Cannabaceae Martinov.: <i>Çeltis caucasica</i> Wild. -NT	
Kserotermik relikտ növlər		
Rosaceae Juss.: <i>Pyrus salicifolia</i> Pall. <i>Amygdalus fenzliana</i> (Fritsch.) Lipsky	Anacardiaceae (R.Br.) Lindl. <i>Pistacia atlantica</i> Dest.- NT	

Turqay florasına aid *Mespilus germanica* L., *Carpinus betulus* L., *Salix alba* L., *Cornus mas* L., *Fraxinus excelsior* L., *Tilia begoniifolia* Stev., *Rhamnus spathulifolia* Fisch.et C.A.Mey., *Ulmus scabra* Mill., kserotermik reliktlərdən *Pyrus salicifolia* Pall. və *Amygdalus fenzliana* (Fritsch.) Lipsky. növlərinin böyümə və inkişafı, meyvə verməsi illər üzrə dəyişir. Elə vaxtlar (20023-cü il) olmuşdur ki, Batbatda meşənin əsasını təşkil edən *Quercus macranthera* Fisch. Et C.A.Mey. növünü payızda demək olar ki, qozalarına rast gəlinməmişdir. Növbəti il isə bol meyvə vermə müşahidə edilmişdir. Bu isə təbii bərpanın normal gətməsinə zəmin yaradır. Bitkilərin meyvə verməsi iqlim amillərinin, xüsusilə yağıntuların illər üzrə dəyişməsindən, ətrafındakı eyni və ya fərqli növlərə aid fərdlərin yerləşmə vəziyyətindən çox asılıdır.

Kölgəyə davamsız növlər yağmurlu illərdə daha az meyvə verir. Bu digər növlərin sürətlə böyüyüb onları sıxışdırması ilə izah edilir. Açıq sahələrdə və nisbətən az kölgəli mühitdə isə normal meyvə verirlər. Axar çay qırağına yaxın yerlərdə olan ağaclarda meyvələr nisbətən gec yetişirlər. Bu da həmin ağacların köklərinin dağ çaylarının nisbətən soyuq suyundan qidalanması ilə əlaqədar ola bilər. Batabat meşəsində *Quercus macranthera* Fisch. Et C.A.Mey., *Carpinus betulus* L., *Fraxinus excelsior* L., *Cornus mas* L., *Tilia begoniifolia* Stev., *Rhamnus spathulifolia* Fisch.et C.A.Mey. növlərini təbii bərpası normal davam edir, 10 m² ərazidə 12-20 ədəd 3-5 illik tinglər müşahidə edilir.

Antropogen təsirlər, xüsusilə də meşələrin mal-qara tərəfindən otarılması, istirahət obyektlərinin fəaliyyəti təbii bərpaya çox ciddi mənfi təsir edir. Ağac və kol bitkilərinin ontogenezinin cücərti, ting və cavan ağac mərhələlərində insanlar, mal-qara tərəfindən diblərinin tapdalanılması kök sisteminin normal tənəffüsünə mənfi təsir edir, ömürlərinin tez başa vurmasına səbəb olur.

Tədqiqatlar zamanı həm meşələrin müxtəlif sahələrində, həm də istirahət mərkəzlərinə yaxın ərazilərdə ağacların bütöv, ya da budaqlarının, gövdələrinin bir hissəsinin kəsildiyi, zədələndiyi də müşahidə edilmişdir. Bir hissəsi kəsilmiş və ya zədələnmiş, dibləri tapdanmış bitkilər stress yaşayır və daha tez xəstəliklərin, zərərvericilərin təsirinə məruz qalır, oradan isə digər ərazilərdəki sağlam bitkiləri yoluxdurur. Belə bitkilər özləri də ömürlərini tez başa vururlar.

İstirahət mərkəzləri ətrafında 300-500 m. bəzən daha geniş radiuslarda *Cornus mas* L., *Pyrus salicifolia* Pall. və *Amygdalus fenzliana* (Fritsch.) Lipsky., *Salix alba* L., meşəsində *Quercus macranthera* Fisch. Et C.A.Mey., *Rosa Azerbaijani* Novopokr.et Rzazade., *R. gadjevii* Chrshan. et. İskenderov., *R.İssaevii* Gadzhieva, *Crataegus eriantha* Pojark., *C. caucasica* C.Koch. növlərinin iki, üç illik tinglərinə demək olar ki, rast gəlinmir. Tapdalanma ot bitkilərini tamamilə məhv edir, ümumilikdə meşə ekosistemini, birgə yaşayış ahəngini pozur.

Azərbaycanın digər əraziləri ilə müqayisədə Naxçıvanda təbiətə, o cümlədən də meşələrə istirahət obyektləri tərəfindən az ziyan dəymişdir. Çünki burada meşə və ona yaxın ərazilərdə istirahət obyektləri çox

azdır. Naxçıvan Muxtar Respublikasında qazlaşdırılma da bütün rayonları, ucqar kəndləri əhatə etdiyindən meşələri odun yandırmaq məqsədilə qırılması halları da xeyli aşağı düşmüşdür. Lakin meşələrin mal-qara, qoyun, keçi tərəfindən otarılması halları davam edir. Ən ciddi antropogen təsirlər də buradan qaynaqlanır.

Nəticələr

Tədqiqatlar nəticəsində *Pyrus salicifolia* Pall. və *Amygdalus fenzliana* (Fritsch.) Lipsky. növləri III dövrün kserotermik reliktlərinə aid edilmişdir.

Naxçıvan Muxtar Respublikasının bitkililiyində 1 meşə bitkiliyi tipi, 3 meşə formasıya sinfi, 14 meşə formasıya qrupu, 1 kolluq bitkiliyi tipi, 2 kolluq formasıya sinfi, 9 kolluq formasıya qrupu müəyyən edilmişdir.

Meşə və kolluq bitkililiyində *Carpinus betulus* L., *Mespilus germanica* L., *Juglans regia* L., *Cerasus incana*(Pall.) Spach. (*C.mahaleb* L.), *Salix alba* L., *Acer hyrcanum* Fisch. et C.A.Mey., *A. velutinum* Boiss., *Tilia begoniifolia* Stev., *Pyrus salicifolia* Pall., *Sorbus boissieri* C.K. Scheid., *Ulmus glabra* Huds., *Punica granatum* L., *Ficus carica* L., *Celtis caucasica* Willd. reliktləri dominant növlər sırasındadırlar.

Naxçıvan dendroflorasında III dövrün reliktlərinə aid 16 fəsiləyə, 19 cinsə aid 21 növ, 15 fəsiləyə, 23 cinsə aid 38 nadir növ yayılmışdır. 5 fəsiləyə 5 cinsə aid 5 növ isə həm relikt, həm də nadir bitkilərdir. 8 fəsiləyə, 9 cinsə aid 13 növ endem ağac, kol və kolcuqlar yayılmışdır. Bunlardan 5 növü nadir, 2 növü isə nadir olmaqla yanaşı həm də relikt bitkilərdir.

Ərazidə yayılmış Poltav florasına məxsus 3 fəsiləyə, 3 cinsə aid 3 relikt ağac və kol növlərinin (*Punica granatum* L., *Gleditsia caspia* Desf. və *Ficus carica* L.) hər biri nadir bitkilərdir. Turqay florasına aid 12 fəsiləyə, 14 cinsə, daxil olan 16 növ müəyyən edilmişdir. Bunlardan *Pinus kochiana* Klotzsh ex. K.Koch. və *Vitis vinifera* L. (*V.sylvestris* C.C.Gmel.) nadir növlərdir.

Naxçıvan dendroflorasının qiymətli relikt, nadir və endem növlərinə ciddi antropogen təsir olaraq mal-qara, qoyun, keçi tərəfindən otarılmanı qiymətləndirmək olar.

Torpaq- iqlim şəraiti, ekocoğrafi xüsusiyyətləri nəzərə alınaraq, relikt növləri tarixi qruplar üzrə təhlil edilərək Batabat meşə massivi mezotermik relikt ərazi, Şərur rayonu Qaraquş dağı, Culfa rayonun Ləkitağ kəndi, Boyəhmədli kəndləri istiqamətində Əlincə çayın ətrafı kserotermik relikt ərazi hesab edilmişdir.

Naxçıvanın qışı çox soyuq, yayı isti kəskin kontinental iqlimini, global iqlim dəyişkənliklərini, xüsusilə quraqlığı və artmaqda olan antropogen təsirləri nəzərə alsaq, bir sıra relikt, nadir və endem növlər üçün gələcəkdə böyük təhlükələr yarana biləcəyini proqnozlaşdırma bilirik.

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CHEMICAL SCIENCES

DEVELOPMENT OF STUDENTS' RESEARCH AND ANALYTICAL SKILLS IN THE STUDY OF ORGANIC CHEMISTRY THROUGH THE USE OF ARTIFICIAL INTELLIGENCE

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Abstract

This article examines the theoretical and methodological foundations of using artificial intelligence to develop students' research and analytical skills in the study of organic chemistry. The main learning difficulties are analyzed, including understanding reaction mechanisms and the relationship between molecular structure and properties. A teaching methodology based on the integration of MolView and ChatGPT tools is proposed. This approach is aimed at developing skills in structural analysis, reaction prediction, synthesis planning, and scientific reasoning. The scientific novelty lies in the development of an integrated model combining visualization tools and artificial intelligence in organic chemistry education.

Keywords: artificial intelligence, organic chemistry, teaching methodology, analytical skills, research skills, digital education.

Introduction

In the modern education system, the use of digital technologies is an important tool for increasing students' active participation in the learning process. In particular, artificial intelligence technologies are being rapidly integrated into education. These changes open up new opportunities, especially in teaching natural sciences, including organic chemistry [1, p. 3-4].

Organic chemistry is one of the most complex subjects, as it requires not only theoretical knowledge but also a high level of analytical and research thinking. Often, students tend to memorize reactions, but they face difficulties in understanding their mechanisms [2, p. 1108].

In this regard, the use of artificial intelligence in teaching organic chemistry enhances students' cognitive engagement and contributes to the development of their research and analytical skills [3, p. 5].

Theoretical Background

The modern educational paradigm focuses not only on acquiring knowledge but also on developing higher-order thinking skills. From this perspective, the formation of analytical and research skills is one of the main objectives of teaching organic chemistry.

The Essence of Analytical Skills. Analytical skills are a set of abilities that enable a learner to organize, analyze, compare, and draw conclusions from information [4, p. 12]. In organic chemistry, these skills manifest in analyzing molecular structures, identifying functional groups, explaining the relationship between structure and properties, and predicting reaction outcomes [5, p. 582]. Analytical thinking is especially important in organic chemistry because students must not only memorize formulas but also understand their internal logic. For example, a change in one functional group can alter the chemical properties of the entire molecule.

The Content of Research Skills. Research skills describe a learner's ability to engage in scientific inquiry. These include identifying a problem, formulating a hypothesis, solving it through experimental or theoretical approaches, analyzing and evaluating results, and drawing conclusions. In organic chemistry, these skills develop through constructing synthesis pathways, explaining reaction mechanisms, and comparing alternative solutions [6, p. 693].

Features of Teaching Organic Chemistry. While studying organic chemistry, students face several challenges: difficulty visualizing molecular spatial structures, complexity in understanding reaction mechanisms, challenges in identifying the relationship between structure and properties, and a tendency to memorize reactions mechanically. To address these issues, it is important to use visualization and interactive methods in teaching.

The Role of Visualization. Visualization is one of the key tools in teaching organic chemistry. The use of 3D molecular models helps develop students' spatial thinking. Tools such as MolView allow for accurate representation of molecular structures, visualization of bonds, understanding of isomerism, and simulation of reactions. Visualization transforms theoretical knowledge into concrete understanding and increases student interest in the subject.

Pedagogical Potential of Artificial Intelligence. Artificial intelligence technologies open new opportunities in modern education. Systems like ChatGPT can support personalized learning paths, provide immediate feedback, explain complex topics, and analyze student errors [1, p. 4]. The main advantage of AI is its interactivity and adaptability. It responds according to each student's level and individualizes the learning process [7, p. 7].

Artificial Intelligence as an "Intelligent Tutor". In the learning process, ChatGPT can be considered an

“intelligent tutor.” It asks guiding questions, stimulates thinking, teaches through explanation rather than giving direct answers, and supports reflection. This approach aligns with constructivist learning theory, where learners actively construct their own knowledge.

Constructivist and Digital Learning Theories. The proposed methodology is based on constructivist theory, which states that learners do not receive knowledge passively but construct it through experience and active engagement. In addition, the methodology relies on principles of digital learning: interactivity, multimedia learning, and personalized education [8, p. 43].

Theoretical Basis for Integrating MolView and ChatGPT. The combined use of MolView and ChatGPT integrates two cognitive processes: visual perception (MolView) and analytical and verbal processing (ChatGPT). This integration promotes deeper understanding, as students simultaneously see, analyze, and explain information [8, p. 316].

The theoretical foundations discussed above demonstrate the effectiveness of integrating artificial intelligence and visualization tools in teaching organic chemistry. This approach enables the systematic development of students’ analytical and research skills [1, p. 4].

Proposed Methodology

The proposed methodology is based on the integrated use of the MolView visualization tool and the ChatGPT artificial intelligence system in teaching organic chemistry. It aims not only to enhance theoretical knowledge but also to systematically develop students’ analytical and research thinking skills [1, p. 4].

The methodology has a staged structure, where each stage is designed to achieve specific didactic goals. In this process, the learner acts not as a passive listener but as an active researcher.

Stage 1: Molecular Visualization

At this stage, MolView is used as the main tool. Students independently construct or analyze the structure of a given organic compound. They:

- draw the 2D structure of the molecule;
- convert it into a 3D format;
- observe the spatial arrangement of atoms;
- study bond angles and geometry.

The pedagogical significance of this stage lies in transforming abstract chemical concepts into concrete visual representations, leading to a deeper understanding of molecular structures.

Stage 2: Structural and Analytical Analysis

At this stage, students conduct a comprehensive analysis of the molecule based on a predefined algorithm or checklist. They:

- identify functional groups;
- determine the class of the compound;
- analyze types of isomerism;
- predict reactivity;
- identify possible chemical reactions.

The teacher plays a guiding role, encouraging students to draw their own conclusions rather than providing ready-made answers [6, p. 693].

Stage 3: Analysis with Artificial Intelligence

At this stage, ChatGPT is used as an “intelligent learning assistant.” Students:

- input the IUPAC name or structure obtained from MolView;
- interact with AI using prepared prompts;
- compare AI-generated answers with their own results;
- identify and correct errors.

The AI:

- provides explanations;
- asks additional questions;
- suggests alternative solutions;
- guides the student’s thinking process.

A key aspect of this stage is critical thinking: students do not accept AI responses uncritically but analyze and evaluate them [4, p. 15].

Stage 4: Research Tasks

At this stage, students perform higher-level tasks involving research activities [6, p. 692]. They:

- propose multiple synthesis routes for a given substance;
- compare their efficiency;
- explain reaction mechanisms;
- draw scientifically grounded conclusions.

Example tasks:

- “Propose two synthesis routes and choose the most efficient one.”
- “Identify errors in the given reaction.”
- “Predict the reaction product and justify your answer.”

This stage develops elements of scientific thinking such as hypothesis formation, reasoning, and conclusion [6, p. 693].

Pedagogical Features and Effectiveness of the Methodology. The proposed methodology has several important features. First, it ensures personalized learning tailored to each student’s level and needs [7, p. 7]. Second, it emphasizes the active role of the learner. Third, it is based on the integration of visualization and analysis, enabling deeper understanding. Fourth, immediate feedback enhances learning efficiency. Fifth, it promotes a research-oriented approach, encouraging students to explore and construct knowledge independently [6, p. 692].

This methodology simplifies the understanding of complex concepts by combining visual and analytical approaches. It increases student engagement through interactive tools and AI capabilities. It allows immediate identification and correction of errors, leading to deeper learning [7, p. 7]. It also connects theoretical knowledge with practical application and fosters a research culture by encouraging questioning, hypothesis generation, experimentation, and conclusion.

Description of Integrated Tasks. The methodology includes five tasks; below are brief descriptions of three of them.

Task 1: Verification of Markovnikov’s Rule. The student asks ChatGPT to predict the product of HBr addition to propene. Then, using MolView, they compare propene and the predicted product (2-bromopropane). They visually confirm that bromine attaches to the second carbon. This task develops prediction (research) and comparison (analytical) skills.

Task 2: Chirality and Enantiomers. ChatGPT provides theoretical explanations of chiral molecules and

enantiomers. The student constructs D-glyceraldehyde in MolView and creates its mirror image (L-isomer), verifying that the two cannot be superimposed. This develops virtual experimentation skills.

Task 3: Analysis of a Complex Molecule (Aspirin). ChatGPT identifies the functional groups in aspirin. The student then locates these groups in the MolView model and studies spatial features such as the aromatic ring and functional group orientation. By combining both sources, the student performs a comprehensive analysis.

Pedagogical Advantages of the Methodology. Compared to separate use, the integrated methodology has several advantages. It ensures the synthesis of theory and visualization, deepening understanding. It develops critical thinking, as students evaluate AI responses rather than accept them blindly. It compensates for the limitations of each tool: ChatGPT lacks spatial visualization, while MolView lacks theoretical explanations. Together, they complement each other.

Moreover, each task follows a full scientific inquiry cycle: hypothesis (ChatGPT), visual verification (MolView), comparison, and conclusion, helping students adopt the logic of real research.

Conclusion

This article proposes a methodology for integrating ChatGPT and MolView in teaching organic chemistry. Compared to separate use, the integrated approach more effectively develops students' analytical and research skills. Three integrated tasks were designed, and their pedagogical logic was described.

The proposed methodology can be applied in higher education organic chemistry courses. Future research will involve quantitative evaluation through pedagogical experiments.

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TEACHING AMINO ACIDS THROUGH VIRTUAL EXPERIMENTS AND SIMULATIONS IN A DIGITAL LABORATORY ENVIRONMENT**Orujov Y.***Baku State University, Master's student***Nagiyev K.***Chemistry faculty, chemistry teaching methodology, head of the department, doctor of chemical sciences, professor**Baku State University,***Abishov N.***Doctor of Pedagogical Sciences, Professor**Baku State University**Baku/Azerbaijan*<https://doi.org/10.5281/zenodo.19573207>**Abstract**

The integration of digital technologies into chemistry education has created new opportunities for improving both conceptual understanding and student engagement. Within this context, the teaching of amino acids can be significantly enriched through the use of virtual experiments and simulations in a digital laboratory environment. Amino acids are among the fundamental topics in school and undergraduate chemistry because they connect organic chemistry, biochemistry, and life sciences. However, many students experience difficulties in understanding their molecular structure, amphoteric nature, classification, and biological significance when the topic is taught only through traditional explanation. This article examines the pedagogical value of digital laboratory tools in the teaching of amino acids and highlights how virtual experimentation can support visual learning, inquiry-based activity, and independent knowledge construction. The study emphasizes that simulations help learners observe molecular behavior, model chemical interactions, and investigate the properties of amino acids in a safe and accessible environment. In addition, digital laboratory activities contribute to the development of analytical thinking, scientific observation, and motivation toward chemistry learning. The article argues that the effective use of virtual experiments does not replace the teacher's role, but rather strengthens instruction by making abstract chemical concepts more concrete, interactive, and meaningful for students.

Keywords: Amino acids, chemistry education, digital laboratory environment, virtual experiments, simulations, interactive learning, chemistry teaching, digital tools

INTRODUCTION

The rapid development of digital educational technologies has substantially transformed the ways in which scientific knowledge is taught and learned. In chemistry education, this transformation is especially important because many chemical concepts are abstract, microscopic, and difficult for students to visualize directly. For this reason, the use of digital laboratory environments has become increasingly relevant in modern teaching practice. Such environments provide broader opportunities for observation, experimentation, and conceptual modeling, allowing students not only to receive information but also to engage actively in the learning process.

The topic of amino acids occupies a special place in chemistry teaching. It stands at the intersection of organic chemistry and biochemistry and serves as a meaningful example of how chemical knowledge is connected with living systems. Amino acids are introduced not merely as organic compounds with specific structural features, but also as biologically important substances that participate in the formation of proteins and many vital physiological processes. Therefore, the teaching of this topic requires an approach that combines theoretical explanation with visual representation, functional interpretation, and research-oriented learning activities [1, p. 1437]

In traditional classroom settings, the teaching of amino acids often depends on verbal explanation, textbook schemes, and static structural formulas. Although these methods remain useful, they are not always sufficient for developing deep understanding. Students may memorize the general formula of amino acids or their classification, yet still struggle to explain their amphoteric properties, stereochemical features, or role in biological systems. In many cases, the lack of experimental opportunities or the limited availability of laboratory resources restricts the teacher's ability to demonstrate these concepts effectively. As a result, students' learning may remain formal rather than meaningful. A digital laboratory environment helps overcome these limitations by making invisible chemical processes more observable and abstract relationships more understandable. Through virtual experiments and simulations, students can explore the structure of amino acids, examine their reactions in different media, compare their physical and chemical properties, and model their behavior under various conditions. These tools support repeated experimentation without safety risks, reduce dependence on costly laboratory materials, and create favorable conditions for differentiated instruction. At the same time, they encourage curiosity, hypothesis formation, analysis of results, and interpretation of chemical phenomena. [2, p. 1537]

Another important advantage of digital simulations is their capacity to increase student motivation.

When learners interact with animated models, manipulate variables, and immediately observe outcomes, chemistry becomes more dynamic and accessible. This is particularly valuable in teaching topics such as amino acids, where the connection between molecular structure and biological function needs to be clearly demonstrated. Digital tools can thus strengthen both cognitive and emotional engagement, making the learning process more effective and relevant to students' interests.

From a pedagogical perspective, the integration of virtual experiments into chemistry teaching corresponds to contemporary educational principles that emphasize student-centered learning, interactivity, and the use of technology for conceptual development. The teacher in this process is not replaced by technology; rather, the teacher becomes a guide who organizes purposeful learning situations, selects appropriate digital resources, and directs students toward scientific reasoning. In this sense, the digital laboratory environment should be viewed not simply as a technical innovation, but as a methodological resource that can improve the quality of chemistry instruction.

This article focuses on the teaching of amino acids through virtual experiments and simulations in a digital laboratory environment. Its purpose is to examine the educational potential of digital laboratory tools in presenting this topic more effectively, to clarify their methodological advantages, and to show how they can support the formation of students' chemical knowledge, practical understanding, and research skills. The relevance of the topic is determined by the growing need to modernize chemistry education and to adapt instructional methods to the demands of contemporary digital learning [3, p. 1203,4, p.456]

LITERATURE REVIEW

Recent developments in chemistry education have demonstrated that digital technologies can play a substantial role in improving the quality of teaching and learning. In particular, virtual laboratories, interactive simulations, and computer-based experimental environments have become increasingly important for presenting abstract chemical concepts in a more visual, dynamic, and student-centered manner. Researchers in science education emphasize that digital learning tools are especially effective in situations where direct laboratory access is limited, where safety concerns are present, or where the studied phenomena occur at the molecular level and cannot be observed directly through ordinary classroom methods.

The existing literature shows that virtual experiments contribute not only to knowledge acquisition but also to the development of scientific thinking. Many authors argue that simulation-based learning supports conceptual understanding by allowing students to manipulate variables, test predictions, observe model-based outcomes, and repeat experimental procedures without material limitations. Such opportunities are highly valuable in chemistry, where learners often encounter difficulties in connecting symbolic representations, microscopic processes, and macroscopic observations. Digital laboratory environments therefore help bridge the gap between theory and practice by making

invisible processes more accessible to learners. A number of studies in chemical education have also shown that simulations improve students' motivation and engagement. When students participate in interactive digital tasks, they tend to demonstrate greater curiosity, stronger concentration, and higher willingness to investigate chemical relationships independently. This is particularly important in topics that require spatial imagination and structural analysis. The teaching of amino acids belongs to this category because it involves the study of molecular structure, functional groups, acid-base behavior, stereochemistry, and biological significance. These aspects can be difficult for students to understand when instruction relies only on textbook explanation and memorization [5, p., 2244]

Scholarly works related to biochemistry and organic chemistry pedagogy indicate that amino acids should be taught not as isolated formulas, but as chemically and biologically meaningful substances. Their amphoteric nature, zwitterionic forms, peptide-bond formation, and classification according to side chains require learners to establish connections between structural features and chemical behavior. Traditional instruction often presents these ideas in a static format, whereas digital simulations enable students to observe transformations, compare molecular models, and analyze reaction conditions in a more active way. For this reason, the use of virtual laboratories has been regarded as a promising approach for teaching biochemically relevant compounds.

At the methodological level, the literature also highlights the role of inquiry-based and constructivist approaches in digital chemistry teaching. Virtual experimentation is most effective when students are not passive observers but active participants who formulate hypotheses, test them through digital tools, and interpret the results. In this framework, the teacher functions as a facilitator who structures the learning environment, selects suitable digital resources, and guides students toward meaningful reflection. Such an approach supports deeper understanding and helps transform digital tools from mere visual aids into instruments of scientific learning.

Despite the growing body of research on digital chemistry education, the specific use of virtual laboratory environments for teaching amino acids remains an area that deserves further methodological attention. Although general studies on simulations in chemistry are relatively widespread, fewer works focus directly on how virtual experiments can be applied to the teaching of amino acids in a systematic and pedagogically grounded way. This creates a need for studies that examine the educational value of digital laboratory environments in relation to this topic, especially in terms of conceptual clarity, student activity, and instructional effectiveness. Thus, the literature suggests that digital laboratory tools have strong pedagogical potential in chemistry education. They support visualization, experimentation, independent exploration, and conceptual integration. In the case of amino acids, these advantages are particularly relevant because the topic requires learners to understand the relationship between structure, properties, and biological function. On this

basis, the present study investigates how virtual experiments and simulations can be used more effectively in teaching amino acids within a digital laboratory environment.

METHODOLOGY

The present study was based on a qualitative and pedagogical analysis of the use of digital laboratory environments in teaching the topic of amino acids. The methodological framework was designed to examine the educational possibilities of virtual experiments and simulations, as well as their contribution to students' understanding of chemical concepts, learning motivation, and classroom activity. The study was not limited to the technical description of digital tools; rather, it focused on their methodological value in the teaching process.

The research relied on several interconnected methods. First, a theoretical analysis of pedagogical, methodological, and chemistry education literature was carried out in order to identify the main scientific approaches to digital learning, simulation-based teaching, and the instructional presentation of amino acids. This stage made it possible to determine the conceptual foundations of the study and to clarify the place of digital laboratory environments in modern chemistry education.

Second, a comparative method was used to evaluate the differences between traditional teaching approaches and digital laboratory-based instruction. In this comparison, attention was given to such criteria as visualization of chemical structures, opportunities for experimentation, student participation, accessibility of laboratory experience, and the possibility of repeated observation. This comparison helped reveal the pedagogical advantages of virtual experiments in the context of amino acid instruction. Third, the study employed methodological modeling. On the basis of the analyzed literature and digital teaching principles, a model for teaching amino acids in a digital laboratory environment was designed. This model included the explanation of amino acid structure, the visualization of functional groups, the demonstration of amphoteric properties, the study of peptide bond formation, and the interpretation of biological significance through simulation-supported tasks. In this methodological model, digital tools were integrated into different lesson stages, including introduction of the topic, conceptual explanation, guided exploration, independent practice, and evaluation of learning outcomes.

The study also incorporated elements of observation and pedagogical interpretation. Virtual laboratory activities were examined from the point of view of how they may influence student engagement, research interest, and conceptual comprehension. Particular attention was paid to the extent to which simulations can support active learning by encouraging learners to manipulate digital models, compare alternative results, and draw conclusions from observed changes. These features were interpreted as important indicators of student-centered chemistry instruction.

In methodological terms, the teaching process was structured around several instructional principles. These included scientific accuracy, visual clarity, interactivity, accessibility, and the connection between theory and practice. The principle of scientific accuracy required that digital content reflect correct chemical knowledge about amino acids and their reactions. Visual clarity was ensured through structural representations, animated processes, and molecular modeling. Interactivity involved the active participation of students in virtual experimental tasks. Accessibility referred to the possibility of repeated use without the limitations of physical laboratory conditions. The connection between theory and practice was achieved by relating chemical properties of amino acids to their biological role and real-life relevance [6, p. , 133]

The proposed methodological approach assumed that students would not only observe ready-made digital demonstrations but would also engage in guided inquiry. For example, they could investigate how the presence of both amino and carboxyl groups determines the chemical behavior of amino acids, compare the structures of different amino acids, or simulate the conditions under which peptide bonds are formed. In this way, the digital laboratory environment was treated as an interactive learning space that promotes analytical thinking and meaningful understanding rather than rote memorization. Therefore, the methodology of the study combined theoretical analysis, comparison, methodological modeling, and pedagogical interpretation. Such a combination made it possible to evaluate the role of virtual experiments and simulations in the teaching of amino acids from both conceptual and instructional perspectives. The selected methodological approach supports the idea that a digital laboratory environment can serve as an effective pedagogical means for making chemistry lessons more engaging, more understandable, and more closely connected with contemporary educational needs.

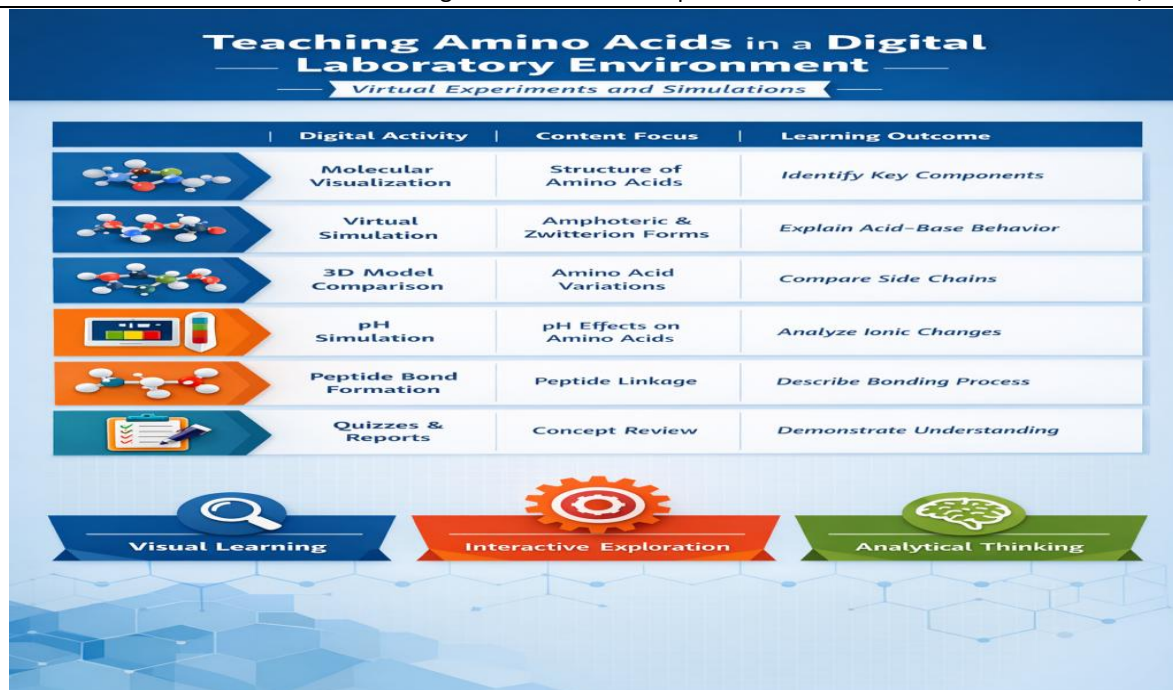


Figure 1. A digital laboratory framework for teaching amino acids through virtual experiments and simulations.

Figure 1 illustrates the stage-based organization of teaching amino acids in a digital laboratory environment. It presents the relationship between digital activities, content focus, and expected learning outcomes, highlighting the role of virtual experiments and simulations in supporting visual learning, interactive exploration, and analytical thinking.

EXPERIMENTAL

The experimental part of the study was designed to examine the educational effectiveness of teaching amino acids through virtual experiments and simulations in a digital laboratory environment. The experiment was pedagogical in nature and focused on the organization of the learning process rather than on chemical synthesis or analytical laboratory procedures. Its main purpose was to determine how digital laboratory tools influence students' understanding of amino acid structure, properties, and biological importance, as well as their participation and interest during chemistry lessons. The experimental teaching model was based on the integration of virtual laboratory activities into the instructional process. At the initial stage, students were introduced to the general structure of amino acids and to the presence of amino and carboxyl functional groups. After this theoretical introduction, they worked with digital simulations that allowed them to observe molecular models, identify structural differences among amino acids, and analyze the relationship between structure and chemical behavior. Through guided virtual tasks, students explored such topics as amphoteric properties, zwitterionic forms, peptide bond formation, and the classification of amino acids according to side-chain characteristics.

The experimental work was organized in several stages. The first stage involved determining students' initial level of understanding of the topic through introductory questions, short written tasks, and classroom

discussion. This stage helped identify common difficulties, including confusion about the dual chemical nature of amino acids and limited understanding of their biological functions. The second stage consisted of the main instructional intervention, during which the topic was taught with the support of digital simulations and virtual experiments. Students interacted with models, observed changes under simulated conditions, compared different amino acid structures, and interpreted the results of virtual laboratory tasks. The third stage involved reflection and evaluation, where students explained their observations, answered analytical questions, and completed follow-up assignments aimed at checking conceptual understanding. Special attention was given to the role of the teacher during the experimental process. The teacher did not merely demonstrate digital materials but guided the students' inquiry, directed their attention to key chemical patterns, and encouraged them to explain what they observed in scientific terms. In this way, the virtual laboratory environment was used not as a substitute for teaching, but as a methodological support that enriched the lesson and made student participation more active and meaningful.

The experimental design also included comparative elements. The learning process in the digital environment was evaluated against the characteristics of traditional explanation-based instruction. In particular, attention was paid to the depth of conceptual understanding, the level of student engagement, the quality of classroom responses, and the ability of learners to relate chemical structure to biological function. Such comparison made it possible to assess the pedagogical value of virtual experimentation in a more grounded way. Thus, the experimental part of the study provided a structured basis for analyzing how digital laboratory tools can be applied in teaching amino acids and how such tools contribute to more interactive, visual, and conceptually rich chemistry instruction.

Table 1.

Teaching amino acids in a digital laboratory environment through virtual experiments and simulations

Lesson stage	Digital activity	Content focus	Expected learning outcome
Introduction to the topic	Interactive molecular visualization	General structure of amino acids, amino group, carboxyl group, side chain	Students identify the main structural components of amino acids
Concept explanation	Virtual simulation of molecular behavior	Amphoteric nature and zwitterion formation	Students explain why amino acids can behave as both acids and bases
Guided exploration	Comparison of 3D molecular models	Structural differences among amino acids	Students compare amino acids according to side-chain properties
Virtual experiment	Simulation of pH-dependent behavior	Changes in ionic forms under different conditions	Students analyze the relationship between pH and amino acid behavior
Applied task	Digital model of peptide bond formation	Condensation reaction and peptide linkage	Students describe how amino acids form peptides
Interdisciplinary connection	Biological simulation or animated model	Role of amino acids in proteins and living systems	Students relate chemical structure to biological function
Reflection and assessment	Online quiz, analytical questions, virtual task report	Review of key concepts and interpretation of observations	Students demonstrate conceptual understanding and analytical thinking

Table 1 presents a structured model for teaching amino acids in a digital laboratory environment through virtual experiments and simulations. It links each lesson stage with a relevant digital activity, a specific content focus, and the expected learning outcome. This shows that the topic can be taught in a systematic and pedagogically meaningful way.

The table also demonstrates that the teaching process develops step by step, from the basic structure of amino acids to more complex ideas such as amphoteric behavior, zwitterionic forms, and peptide bond formation. Through digital tools, these abstract concepts become more visible and easier for students to understand. In addition, the table highlights the methodological value of digital laboratory activities in promoting observation, comparison, analysis, and active participation. Overall, it shows that virtual experiments and simulations can improve both conceptual understanding and student engagement in learning amino acids.

RESULTS AND DISCUSSION

The results of the study showed that the use of virtual experiments and simulations in teaching amino acids had a positive effect on students' learning activity and conceptual understanding. One of the most important findings was that digital laboratory tools made the topic more accessible to students by transforming abstract chemical information into observable and interactive representations. Concepts that are often difficult to explain in a traditional classroom, such as amphoteric behavior, zwitterion formation, and peptide bond development, became clearer when students were able to see modeled processes and manipulate digital structures directly.

Another important result concerned student engagement. During digital laboratory activities, learners

demonstrated greater interest in the topic and participated more actively in classroom discussion. They were more willing to ask questions, compare observations, and propose explanations for the behavior of amino acids under different simulated conditions. This suggests that the digital environment created a more motivating learning atmosphere than traditional explanation alone. The opportunity to repeat virtual experiments, test different conditions, and receive immediate visual feedback strengthened students' curiosity and sustained their attention throughout the lesson.

The study also revealed that virtual simulations supported deeper understanding of the relationship between molecular structure and chemical properties. In conventional instruction, students often memorize the general formula of amino acids without fully grasping why these compounds behave as both acids and bases. In the digital laboratory environment, however, students were able to observe how structural features determine reactivity and function. This helped move learning beyond memorization and encouraged more analytical interpretation. As a result, students became better able to explain the logic behind chemical behavior rather than simply reproduce textbook information. An additional result was connected with the interdisciplinary value of the topic. Because amino acids link chemistry with biology, the use of simulations helped students recognize that the studied compounds are not merely abstract molecules but biologically meaningful substances. Virtual models made it easier to discuss proteins, metabolism, and the physiological significance of amino acids in a more integrated way. This increased the educational richness of the lesson and contributed to a broader scientific understanding.

The discussion of these results confirms the view found in modern pedagogical literature that digital technologies are most effective when they are methodologically integrated into the learning process. The positive outcomes observed in this study were not produced by technology alone, but by the purposeful combination of teacher guidance, inquiry-based tasks, and virtual experimentation. Digital simulations proved to be especially useful because they supported visualization, repeated observation, and active student involvement. At the same time, they enhanced the teacher's ability to explain complex concepts in a more concrete and engaging form. However, the findings also suggest that virtual tools should be used thoughtfully. Their educational value depends on the quality of the selected simulations, the clarity of the teacher's instructional goals, and the extent to which students are guided toward analysis and reflection. If digital resources are

used only for passive demonstration, their pedagogical impact may remain limited. Therefore, effective teaching requires not simply the introduction of technology, but its integration into a structured methodological framework.

Overall, the results indicate that a digital laboratory environment is a productive means of teaching amino acids. It improves conceptual clarity, increases student engagement, strengthens the connection between theory and practice, and creates more favorable conditions for interactive learning. For this reason, virtual experiments and simulations can be considered an important methodological resource in modern chemistry education, particularly in teaching topics that involve complex molecular structures and processes [7, p., 3197.]

Table 2.

Comparative analysis of traditional instruction and digital laboratory-based teaching in the study of amino acids

Instructional criteria	Traditional teaching approach	Digital laboratory-based approach
Presentation of amino acid structure	Amino acid structure is mainly introduced through textbook formulas and teacher explanation	Amino acid structure is presented through interactive molecular visualization and three-dimensional digital models
Explanation of amphoteric properties	Amphoteric behavior is explained theoretically and may remain abstract for students	Amphoteric behavior is demonstrated through virtual simulations that illustrate acid–base interactions more clearly
Representation of zwitterionic forms	Zwitterionic forms are usually shown in static diagrams without dynamic interpretation	Zwitterionic forms are visualized dynamically, allowing students to observe structural changes under different conditions
Teaching of peptide bond formation	Peptide bond formation is described conceptually, often without experimental support	Peptide bond formation is demonstrated through simulation-based activities and guided digital tasks
Student engagement	Student participation is often limited to listening, note-taking, and answering questions	Students participate more actively through observation, manipulation, comparison, and interpretation of virtual models
Opportunities for repeated practice	Repetition is restricted by classroom time and available teaching resources	Activities can be repeated multiple times in a flexible and accessible digital environment
Development of analytical thinking	Analytical thinking depends primarily on verbal questioning and discussion	Analytical thinking is enhanced through simulation, comparison of results, and interpretation of observed changes
Interdisciplinary understanding	The connection between chemistry and biology may remain insufficiently developed	The relationship between amino acid chemistry, protein structure, and biological significance is presented more integratively

Table 2 presents a comparative analysis of two instructional approaches used in the teaching of amino acids: the traditional teaching model and the digital laboratory-based model. The comparison shows that the digital approach provides broader methodological opportunities for the presentation of abstract chemical concepts, particularly in relation to molecular structure, amphoteric behavior, zwitterionic forms, and peptide bond formation.

The table also demonstrates that digital laboratory tools create more favorable conditions for active student participation. Unlike traditional instruction, which often depends on verbal explanation and static representations, the digital environment enables learners to interact with visual models, observe simulated processes, and repeat activities when necessary. This con-

tributes to greater conceptual clarity and a deeper understanding of the relationship between structure and function.

In addition, the comparative data indicate that digital laboratory-based teaching supports the development of analytical thinking and interdisciplinary understanding more effectively. By linking chemical properties of amino acids with their biological role, the digital approach helps students develop a more integrated and meaningful understanding of the topic. Overall, the table highlights the pedagogical advantages of virtual experiments and simulations in modern chemistry education.

CONCLUSION

In conclusion, the teaching of amino acids through virtual experiments and simulations in a digital laboratory environment has considerable pedagogical value. The study shows that digital tools make this complex topic more understandable by presenting molecular structures, chemical properties, and biologically significant processes in a visual and interactive form. Such an approach helps students move beyond mechanical memorization and develop a deeper understanding of the relationship between structure, behavior, and function.

The findings also indicate that virtual laboratory activities contribute positively to student engagement, motivation, and classroom participation. When learners are given the opportunity to observe simulated processes, manipulate variables, and interpret outcomes, they become more active participants in the learning process. This strengthens not only their subject knowledge but also their analytical thinking, observation skills, and ability to explain chemical phenomena in a reasoned way.

At the same time, the study confirms that the effectiveness of digital laboratory environments depends on sound methodological integration. Virtual experiments are most beneficial when they are used purposefully, supported by teacher guidance, and connected with clearly defined learning objectives. In this sense, digital tools should be regarded not as a replacement for the teacher, but as an important pedagogical resource that enriches instruction and improves the quality of chemistry education.

Therefore, the use of virtual experiments and simulations in teaching amino acids can be considered an effective and modern instructional approach. It creates favorable conditions for conceptual clarity, active learning, and interdisciplinary understanding, while also responding to the broader demands of contemporary digital education. For these reasons, digital laboratory environments deserve greater attention in the methodological practice of chemistry teaching.

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SYSTEMATIZATION OF TYPES OF INDIVIDUAL TASKS IN THE CONTEXT OF DEVELOPING STUDENTS' CRITICAL THINKING

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ЖЕКЕ ТАПСЫРМАЛАР ТҮРЛЕРІН БІЛІМАЛУШЫЛАРДЫҢ СЫНИ ОЙЛАУЫН ДАМУЫ ТҮРҒЫСЫНАН ЖҮЙЕЛЕУ

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Abstract

The article examines the issue of theoretical systematization of individual tasks used in the educational process from the perspective of developing students' critical thinking. The study aims to classify types of individual tasks based on their content and structural characteristics and to identify their pedagogical potential in forming the core components of critical thinking. The research is based on methods of theoretical analysis of scientific literature, content analysis, comparative analysis, and systematization.

Аннотация

Мақалада білім беру үдерісінде қолданылатын жеке тапсырмаларды білім алушылардың сыни ойлауын дамыту тұрғысынан теориялық негізде жүйелеу мәселесі қарастырылады. Зерттеудің мақсаты-жеке тапсырмалар түрлерін мазмұндық және құрылымдық ерекшеліктеріне қарай жіктеп, олардың сыни ойлаудың негізгі компоненттерін қалыптастырудағы педагогикалық әлеуетін айқындау. Зерттеу ғылыми әдебиеттерге теориялық талдау, мазмұндық сараптау, салыстырмалы талдау және жүйелеу әдістеріне негізделді.

Keywords: individual tasks, critical thinking, cognitive independence, problem-based tasks, mind map, analytical activity, reflection.

Кілт сөздер: жеке тапсырмалар, сыни ойлау, танымдық дербестік, проблемалық тапсырмалар, ментальды карта, талдамалық әрекет, рефлексия.

Кіріспе.

Қазіргі білім беру парадигмасы мазмұнды меңгертумен қатар, білім алушының танымдық дербестігін, аналитикалық қабілеттерін және негізделген шешім қабылдау мәдениетін қалыптастыруды талап етеді. Осы тұрғыдан алғанда, сыни ойлау білім алушының интеллектуалдық жетілуін қамтамасыз ететін негізгі құзыреттердің бірі болып саналады [7].

Химия пәнінің мазмұны абстрактілі ұғымдар жүйесі мен күрделі теориялық заңдылықтарға және тәжірибелік дағдыларға негізделгендіктен, білім алушының терең әрі саналы түсінуін талап етеді. Ол берілген ақпараттарға талдау жасап, себеп-салдарлық байланыстарды анықтай отырып, өз интерпретациясын ғылыми тұрғыдан дәйектеуі қажет [1]. Сыни ойлауды қалыптастыруда жеке тапсырмалардың рөлі ерекше. Проблемалық есептер, талдамалық сұрақтар мен зертханалық тәжірибе нәтижелерін өз бетінше түсініп, пайымдау барысында білім алушы нақты дәлелдерге сүйеніп, қорытынды жасауға дағдыланады. Мұндай дербес

жұмыс метатанымдық қабілеттерді дамытып, химиялық білімнің сапалы әрі терең меңгерілуіне негіз болады [2,3,6].

Осыған байланысты химияны оқытуда жеке тапсырмаларды тиімді ұйымдастыру арқылы білім алушылардың сыни ойлауын қалыптастыру мәселесі ғылыми-әдістемелік тұрғыдан өзекті. Зерттеудің мақсаты-білім алушының танымдық белсенділігін арттыратын тапсырмалардың тиімді құрылымын айқындау.

Материалдар мен әдістер.

Зерттеу жұмысының теориялық-әдіснамалық негізін химияны оқыту әдістемесі, сыни ойлау теориясы, құзыреттілікке бағытталған білім беру тұжырымдамасы және білім алушының метатанымдық реттелуі мәселелеріне арналған ғылыми еңбектер қарастырылды. Зерттеу материалдары ретінде рецензияланған ғылыми мақалалар, оқу бағдарламалары, пәндік стандарттар, әдістемелік нұсқаулықтар және химия пәніне арналған тапсырмалар жинақтары пайдаланылды. Материалдарды іріктеу барысында

олардың ғылыми дәйектілігі, теориялық негізділігі, практикалық қолданбалығы және зерттеу тақырыбына сәйкестігі ескерілді. Әсіресе химияны оқыту үдерісінде сыни ойлауды дамытуға бағытталған проблемалық оқыту, зертханалық жұмыстарды ұйымдастыру, аргументация мәдениетін қалыптастыру және рефлексияны енгізу мәселелеріне арналған еңбектерге басымдық берілді.

Зерттеу барысында келесі ғылыми әдістер қолданылды:

1. Ғылыми әдебиеттерге теориялық талдау жасау әдісі арқылы сыни ойлау ұғымының мәні, құрылымдық компоненттері, оны қалыптастырудың педагогикалық шарттары және химия сабағында жеке тапсырмаларды ұйымдастырудың рөлі мен ерекшеліктері қарастырылды. Өртүрлі авторлардың көзқарастары салыстырылып, ортақ тұжырымдар айқындалды.

2. Жүйелеу және жинақтау әдісі. Әдеби дереккөздерде ұсынылған жеке тапсырмалардың түрлері сараланып, олардың сыни ойлаудың нақты компоненттеріне ықпалы жүйеленді. Нәтижесінде жеке тапсырмалардың білім алушылардың жас ерекшеліктеріне сәйкес тақырыптық байланыстарды теориялық түрде жүйеленді.

3. Салыстырмалы талдау әдісі. Өртүрлі педагогикалық тәсілдерде жеке жұмыс түрлерінің қолданылуы салыстырылып, олардың білім алушылардың талдау, дәлелдеу, бағалау және

қорытынды жасау дағдыларын қалыптастыруда мүмкіндіктері айқындалды.

4. Мазмұндық талдау әдісі. Химия пәніне арналған оқу бағдарламалары мен әдістемелік нұсқаулықтардағы тапсырмалар мазмұны зерттеліп, олардың сыни ойлауды дамыту әлеуеті тұрғысынан талдау жасалды.

Зерттеу үдерісінде алынған мәліметтер логикалық талдау негізінде өңделіп, теориялық тұжырымдар жасалды. Жүргізілген шолу жұмысы химияны оқытуда жеке тапсырмаларды мақсатты және жүйелі түрде қолдану білім алушылардың сыни ойлауын дамытуда маңызды педагогикалық құрал бола алатынын негіздеуге мүмкіндік берді.

Нәтижелер мен талқылаулар.

Жүргізілген теориялық және мазмұндық талдау химияны оқыту үдерісінде жеке тапсырмаларды ғылыми-әдістемелік тұрғыдан негіздеп ұйымдастыру білім алушының сыни ойлау дағдыларын қалыптастыруда айқындаушы мәнге ие екенін көрсетті. Тапсырмалардың құрылымы мен мазмұндық тереңдігі білім алушының танымдық әрекетінің сипатын анықтайтыны байқалды. Оқу материалдарын саралау нәтижесінде алгоритмдік сипаттағы тапсырмалар басым болған жағдайда білім алушы көбіне дайын үлгіні қайталаумен шектелетіні анықталды. Мұндай жағдайда ұғымдардың ішкі логикасын түсіну мен себеп-салдарлық байланыстарды пайымдау жеткілікті деңгейде жүзеге аспайды.

Кесте 1

Төменде сыни ойлауға негізделген тапсырмалар түрлері.

Сыни ойлауға негізделген тапсырмалар түрі	Тапсырма мысалдары	Дамытылатын ойлау дағдылары	Күтілетін педагогикалық нәтиже
Салыстыру, заттардың немесе құбылыстардың ұқсастықтары мен айырмашылықтарын табуға негізделген	Металдар мен бейметалдардың физикалық қасиеттерін салыстыру	Аналитикалық талдау, ұқсастық пен айырмашылықты табу	Жүйелі ойлау, заттарды жіктеу дағдысы қалыптасады
Гипотеза (жорамал) ұсыну арқылы, оны дәлелдеуге мүмкіндік беретін тапсырмалар	"Егер реакция температурасын 10°C-қа арттырсақ, жылдамдық қалай өзгереді?"	Болжам жасау	Ғылыми болжам жасау және оны дәлелдеу қабілеті артады
Заңдылықты тағайындауға мүмкіндік беретін тапсырма	Периодтық жүйедегі элементтердің радиусының өзгеруін анықтау	Дедукция, заңдылықтарды іздеу	Теориялық білімді практикада қолдану дағдысы бекиді
Ментальды карта – ақпаратты жазуға және өңдеуге мүмкіндік беретін ойлау тапсырмасы	"Көмірсутектердің жіктелуі" тақырыбына схема сызу	Ақпаратты құрылымдау, визуализация	Күрделі тақырыпты жүйелеу және есте сақтау деңгейі артады

Салыстыру мазмұнындағы тапсырмалар енгізілген кезде білім алушының ойлау әрекеті мазмұндық жағынан күрделене түседі. Мәселен, химиялық тепе-теңдікке әсер ететін факторларды талдауға бағытталған тапсырмалар білім алушыдан тек ережені еске түсіруді емес, нақты жағдайды сараптап, өз болжамын ғылыми тұрғыдан

негіздеуді талап етеді. Мұндай танымдық әрекет логикалық пайымдау мен дәлелдеу дағдыларының белсенді дамуына ықпал етеді. Нәтижесінде білім алушы химиялық құбылыстарды формальды емес, мәндік деңгейде түсінуге ұмтылады.

Ментальды карта жасау жұмыстары да сыни ойлаудың қалыптасуына елеулі әсер ететіні

байқалды. Бұл тұста тек қана ақпаратты жазып қана қоймай, ақпараттармен ары қарай жұмыс жасауы ерекшеленді. Яғни, берілген ақпаратты өңдеу, құрылымдау, визуализациялау, жүйелеу танымдық белсенділікті айтарлықтай арттырады. Мұндай ұйымдастыру ғылыми деректерді сыни тұрғыдан тақырыпты жүйелеуге және есте сақтауға мүмкіндік береді.

Заңдылықты тағайындауға мүмкіндік беретін тапсырмалар білім алушының заңдылықтармен жұмыс жасау мәдениетін жетілдіруге дағдыланған. Периодтық жүйедегі элементтердің радиусының өзгеруін анықтау барысында білім алушы тек сипаттамалық мәліметтермен шектелмей, дедукциялау мен заңдылықтарды іздеуге тырысады. Нәтижесінде теориялық білімді практикада қолдану дағдысы бекиді.

Жеке тапсырмалардың педагогикалық тиімділігі олардың мазмұндық күрделілігімен қатар, ұйымдастырылу логикасына да тәуелді екені анықталды. Проблемалық жағдаятқа негізделген, дәлелді жауапты талап ететін және баламалы

шешімдерді қарастыруға мүмкіндік беретін тапсырмалар білім алушының зияткерлік белсенділігін арттырады. Теориялық білім мен тәжірибелік әрекетті өзара ықпалдастыру химиялық ұғымдардың терең әрі саналы меңгерілуіне жағдай жасайды. Осы тұрғыдан қарағанда, химияны оқыту барысында жеке тапсырмаларды жүйелі әрі ғылыми негізде құрастыру білім алушының сыни ойлауын қалыптастырудың нәтижелі тетігі ретінде сипатталады. Мұндай ұйымдастыру білім алушыны ақпаратты пассивті қабылдаушы емес, оны талдайтын, бағалайтын және негізделген шешім ұсынатын белсенді таным субъектісі деңгейіне көтереді [4-5].

Зерттеу барысында жеке тапсырмалардың мазмұны білім алушылардың жас ерекшелігі мен химиялық білім деңгейіне қарай сатылай күрделенетіні анықталды. Мысал ретінде «Заттардың бөлшектері» бөлімі негізінде 7,8,9 сыныптардың тақырыптары зерттеуде қарастырылған болатын.

Кесте 2

Жас ерекшеліктеріне байланысты сыни ойлауды қалыптастырудағы жеке тапсырмалардың сипаты.

Сынып	Тақырыбы	Оқу мақсаты	Сыни ойлауға негізделген жеке тапсырма түрі
7	Атомдар мен молекулалар. Химиялық элементтер. Периодтық кесте.	Атомдар мен молекулаларды ажырату. Элемент таңбаларын жатқа білу. Периодтық кестенің алғашқы құрылымын түсіну.	Салыстырмалы талдау. Жіктеу және дәлелдеу. Ментальды карта
8	Атомдағы электрондардың қозғалысы. Энергетикалық деңгейлер. Периодтық заң.	Атом құрылысын (протон, нейтрон, электрон) сипаттау. Электрондық қабаттардың толуын түсіндіру. Элемент қасиеттерінің өзгеруін болжау.	Модельдеу (Ментальды карта). Заңдылықты тағайындау.
9	Химиялық байланыстың түрлері.	Металдық байланыс пен металдық кристалдық тор жайындағы білімдерін қолданып металдардың қасиетін түсіндіре алу;	Проблемалық есеп. Зерттеушілік тапсырма. Интерпретациялық тапсырма

Химия пәнінің іргетасы болып табылатын «Атом құрылысы және периодтық жүйе» тарауы білім мазмұнының спиральді қағидамен дамуын айқын көрсететін негізгі бөлігі болғандықтан, зерттеу нысаны ретінде мысалға алынған болатын. Бұл тарауды талдау арқылы оқушының химиялық деректерді қабылдаудан күрделі заңдылықтарды болжауға дейінгі когнитивті өсу жолын бақылауға болады. Осы кестеден жалпы 7-8 сыныптар үшін сыни ойлауға негізделген жеке тапсырма түрі 9 сыныптан айырмашылығы - төменгі сыныптарда тапсырмалар көбіне сипаттамалық, бақылау мен салыстырмалы сипатта болып, білім алушының базалық аналитикалық дағдыларын қалыптастыруға бағытталады. 8-сыныпта тапсырмалар жүйелеу мен заңдылықтарды іздеуге (дедукцияға) ойысады. Ал 9-сыныпта тапсырмалар толықтай талдамалық, болжамдық және күрделі

проблемалық деңгейге ауысып, білім алушыдан жоғары деңгейдегі себеп-салдарлық байланыстарды орнатуды талап етеді.

Бұл тәсіл білім алушыны ақпаратты тек қана есте сақтаушы емес, оны терең талдайтын, бағалайтын және өзіндік ғылыми негізделген шешім ұсынатын белсенді таным субъектісі деңгейіне көтереді. Жеке тапсырмалардың мұндай жүйелілігі химиялық білімнің сапалы әрі саналы меңгерілуіне негіз болады.

Қорытынды.

Қорытындылай келе, зерттеу барысында химияны оқыту үдерісінде жеке тапсырмаларды жүйелеу білім алушылардың сыни ойлауын қалыптастырудың әдістемелік негізін айқындауға мүмкіндік берді. Жеке тапсырмалар мазмұндық және құрылымдық ерекшеліктеріне қарай сыни ойлаудың әртүрлі компоненттерін дамытуға бағытталатыны анықталды. Заңдылықты

тағайындауға мүмкіндік беретін тапсырма логикалық пайымдау мен себеп-салдарлық байланыстарды айқындауға ықпал етсе, ментальды карта ақпаратты өңдеу, құрылымдау, визуализациялау және ғылыми негізделген қорытынды жасау мәдениетін қалыптастырады. Талдамалық тапсырмалар аргументациялық дағдыларды жетілдіріп, рефлексиялық әрекеттер метатанымдық реттеуді дамытады.

Химия пәнінің теориялық мазмұны мен тәжірибелік бағыты жеке тапсырмаларды сыни ойлауды дамыту құралы ретінде тиімді қолдануға мүмкіндік береді. Тапсырмаларды проблемалық мазмұнда құрастыру, дәлелді жауап талап ету, баламалы шешімдерді қарастыруға жағдай жасау және рефлексия элементтерін енгізу білім алушының танымдық белсенділігін арттырады.

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COGNITIVE FEATURES OF PROSPECTIVE CHEMISTRY EDUCATORS AND PATHWAYS FOR DEVELOPING THEIR DIVERGENT POTENTIAL**Sapakova A.***Candidate of biological sciences, Senior Lecturer
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«Shakarim University of Semey»***БОЛАШАҚ ХИМИЯ ПЕДАГОГТАРЫНЫҢ КОГНИТИВТІК ЕРЕКШЕЛІКТЕРІ ЖӘНЕ ДИВЕРГЕНТТІ ӘЛЕУЕТІН ДАМУ ЖОЛДАРЫ****Сапакова А.К.***Биология ғылымдарының кандидаты, аға оқытушы
Химия және биология кафедрасы
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<https://doi.org/10.5281/zenodo.19573211>***Abstract**

This paper investigates the cognitive features and divergent thinking levels of future chemistry teachers using the methodologies of I.P. Pavlov and E. Torrance. Empirical findings indicate a low level of idea elaboration skills among students, alongside a shift towards convergent (standardized) thinking in upper-level courses. Therefore, to foster the creative potential of students, the article justifies the need for the systematic introduction of multi-answer chemical experimental tasks and predictive questions into the curriculum.

Аңдатпа

Бұл мақалада И.П. Павлов және Э. Торренс әдістемелері негізінде болашақ химия мұғалімдерінің когнитивтік ерекшеліктері мен дивергентті ойлау деңгейі зерттелді. Эмпирикалық нәтижелер студенттердің идеяларды толықтыру дағдыларының төмендігін және жоғары курстарда конвергентті (стандартты) ойлауға бейімделуін көрсетті. Осыған орай, студенттердің шығармашылық әлеуетін дамыту мақсатында оқу процесіне химиялық көпжауапты эксперименттік есептер мен болжамдық сұрақтарды жүйелі енгізу қажеттілігі негізделген.

Keywords: divergent thinking, future chemistry teachers, creative potential, brain hemisphere asymmetry, creativity, cognitive characteristics.

Түйін сөздер: дивергентті ойлау, болашақ химия мұғалімдері, шығармашылық әлеует, ми жартышарларының асимметриясы, креативтілік, когнитивтік ерекшеліктер.

Қазақстан Республикасының білім беру саласындағы нормативтік құжаттарында тұлғаны шығармашылық тұрғыдан дамыту қажеттілігі туралы идея негізгі орында тұр. Болашақ білім беру мекемелерінің басты ерекшелігі — заманауи ақпараттық қоғамда бағдар ала білетін, жаңашылдыққа ашық, оқу процесіне шығармашылық тәсіл таба алатын педагогтың жаңа типін қалыптастыру. Осылайша, заманауи химия мұғалімінің алдында күрделі міндет тұр: студентті ақпаратпен және әртүрлі ақпарат көздерімен жұмыс істеуге үйрету. Өз кезегінде, білім алушылар үшін негізгі міндет — қажетті ақпаратты табу, оны қабылдау, сондай-ақ оны мұқият әрі сыни тұрғыдан зерттеу. Сонымен қатар, мектеп стандарттарында оқушылардың дербес пайымдауы мен жоспарлауы, танымдық қызметке мотивациясы және ғылыми ойлау типін қалыптастыруы сияқты қасиеттердің маңыздылығы атап көрсетілген. Алайда, практика көрсеткендей, қазіргі оқушыны танымдық әрекетке ынталандыру өте қиын. Загашевтің пікірінше, бұл

балалардың барлық мектеп пәндері бойынша оқу материалын қабылдауда елеулі қиындықтарға тап болуынан туындайды. Оның себебі — ойлаудың, ең алдымен, сыни және дивергентті ойлау деңгейінің жеткіліксіздігі.

Бүгінгі таңда бұл мәселе әдебиеттерде егжей-тегжейлі қарастырылғанымен, білім беру мекемелерінің тәжірибесінде тиісті деңгейде көңіл бөлінбей отыр және оны ғылыми негіздеу, әдістемелік базаны әзірлеуді талап етеді. Бұл болашақ химия педагогтарында дивергентті ойлауды қалыптастыру мәселесін ерекше өзекті етеді. Сонымен қатар, көп жағдайда студенттер дивергентті ойлауды қалыптастыру әдістемесі туралы жеткілікті хабардар емес, ал оқу бағдарламаларында бұл мәселе тиісті деңгейде көрініс таппаған. Соның салдарынан бұл кәсіби-тұлғалық қасиет тиімсіз дамып, болашақ мамандардың оқу-кәсіби қызметінің нәтижелеріне кері әсерін тигізеді [1, б.160].

Ойлау — бұл екі түрлі психофизиологиялық механизмге негізделген нақты дүниені бейнелеу процесі: біріншіден, пайымдаулар мен тұжырымдар жасау, ұғымдар қорын толтыру. Екіншіден, ойлау қоршаған ортаның бірінші сигналдық жүйе арқылы тікелей қабылданбайтын қасиеттері мен қатынастары туралы жаңа білім алуға мүмкіндік береді.

Американдық психолог Дж. Гилфорд зерттеулерді қорытындылай келе, ойлаудың екі типін бөліп көрсетті:

1. Конвергентті ойлау (лат. *convergere* – түйісу) — жалғыз дұрыс шешімді іздеу. Бұл логикалық, сызықтық ойлау, ол көбінесе IQ деңгейімен және дәстүрлі оқыту әдістерімен байланыстырылады.

2. Дивергентті ойлау (лат. *divergere* – алшақтау) — тек мүлдем жаңа өнім жасаумен ғана емес, сонымен бірге танымдық қызметтегі мақсаттар, мағыналар мен мотивациялардың жаңаруымен сипатталатын ойлау түрі. Ол дайын білімді қолданатын репродуктивті ойлаудан ерекшеленеді.

Мысалы, кейбір адамдар мәселені шешудің тек бір дұрыс жолы бар деп есептейді және оны логика арқылы іздейді (конвергентті). Ал басқалары, керісінше, мүмкін болатын барлық бағыттар бойынша ізденіс бастайды, бұл стандартты емес шешімдерге әкеледі (дивергентті).

Өкінішке орай, қазіргі оқытудың барлығы дерлік конвергентті ойлауды дамытуға бағытталған. Бұл педагогикадағы үрдіс шығармашыл адамды дамытпайды, керісінше оны басып тастайды. Шығармашыл адамдар көпшілік стандартты түрде қолданатын элементтерден жаңа комбинациялар жасай алады. Мысалы, дөңгелек негізінде сурет салу тапсырмасында көпшілігі «күн, апельсин, бет» сияқты стандартты жауаптар береді. Ал дивергентті ойлайтын адамдар «Ламбер ірімшігінің кесегі», «дөңгелек бөтенке киген жануардың ізі», «шөл дала аясындағы тегіс оазис» сияқты ерекше жауаптар ұсынады. Егер инновациялық дамудың басында дивергентті ойлауы бар адамдар тұрса ғана жағдай түбегейлі өзгеруі мүмкін. Ол үшін білім беру жүйесін барлық деңгейде оқушылардың шығармашылық қабілеттерін дамытуға бағыттап, қайта құру қажет [2, б.53].

Зерттеушілер шығармашылықты көбінесе креативті ойлаумен байланыстырады. Креативті ойлаудың негізгі механизмі - дивергенттілік. Дивергентті ойлау тұжырымдамасының авторы, американдық психолог Джой Пол Гилфорд өзінің зерттеулерінде: «Дивергентті ойлау операциялары кезінде біз әртүрлі бағытта ойланамыз, кейде ізденіс жасап, кейде айырмашылықтарды табамыз» - деп жазған.

Шығармашылық ойлау сонымен қатар психологиялық бағытпен де зерттелді. Бұл жерде біз Дж. Гилфордтың және Э. Торренстің креативтілік концепциясын айта кетеніміз жөн. Олар креативтілікті таным-шығармашылық, әмбебап қабілет деп қарастырған. Мидың

жартышараралық асимметриясы — бұл жүйке-психикалық функциялардың оң және сол жартышарлар арасында біркелкі емес бөлінуін сипаттайтын мидың күрделі қасиеті. Өткен ғасырдың 60-шы жылдарында миды «бөлу» (*split-brain*) және әр жартышарды жеке зерттеу әдістемелерінің енгізілуі ми функциялары мен ойлау, оқу қабілеті, танымдық процестердің ерекшеліктері, бейімделу секілді феномендер арасындағы өзара байланысты айқындауға мүмкіндік берді.

Басым жартышарды анықтау үшін Павлов тесті қолданылады. И. П. Павлов жоғары жүйке қызметінің ерекшеліктерін сипаттау мақсатында адамдарды екі негізгі типке бөлді: «ойшыл» және «көркемөнерпаз» типі. Ғалымның пайымдауынша, адамдарды екі үлкен санатқа жіктеуге болады: «Өмір адамдардың екі категориясын айқын көрсетеді: көркемөнерпаздар мен ойшылдар. Олардың арасындағы айырмашылық өте үлкен. Біріншілері — жазушылар, музыканттар, суретшілер және т.б. — шындықты еш бөлшектеместен, тұтас, тірі күйінде қабылдайды. Ал екіншілері — ойшылдар — керісінше, шындықты бөлшектерге бөліп, одан уақытша "қаңқа" жасап, содан кейін ғана сол бөлшектерді біртіндеп жинап, қайта жандандыруға тырысады. Алайда, оларға бұл істі толықтай жүзеге асыру әрдайым мүмкін бола бермейді» [3, б.124]. Адамдардың «ойшылдар» мен «көркемөнерпаздар» болып бөлінуі олардың психикалық іс-әрекетіндегі оң немесе сол жартышарлардың басымдылығымен тікелей байланысты. И. П. Павлов адамдарды көркемөнерпаз және ойшыл типтерге жіктеу тұжырымдамасын балаларды бақылау барысында қалыптастырды. Балалық шақта детальдарға бөлшектемей, дүниені тұтас қабылдауға негізделген көркем тип басым болады. Бұл заңдылықтың негізі мынада: екінші сигналдық жүйе әлі толық дамымаған кезеңде әрбір бала шартты түрде «оң жақ жартышарлы» болып келеді, яғни қоршаған ортаны аналитикалық талдау арқылы емес, бейнелі түрде қабылдайды. Жасы ұлғайған сайын екінші сигналдық жүйе нығайып, сол жақ жартышардың рөлі арта түседі. Осыған байланысты, «сол жақ жартышарлы» немесе «оң жақ жартышарлы» деген терминдерді тура мағынада түсінбеу қажет. Мидың екі жартышары да тең жұмыс істейді, бірақ олардың бірі белгілі бір функцияларға қатысты басымдық танытып, ми қыртысы қызметінің негізінен көркем немесе ойшыл типін қалыптастырады.

Қазіргі заманауи зерттеулер дивергентті (шығармашылық) ойлау процесінде оң жақ жартышардың, ал интеллектуалды-логикалық тапсырмаларды шешуде сол жақ жартышардың басымдық танытатынын дәлелдейді. Ақпаратты іріктеу тұрғысынан алғанда, дивергентті ойлау нейрондық желілердің кең ауқымын қамтитын «дефокусталған» (шашыраңқы) зейінмен байланыстырылса, конвергентті ойлау, керісінше, зейіннің жоғары шоғырлануын талап етеді. Дегенмен, бұл заңдылықтар негізінен оңай

респонденттер негізінде анықталған. Солақайларда когнитивтік функциялардың амбилатералды (екі жақты) орналасуы және жартышараралық байланыстардың өзгеше сипаты олардың креативтілігі мен интеллектуалды процестерінің басқаша жүретінін болжауға мүмкіндік береді [4, 6.446].

Зерттеу жұмысына Семей қаласы «Шәкәрім университеті» КеАҚ жоғары оқу орнында «6В01509 - Химия-Биология» білім беру бағдарламасы бойынша білім алатын 62 студент (2-курс «28», 3-курс «34») қатысты. Қатысушылардың жас аралығы 17–20 жасты құрады және барлығының көру қабілеті қалыпты деңгейде болды.

Зерттеу әдістемесі: Павлов тесті - бұл адамның ойлау типін және ақпаратты өңдеу ерекшеліктерін

(мидың қай бөлігі басым екенін) анықтауға арналған психологиялық диагностикалық әдістеме. Бұл әдістеме физиолог И.П. Павловтың жоғары жүйке әрекеті (бірінші және екінші сигналдық жүйелер) туралы іліміне негізделген.

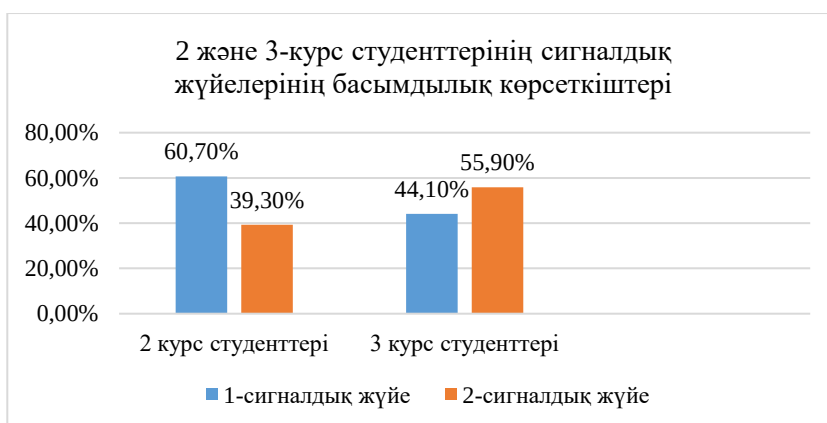
Когнитивтік процестерді бағалау мақсатында— Э. Торренстің «Суретті аяқта» субтесті таңдап алынды. Торренс креативтілік тесті - Адамның шығармашылық әлеуетін зерттеудегі ең танымал әдістемелердің бірі. Автор креативтілікті (лат. *creatio* — жарату) проблемаларға, білімдегі олқылықтар мен үйлесімсіздікке деген жоғары сезімталдық ретінде анықтайды. Бұл процесс гипотезалар құруды, оларды тексеруді және нәтижесінде жаңа шешімдер табуды қамтиды.

Зерттеу нәтижелері:

1-кесте. 2-ші және 3-курс студенттерінің сигналдық жүйелерінің басымдылық көрсеткіштері (И.П. Павлов тесті бойынша)

Курс (студенттер саны)	1-ші сигналдық жүйе басым (Көркемдік тип / Оң жақ жартышар)	2-ші сигналдық жүйе басым (Ойлау типі / Сол жақ жартышар)
2-курс (n=28)	17 студент (60,7%)	11 студент (39,3%)
3-курс (n=34)	15 студент (44,1%)	19 студент (55,9%)
Жалпы көрсеткіш (n=62)	32 студент (51,6%)	30 студент (48,4%)

2-сурет. Студенттердің сигналдық жүйелерінің басымдылық көрсеткіштерінің курстар бойынша орташа көрсеткіштері



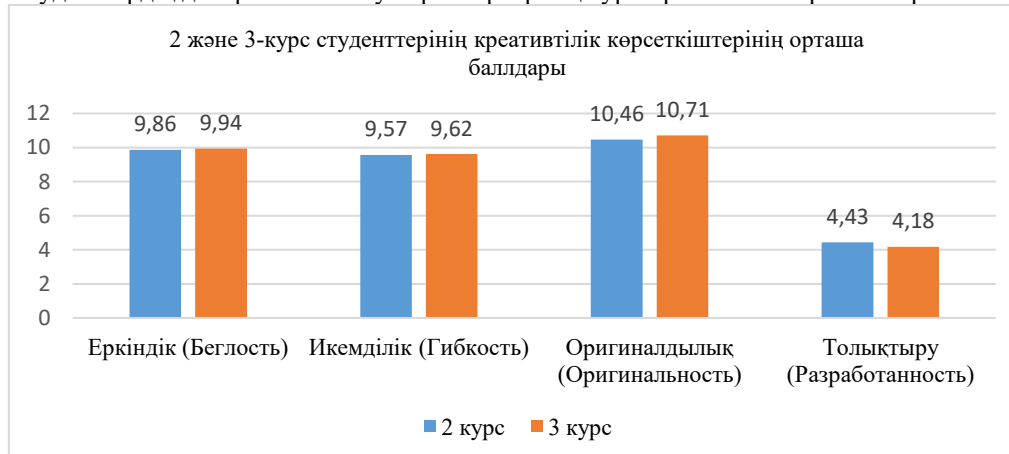
Зерттеу мәліметтері көрсеткендей, 2-курс студенттері (60,7%) ақпаратты тұтас әрі бейнелі түрде қабылдауға бейім келеді (бірінші сигналдық жүйе басымдылығы). Бұл кезеңде білім алушыларда еркін қиялдау мен дивергентті ойлау қабілеті айқын байқалады. Бірақ 3-курста жағдай өзгереді: респонденттердің 55,9%-ы аналитикалық және логикалық процестерді реттейтін екінші сигналдық жүйеге сүйене бастайды. Студенттердің когнитивтік стратегиясындағы бұл динамика олардың кәсіби дағдыларының қалыптасуымен және оқуға деген көзқарастарының прагматикалық сипат алуымен түсіндірілуі мүмкін. Мысалы,

төменгі курстарда студенттер берілген тапсырмаға креативті тұрғыдан қараса, жоғары курстарда олар «нақты дұрыс жауапты» (конвергентті шешімді) табуға көбірек фокусталады, өйткені химиялық заңдылықтар мен реакциялар нақты алгоритмдерді қажет етеді. Студенттердің ми қызметі осы кәсіби талаптарға бейімделгендіктен, олардың бастапқы шығармашылық еркіндігі тарыла түседі. Осыны ескере отырып, болашақ педагогтардың бойындағы дивергентті ойлауды тежемеу үшін оқу процесіне шығармашылық ізденісті талап ететін бейшаблонды тапсырмаларды жүйелі түрде енгізудің маңызы зор.

2-ші және 3-курс студенттерінің креативтілік көрсеткіштерінің орташа баллдары (Э. Торренс тесті бойынша)

Креативтілік көрсеткіштері	2-курс (n=28) Орташа балл (Жалпы балл)	3-курс (n=34) Орташа балл (Жалпы балл)
Еркіндік (Беглость) - шығармашылық өнімділік	9,86 (276)	9,94 (338)
Икемділік (Гибкость) - идеялар мен стратегиялардың әртүрлілігі	9,57 (268)	9,62 (327)
Оригиналдылық (Оригинальность) - стандартты емес идеялар ұсыну қабілеті	10,46 (293)	10,71 (364)
Толықтыру (Разработанность) - идеяны бөлшектеп, соңына дейін дамыту	4,43 (124)	4,18 (142)

2-сурет. Студенттердің дивергентті ойлау параметрлерінің курстар бойынша орташа көрсеткіштері



Эмпирикалық зерттеу нәтижелерін салыстырмалы түрде қарастыру барысында екі курста да «Еркіндік», «Икемділік» және «Оригиналдылық» деңгейлерінің орташа статистикалық нормаға сай келетіні және өзара шамалас екені анықталды. Бұл көрсеткіштер болашақ химия педагогтарының бойында жаңа ақпарат іздеу және креативті шешімдерді табу әлеуетінің қалыптасқандығын айғақтайды. Дегенмен, зерттеудің ең өзекті түйіні ретінде екі топ студенттерінің де «Толықтыру» (Разработанность) критерийі бойынша өте төмен ұпай жинағанын (2-курста – 4,43; 3-курста – 4,18) атап өткен жөн. Э. Торренс тұжырымдамасына сәйкес, аталмыш өлшемнің төмен болуы тұлғаның тың идеяны ұсына алғанымен, оны тереңдетіп өңдеуге, құрылымдауға және ұсақ элементтерін нақтылауға мән бермейтіндігін білдіреді. Дивергентті ойлауды дамыту аясында бұл елеулі кедергі болып саналады: яғни, студенттер химиялық немесе оқу-тәрбиелік жағдаяттардан шығудың тың жолын тапқанымен, оны іске асырудың нақты алгоритмін құрастыруда және тәжірибеде қолдануда айтарлықтай қиындық көреді. Осы жайт жоғары білім беру жүйесіне студенттердің креативті идеяларын жүзеге асыру дағдыларын жетілдіретін арнайы педагогикалық құралдарды, әсіресе химия пәні бойынша көпнұсқалы тәжірибелік тапсырмаларды кеңінен енгізу қажеттілігін тікелей негіздейді.

Зерттеу жұмысын қорытындылай келе, қазіргі заманауи білім беру жүйесінде болашақ химия мұғалімдерінің дивергентті ойлауын қалыптастыру педагогикалық процестің ең өзекті әрі күрделі

міндеттерінің бірі екенін атап өткен жөн. Жүргізілген кешенді психофизиологиялық және психологиялық диагностика нәтижелері студенттердің когнитивтік-шығармашылық дамуындағы бірқатар маңызды заңдылықтар мен қарама-қайшылықтарды айқындап берді. Біріншіден, И.П. Павлов әдістемесімен жүргізілген талдау студенттердің кәсіби біліктілігі артқан сайын (2-курстан 3-курсқа өткенде) бейнелі-шығармашылық (дивергентті) ойлаудан логикалық-алгоритмдік (конвергентті) ойлауға ауысу тенденциясын көрсетті. Бұл химия пәнінің академиялық күрделілігіне бейімделуден туындағанымен, болашақ педагогтардың стандартты емес шешімдер қабылдау еркіндігін тарылтатыны дәлелденді. Екіншіден, Э. Торренс тестінің нәтижелері студенттердің тың идеяларды генерациялау қабілеті («Еркіндік», «Икемділік», «Оригиналдылық») жоғары болғанымен, оны іс жүзінде құрылымдап, соңына дейін дамыту, яғни «Толықтыру» (Разработанность) дағдысының өте төмен екенін көрсетті. Бұл — педагогикалық тәжірибеде жаңашыл идеялардың толыққанды іске аспай қалу қаупін тудыратын негізгі фактор. Осы анықталған олқылықтардың орнын толтыру үшін жоғары оқу орындарындағы химия пәндерін оқыту әдістемесін түрлендіру қажеттілігі туындайды. Студенттерді тек дайын алгоритмдермен жұмыс істеуге емес, стандартты емес педагогикалық және химиялық мәселелерді шешуге дағдыландыру маңызды. Ол үшін жоғары мектептің оқу процесіне мынадай әдістемелік құралдарды жүйелі түрде енгізу ұсынылады:

1. Бірнеше дұрыс шешімі бар көпжауапты эксперименттік есептерді қолдану;
2. Ғылыми қиял мен креативтілікті талап ететін болжамдық сұрақтарды талқылау;
3. Идеяны жай ғана ұсынып қоймай, оны кезең-кезеңімен нақтылауды талап ететін шығармашылық-қолданбалы тапсырмаларды көбейту.

Осындай кешенді әдістемелік тәсілдер болашақ химия мұғалімдерінің тұлғалық-кәсіби қасиеттерін толыққанды ашып, дивергентті ойлау әлеуетін арттыруға және заманауи ақпараттық қоғамдағы бәсекеге қабілеттілігін қамтамасыз етуге берік негіз болады.

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EARTH SCIENCES

TOPONYMS AND GEOGRAPHICAL-DEMOGRAPHIC FEATURES OF THE GOYGOL DISTRICT OF AZERBAIJAN

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Abstract

This article examines the toponymic structure and the geographical and demographic features of the Goygol District of Azerbaijan. An analysis of the origin and semantics of geographical names is carried out, and the relationship between natural conditions and patterns of population settlement is identified. Particular attention is paid to the role of Lake Goygol as a key natural feature influencing the formation of the toponymic system and the spatial development of the region. The results of the study confirm a close interrelationship between natural, historical, and demographic factors.

Keywords: Goygol, toponymy, geo-demographic processes, population settlement, Lesser Caucasus, Azerbaijan, Lake Goygol

Introduction

Toponyms constitute an important source of geographical information, reflecting the characteristics of the natural environment, historical development, and economic activities of the population. They represent a unique “language of the landscape,” in which the results of long-term interaction between humans and nature are embedded. The study of toponyms makes it possible to identify patterns in the formation of geographical space, trace the stages of territorial development, and determine the features of the territorial organization of society and population settlement.

Toponymic studies are of particular importance in regions with complex natural structures and a rich history of population formation. In this context, the Goygol District represents a valuable object of scientific analysis. This region is located within the Lesser Caucasus and is characterized by significant diversity of natural conditions, including mountainous relief, a well-developed hydrographic network, and rich forest ecosystems. These features have a substantial influence on both the formation of the toponymic system and the processes of population settlement.

The historical development of the territory has also played an important role in shaping toponyms. Throughout various historical periods, the region has been influenced by diverse ethnocultural and socio-economic processes, which are reflected in geographical names. As a result, the toponymic structure of the

Goygol District represents a complex system that includes elements of different origins and semantics.

The geographical and demographic features of the region are shaped by natural and economic factors. Mountainous terrain, climatic conditions, and the availability of natural resources determine the nature of population settlement, population density, and directions of economic activity. In turn, demographic processes exert a feedback influence on the transformation of geographical space, including the modification and consolidation of toponyms.

The relevance of this study is determined by the need for a comprehensive examination of the toponymic system in combination with an analysis of the geographical and demographic characteristics of the region. This approach makes it possible to identify the relationships between the natural environment, historical development, and contemporary socio-economic processes.

The aim of the study is to analyze the toponyms and geographical-demographic features of the Goygol District. To achieve this aim, the following objectives are set: to examine the factors influencing the formation of toponyms, to systematize and classify them, and to identify the impact of natural conditions on population settlement patterns and the demographic structure of the region.

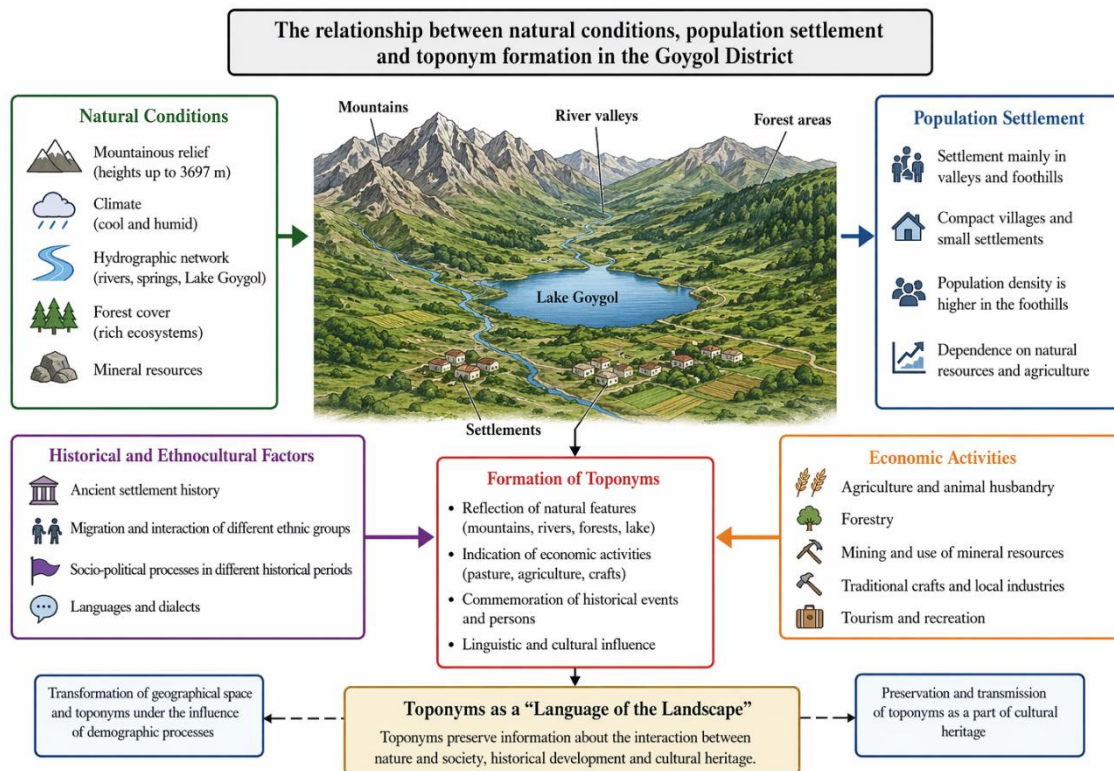


Figure 1. The interrelationship between natural conditions, population settlement, and the formation of toponyms in the Goygol District

Materials and Methods

Within the framework of this study, a comprehensive scientific approach was employed to ensure a thorough analysis of the toponymic system and the geographical and demographic features of the Goygol District. The use of a set of complementary methods made it possible to identify patterns in the formation of toponyms and their relationship with natural and socio-economic conditions.

In particular, the following research methods were applied: comparative geographical analysis, which made it possible to compare the natural and territorial characteristics of different parts of the region and to identify their influence on the formation of toponyms; toponymic analysis, aimed at studying the origin, semantics, and classification of geographical names, as well as identifying the factors influencing their for-

mation; statistical methods, applied to analyze demographic indicators, including population size, population density, and territorial differences; analysis of cartographic materials, which provided a spatial interpretation of the obtained data and made it possible to identify territorial patterns in the distribution of toponyms and population.

The information base of the study consisted of data from the State Statistical Committee of the Republic of Azerbaijan, as well as materials from scientific publications, geographical studies, and reference literature. In addition, cartographic sources and thematic maps reflecting the natural and demographic features of the Goygol District were used.

The application of this methodological approach ensured the reliability of the obtained results and allowed for a comprehensive analysis of the study area.

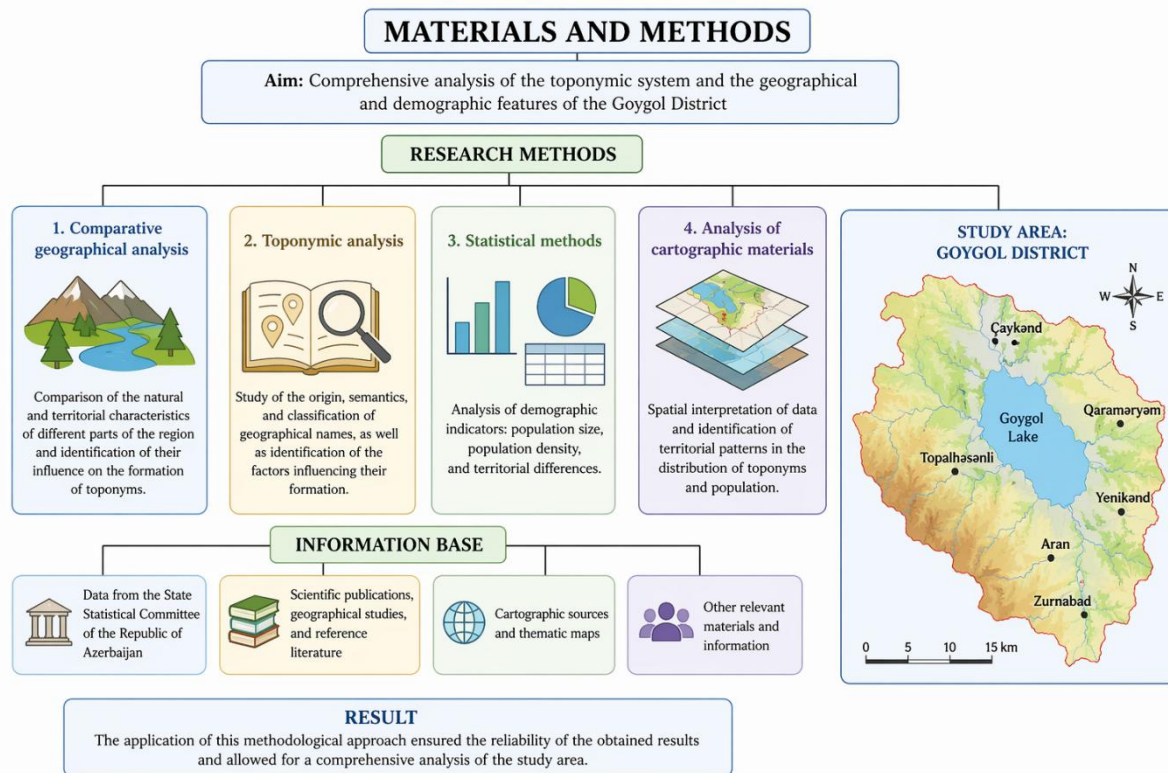


Figure 2. Materials and Methods of the Study on the Toponymic and Geographical-Demographic Characteristics of the Goygol District

Toponymic Analysis of the Goygol District

The toponym “Goygol” originates from the Azerbaijani words “goy” (blue) and “gol” (lake), which is directly associated with Lake Goygol—one of the most well-known natural features of the region, distinguished by the high transparency of its water and its characteristic blue color. This name reflects not only the visual features of the natural object but also serves as an example of the close relationship between toponymy and the natural environment.

The toponymic system of the Goygol District has been formed under the influence of a complex combination of natural, historical, and ethnocultural factors. The structure of regional toponyms demonstrates functional and semantic heterogeneity, which allows them to be classified into the following main groups: hydronyms — names of water bodies (rivers, lakes, springs), reflecting the hydrological features of the territory and often associated with qualitative characteristics of water; oronyms — names of relief forms (mountains,

ridges, elevations), reflecting the morphology and orographic features of the area; phytonyms — names related to vegetation cover, indicating dominant plant species or landscape characteristics.

An analysis of the toponymic material shows that a significant portion of geographical names in the region has a natural origin and reflects specific physical and geographical characteristics of the territory. At the same time, the toponymic system also includes names formed under the influence of historical events, economic activities, and ethnocultural processes, which indicates the multi-layered nature of its formation.

Thus, the toponyms of the Goygol District represent an important source of information about the natural environment and the historical development of the territory, making it possible to reconstruct the features of interaction between humans and the surrounding landscape [1, 2].

Toponymic Structure of Goygol District (Pie Chart)

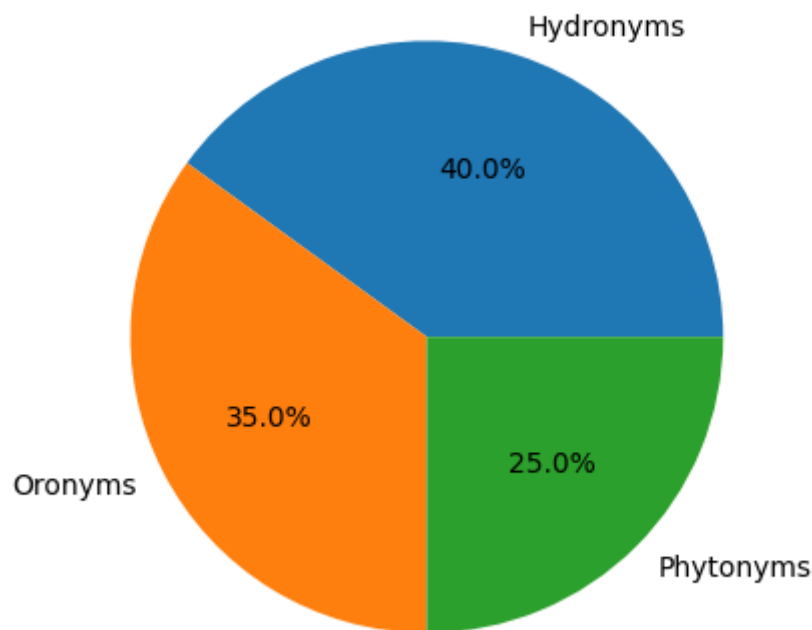


Figure 2. Geographical and Toponymic Features of the Goygol District

Geographical Features

The Goygol District is characterized by a complex mountainous terrain and a significant diversity of natural conditions, caused by its location

The Goygol District is characterized by a complex mountainous terrain and a significant diversity of natural conditions, due to its location within the Lesser Caucasus mountain system.

The geographical position of the region determines a pronounced altitudinal zonation, as well as the formation of diverse natural-territorial complexes that replace one another depending on altitude, slope exposure, and climatic factors.

The relief of the district is highly dissected and is represented by an alternation of mountain ridges, intermountain depressions, and valleys. Significant elevation differences (from foothill plains to high-mountain areas) create conditions for the formation of various types of landscapes—from forest and meadow to sub-alpine and alpine zones. These relief features have a direct impact on climatic parameters, soil cover, and vegetation distribution.

The main physical and geographical characteristics of the district include: location within the Lesser Caucasus mountain system; significant elevation differences determining a complex orographic structure; the presence of extensive forest ecosystems (broadleaf and mixed forests) performing water-protection, soil-conservation, and climate-regulating functions; a well-developed hydrographic network, including mountain rivers, streams, and lake systems; a moderately continental climate with relatively cool summers and mild winters in the foothills, and more severe conditions in high-mountain areas.

The climatic conditions of the district are formed under the influence of both regional atmospheric processes and local factors related to relief. In particular, orographic barriers contribute to the redistribution of air masses, changes in precipitation patterns, and the formation of microclimatic zones. This, in turn, affects the hydrological regime of the territory and the stability of ecosystems.

The hydrographic network of the district is characterized by high density and is represented by numerous watercourses originating in mountainous massifs. Rivers are mainly fed by snow and rain and exhibit a pronounced seasonal runoff regime. Lakes of glacial and tectonic origin also play an important role, serving as key elements of the natural framework of the territory.

Lake Goygol holds special significance within the natural system of the district. It was formed as a result of a massive landslide in the 12th century and represents one of the most picturesque and ecologically important water bodies in the region. The lake significantly influences the formation of the local microclimate, moderating temperature fluctuations and increasing air humidity in adjacent areas. In addition, it serves as an important center of biodiversity, providing habitat for numerous species of flora and fauna, including rare and endemic species.

The forest ecosystems surrounding the lake and adjacent areas play a key role in maintaining the ecological balance of the region. They contribute to the conservation of water resources, prevent erosion processes, and ensure the resilience of landscapes to anthropogenic impact. Taken together, the natural features of the Goygol District form a unique geoeological system of considerable scientific and practical

interest for research in physical geography, climatology, and ecology [3].

Table 1.

Geographical Features of Goygol District

Category	Description
Location & Relief	The Goygol District is located within the Lesser Caucasus mountain system and is characterized by a complex mountainous terrain. The relief is highly dissected, including mountain ridges, intermountain depressions, and valleys.
Altitudinal Zonation	The geographical position creates pronounced altitudinal zonation, forming different natural complexes depending on elevation, slope exposure, and climate.
Landscapes	Significant elevation differences (from foothills to high mountains) lead to diverse landscapes: forest, meadow, subalpine, and alpine zones.
Climate	Moderately continental climate: relatively cool summers and mild winters in foothills, harsher conditions in high mountains. Climate is strongly influenced by relief and orographic barriers.
Forest Ecosystems	Extensive broadleaf and mixed forests provide water protection, soil conservation, and climate regulation functions.
Hydrography	Dense hydrographic network with mountain rivers and streams, mainly fed by snow and rain, with seasonal runoff patterns.
Lakes	Presence of lakes of glacial and tectonic origin that are important elements of the natural system.
Lake Goygol	Formed by a landslide in the 12th century. It is ecologically significant, influences local microclimate, increases humidity, moderates temperature, and supports biodiversity including rare species.
Biodiversity	High ecological diversity due to varied relief, climate, and vegetation zones; includes rare and endemic species.
Environmental Role	Forests and water systems maintain ecological balance, prevent erosion, conserve water resources, and reduce anthropogenic impact.
Scientific Importance	The region is a unique geoecological system of interest for physical geography, climatology, and ecology research.

Geographical and Demographic Characteristics

Population settlement in the Goygol District is shaped by a combination of natural and socio-economic factors, among which the most significant are relief features, climatic conditions, accessibility of transport infrastructure, and the level of economic development of the territory. The location of the district within the Lesser Caucasus determines a pronounced territorial differentiation of living conditions, which is directly reflected in settlement patterns.

One of the key features is the predominance of the rural population. This is associated with the historically established agrarian orientation of the region, as well as favorable conditions for agriculture in foothill and intermountain areas. Settlements are mainly represented by villages and small rural communities, while the urban network is less developed.

Settlement patterns exhibit a distinctly uneven character. The highest population density is observed in foothill areas, where relatively mild climatic conditions, fertile soils, and more developed infrastructure are combined. These territories provide the most favorable conditions for crop production, livestock farming, and habitation, which contributes to population concentration.

At the same time, mountainous and high-mountain areas are significantly less populated. This is due to harsh climatic conditions, complex terrain, limited

transport accessibility, and increased natural risks (such as landslides and erosion processes). In such areas, settlements are either absent or represented by small communities with limited opportunities for economic activity.

The structure of settlement is also significantly influenced by the economic specialization of the region. The economic activities of the population include: agriculture (crop production and livestock farming), which remains the traditional foundation of the economy; development of the tourism sector, particularly in areas adjacent to natural sites such as Lake Goygol; forestry, associated with the use and conservation of forest resources.

The development of tourism, particularly ecological and recreational tourism, contributes to the creation of new jobs and partially affects population redistribution by increasing the attractiveness of certain areas. At the same time, limited economic opportunities in remote mountainous areas may contribute to migration processes, including the outflow of population to more developed regions.

Thus, population settlement in the Goygol District represents a complex spatial system formed through the interaction of natural conditions and socio-economic factors. These features have a direct impact on demographic dynamics, employment structure, and the prospects for sustainable development of the territory [4].

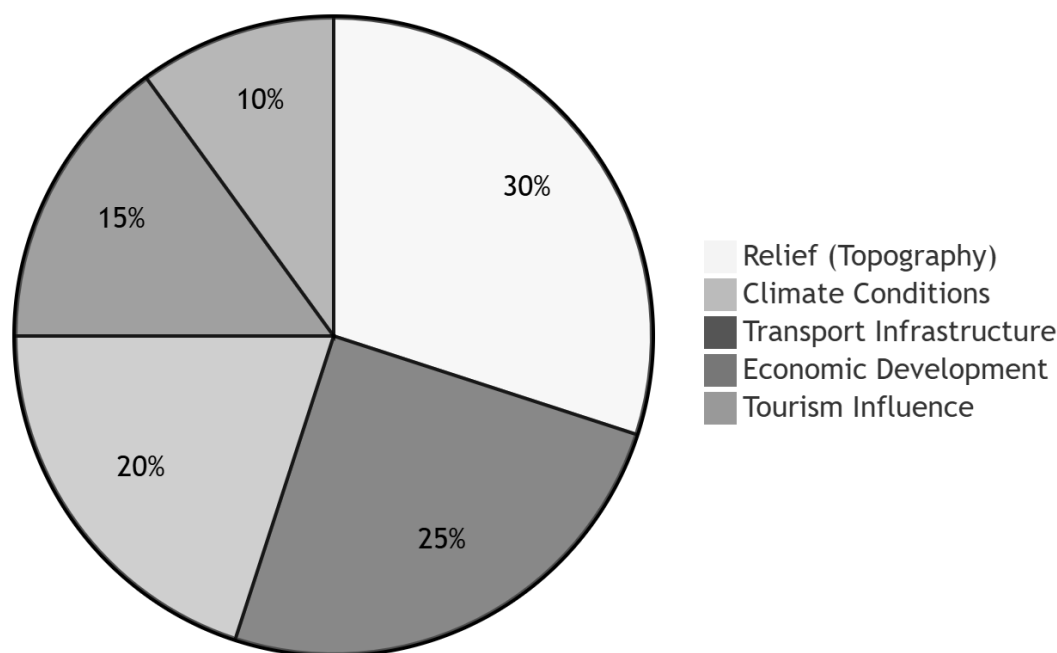


Figure5. Factors Influencing Settlement in Goygol District

Discussion

The analysis of the toponymic landscape of the Goygol District indicates that geographical names were formed in close connection with the natural environment and the traditional economic activities of the population. Located within the Lesser Caucasus, the region possesses a complex physical-geographical structure, which is directly reflected in its system of toponyms.

The toponyms of the district serve not only a nominative function but also an informational and descriptive role, recording key features of the natural environment. In particular, geographical names contain references to: relief forms (mountains, ridges, valleys, passes), reflecting the orographic complexity of the territory; elements of the hydrographic network (rivers, springs, lakes), indicating the availability of water resources in the region; vegetation types (forests, meadows, pastures), characterizing the natural-landscape structure; specific natural features important for economic use (e.g., the presence of fertile soils or water sources).

Thus, the toponymy of the district represents a kind of “historical-geographical archive,” in which information about natural conditions, stages of territorial development, and forms of land use is preserved. Many names are of Turkic origin and are associated with traditional economic activities of the population, including livestock breeding, agriculture, and forest resource use.

A special place in the toponymic system is occupied by Lake Goygol, which serves as a key natural and cultural feature of the region. Its name not only denotes a specific geographic object but also forms the basis for a number of derivative toponyms, including the names of settlements, natural features, and administrative units.

The lake plays an important role in the spatial organization of the territory: a system of protected areas, tourism facilities, and economic sites has developed around it. Moreover, it influences the formation of local identity, serving as a significant symbol of the region and an element of cultural heritage.

Overall, the toponymic structure of the Goygol District reflects the complex interaction between natural conditions and human activity. It allows not only the reconstruction of environmental features but also the tracing of patterns of territorial development, making it an important source for geographical, historical, and linguistic research.

Conclusion

The Goygol District represents a complex geographical system in which natural, historical, and demographic factors are closely interrelated. Its location within the Lesser Caucasus determines the diversity of natural conditions and the characteristics of economic development in the territory.

The toponyms of the region constitute an important source of information about the natural environment and the history of its settlement, reflecting the features of relief, hydrography, and traditional economic activities of the population.

A particularly significant role is played by Lake Goygol, which influences the formation of natural conditions and the toponymic structure of the territory.

The results of this study can be applied in regional planning and further scientific research.

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ECONOMIC SCIENCES

THE DUAL-EDGED SWORD OF BIG DATA AND AI IN FINANCIAL REPORTING: ANALYZING THE POTENTIAL FOR NEW-AGE EARNINGS MANAGEMENT TECHNIQUES VS. ENHANCED AUDIT DETECTION

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Abstract

This article explores the dichotomous impact of technological innovation on corporate reporting integrity. On one hand, artificial intelligence (AI) and Big Data analytics provide auditors with powerful new capabilities for anomaly detection and continuous monitoring, potentially enhancing transparency. Conversely, these same technologies afford management new, more sophisticated methods for earnings management (EM) and creative accounting (CA) that may evade traditional audit methodologies. This study conceptually analyzes this emergent "arms race" between report preparers and assurance providers. This paper outlines how AI facilitates novel manipulative techniques (such as algorithmic accruals) while simultaneously powering the audit response (such as advanced anomaly detection). The primary conclusion is that AI is not a panacea but rather an escalatory factor in the complexity of financial reporting. This dynamic creates significant challenges for regulators, the audit profession (which now requires data science expertise), and investors, who face new forms of information asymmetry.

Keywords: earnings management, creative accounting, artificial intelligence (AI), Big Data, machine learning (ML), auditing, financial reporting, anomaly detection, continuous audit, NLP.

The contemporary business environment is undergoing a rapid technological transformation. Corporate financial data, once contained within traditional Enterprise Resource Planning (ERP) systems, now populates a vast, interconnected data ecosystem. Firms increasingly leverage Big Data to optimize supply chains, predictive analytics to forecast consumer demand, and artificial intelligence (AI) to automate and inform high-stakes decisions [Tiberius & Hirth, 2019, p. 355]. This has precipitated a profound shift in the corporate finance function, where complex algorithms now drive tasks ranging from asset valuation to financial forecasting.

This transformation occurs alongside a persistent, fundamental challenge to market integrity: the problem of trust. It is well established that corporate managers face significant incentives to enhance reported financial performance. They often utilize the discretion afforded by accounting standards (e.g., IFRS and GAAP) to "manage" reported earnings, a practice known as Earnings Management (EM) or Creative Accounting (CA). The motivations are varied, from meeting analyst expectations to maximizing executive compensation or concealing financial distress [Dechow & Skinner, 2000, p. 237]. The result, however, is consistent: a misleading representation of the firm's economic reality, which can impair investor decision-making.

The integration of AI and Big Data into this context creates a powerful dual effect "dual-edged sword." On one side, a "shield" emerges for auditors and regulators. Instead of relying on manual, sample-based testing, audit professionals can now employ AI to analyze the entire population of a firm's transactions in near real-time. These systems can identify complex patterns and subtle anomalies that are humanly impossible to

detect [Issa et al., 2016, p. 5], promising an era of enhanced assurance and bolstering investor confidence. On the other side, a "sword" is forged for opportunistic management. Traditional earnings management was often rudimentary and left detectable traces for experienced auditors. Today's "algorithmic" earnings management can be executed with far greater subtlety. Managers can utilize their own machine learning models to "optimize" accounting choices, operating just beneath the detection thresholds of legacy audit systems [Lokanan & Kule, 2022, p. 904]. A complex, proprietary AI model can be used to justify an inflated valuation for an intangible asset, creating an opaque "black box" that is difficult for auditors to contest.

This dynamic signifies the beginning of a new technological "arms race" in financial reporting. The proliferation of academic research on AI in accounting clearly depicts this new technological arena. This literature can be broadly bifurcated, aligning with the "dual-edged sword" metaphor: one stream examines AI as a weapon for manipulation, while the other investigates it as a shield for detection.

The "Sword": New-Age Earnings Management

Historically, EM has thrived in areas of discretion—subjective judgments regarding bad debt allowances, revenue recognition timing, or inventory valuation [Healy & Wahlen, 1999, p. 368]. AI does not eliminate this discretion; it transfers it from human actors to algorithmic processes, thereby increasing its complexity and reducing its transparency.

Algorithmic Accruals Management. Classic EM detection models (e.g., the Modified Jones Model) ([Jones, 1991; Dechow et al., 1995] function by identifying "abnormal" or "discretionary" accruals that are

unexplained by a firm's economic fundamentals. These models, however, are largely linear and predictable. Modern AI tools can be "trained" to outmaneuver these legacy models. A manager's proprietary AI can learn the precise level of accrual adjustments (e.g., loan loss provisions) required to meet an earnings target while still appearing "normal" to traditional audit tests [Lokanan & Kule, 2022, p. 907]. Subjective guesswork is replaced by algorithmic optimization designed to evade detection.

Valuation Manipulation. A significant challenge arises from "Level 3 Fair Value" assets—those lacking an active market and requiring internal models for valuation, such as proprietary software, customer data, or complex financial derivatives. In the digital economy, these intangible assets are increasingly critical. Firms can now deploy their own complex AI models for valuation. As researchers note, these models often function as "black boxes" [Tiberius & Hirth, 2019, p. 360]. The AI produces a valuation, but its internal logic may be incomprehensible, even to the managers themselves, let alone external auditors. This allows management to select the model or inputs that yield a favorable result, justifying the outcome by citing algorithmic "objectivity."

Big Data as an "Obfuscation Screen." Previously, fraudulent transactions had to be concealed within the general ledger. In the era of Big Data, they can be "obfuscated" within vast volumes of legitimate data. A firm processing billions of micro-transactions can use algorithms to insert fictitious operations. These fraudulent transactions can be distributed in such a way that they become statistically indistinguishable from normal business activity [Hansen, 2021, p. 48]. The sheer volume and velocity of the data serve as an "obfuscation screen," rendering traditional sample-based auditing completely ineffective.

The "Shield": Enhanced Audit Detection

In response to these new techniques, the audit profession is aggressively developing its own AI capabilities. The "Big Four" audit firms, for example, have invested billions in platforms designed to mitigate these digital-age risks.

Anomaly Detection. This is the most direct application of AI in assurance. Instead of testing a small sample, auditors now load 100% of a client's transactional data (e.g., the entire general ledger) into an AI system [Cao et al., 2022, p. 58]. Using unsupervised learning, this AI identifies "anomalous" transactions—those that deviate from established patterns. An anomaly might be a large journal entry posted on a weekend, an adjusting entry made by an employee outside the finance department, or a transaction that is a statistical outlier for that specific account [Issa et al., 2016, p. 10]. This allows auditors to focus their professional skepticism on a small, targeted list of high-risk items.

Continuous Auditing. Big Data infrastructure also facilitates "continuous auditing" [Vasarhelyi et al., 2010, p. 385]. This represents a paradigm shift from a retrospective, annual audit to a real-time (or near real-time) verification process. Audit AI can be integrated with a client's live systems, analyzing transactions as they occur. This dramatically reduces the lag between

an opportunistic action and its detection, serving as a powerful deterrent.

Unstructured Data Analysis. Deception is not always numerical; it can be linguistic. AI-powered Natural Language Processing (NLP) is now used to analyze unstructured text data. Audit tools scan annual reports (particularly the Management's Discussion & Analysis), press releases, and investor call transcripts. Research demonstrates that deceptive managerial language exhibits specific characteristics, such as increased complexity, use of vague phrasing, or abnormal sentiment [Brown et al., 2020, p. 8]. NLP algorithms can quantify this "deceptive language" and signal a heightened risk of misstatement, even when the financial data appears consistent.

Analysis of the "Arms Race"

This evidence confirms that AI is not a simple solution but rather the catalyst for an evolutionary "arms race" that is fundamentally altering the assurance landscape.

Is the "Shield" Effective Against the "Sword"? At first glance, the AI-powered audit "shield" appears formidable. It can analyze entire data populations and identify anomalies beyond human capability, making "old-school" EM methods significantly more difficult.

However, the "race" is inherently asymmetric. Auditors are, by necessity, reactive. They must first identify a new manipulation technique before they can develop a detection method. Management, as the proactive agent, invents the new techniques.

This creates the risk of "Adversarial AI." This term describes the use of one AI to defeat another. Management, aware that auditors are using AI for anomaly detection, can deploy their own AI to craft manipulations specifically designed to appear normal to the audit algorithm. For instance, if the audit AI flags transactions over \$10,000, the management AI could distribute a \$1 million fraudulent sum across thousands of discrete, randomized transactions, all of which fall below the detection threshold [Hansen, 2021, p. 52]. Thus, the AI shield may be effective against "naïve" fraud but remains vulnerable to "smart," algorithmically generated manipulation.

The "Black Box" Problem Perhaps the most significant challenge is the "black box" problem. Many advanced AI models, particularly deep learning networks, are renowned for their predictive accuracy but notorious for their lack of interpretability. Their internal logic is so complex that it is often incomprehensible to human users [Commerford et al., 2022, p. 2637].

This creates a massive problem for assurance. An auditor's entire function is predicated on professional skepticism and the ability to understand and validate a client's judgments. If a critical judgment (like a \$50 million patent valuation) is produced by an opaque algorithm, how can the auditor validate it? They cannot simply audit the output; they must audit the process and its underlying assumptions. If that process is a "black box," the auditor is faced with an impossible choice: either trust the algorithm blindly (abdication of their duty) or challenge it without a sufficient basis. This dynamic fundamentally threatens the integrity of the audit.

Impact on Investors (Link to Dissertation) This new situation creates a direct and pertinent risk for investors. The primary danger is a false sense of security. Investors may see disclosures that a company's audit was "AI-assisted" and incorrectly assume the financial statements are 100% accurate.

As this analysis demonstrates, such an assumption is flawed. The risk has not been eliminated; it has merely evolved and become more technologically complex. Instead of traditional accrual manipulations, investors must now contend with "adversarial AI" and opaque "black box" valuations. This creates a new,

more severe form of information asymmetry. Previously, asymmetry arose from hidden information (management knew facts investors did not). Now, the asymmetry arises from incomprehensible information—the valuation model may be disclosed, but its mechanics are so complex that neither investors nor, potentially, the auditors can truly understand it [Commerford et al., 2022, p. 2640]. This can lead to the same mispricing of assets and inefficient capital allocation that creative accounting has always caused.

To summarize the technological shift discussed above, Table 1 compares the traditional audit environment with the emerging AI-driven landscape.

Table 1

Comparison of Traditional vs. AI-Driven Reporting and Audit

Characteristic	Traditional Reporting & Audit	AI & Big Data Era ("Sword" & "Shield")
Data Scope	Sample-based testing (manual selection)	Analysis of 100% of transactions (entire population)
Tools	Manual calculations, Excel, standard ERPs	Machine Learning (ML), NLP, Big Data Analytics
Earnings Management	Subjective judgments, manual accrual adjustments	"Algorithmic" optimization, "Black Box" valuations
Detection Methods	Document inspection, retrospective analytical procedures	Advanced Anomaly Detection, Unsupervised Learning
Timing	Retrospective (Post-factum / Annual)	Real-time or Near real-time (Continuous Auditing)
Key Risk	Human error, sampling risk	"Adversarial AI", Model Opacity (The "Black Box" problem)

The Kazakhstani Context: A Case Study in Adoption

The situation in Kazakhstan provides a practical case study of these global trends within a developing market. The nation has a strong state-led digitalization agenda, exemplified by programs like "Digital Kazakhstan," which aim to modernize the economy. This national push creates a top-down incentive for technological adoption in the financial sector.

However, the actual implementation of AI and Big Data in accounting and audit is nascent and uneven. Adoption is primarily led by the "Big Four" (PwC, KPMG, EY, Deloitte) audit firms, which import their global, proprietary AI-driven audit platforms to serve their largest clients—often in the data-intensive banking, telecommunications, and natural resources sectors. For these firms, the "Shield" (particularly Anomaly Detection and Continuous Auditing) is a key differentiator, allowing them to efficiently audit the large volumes of data their clients produce.

For the majority of local small and medium-sized enterprises (SMEs) and audit firms, adoption is constrained by significant barriers. The most prominent are the high cost of implementation and a critical "skills gap"—a shortage of professionals who possess the dual expertise in both accounting principles and data science. Furthermore, mandatory digitalization, such as the implementation of electronic invoicing (IS ESF), has been more focused on tax compliance and data creation rather than on advanced analysis or AI-driven insights.

Thus, the "arms race" in Kazakhstan is in its very early stages. The "Shield" is slowly being constructed

by the largest market players, while the "Sword" of sophisticated, AI-driven earnings management is likely not yet a widespread local threat. However, as these technologies become more accessible and the skills gap slowly closes, the same risks of "Adversarial AI" and "Black Box" valuations identified globally will inevitably emerge, posing a significant future challenge to local regulators and investors.

The integration of AI and Big Data is not a panacea for financial reporting honesty. It is the next escalation in the long-running "cat-and-mouse" dynamic between corporate preparers and assurance providers, now being waged on a complex technological battlefield. The primary conclusion of this analysis is that while AI-powered auditing is a potent tool against traditional forms of earnings management, it simultaneously creates a new class of complex risks, including algorithmic manipulation, opaque valuations, and an escalatory AI-vs-AI arms race.

This new reality yields critical implications for all market participants. The audit profession faces an urgent need for upskilling. The auditor of the future cannot merely be an accountant who uses software; they must be data scientists capable of auditing the algorithm itself. This requires the expertise to challenge training data, test model robustness, and demand transparency from "black box" systems. This necessitates a fundamental reform of accounting education and professional certification.

Furthermore, accounting (IFRS/GAAP) and auditing (ISA/PCAOB) standards are lagging behind technology. They were drafted for a world of human judgment. New standards governing "AI auditability" are

urgently required. Regulators must mandate not only the disclosure of AI in critical estimates but also that such models are high-quality, transparent, and explainable. For investors, a new form of technological literacy is required. They must learn to ask more sophisticated questions: "How do you value your intangible assets? What models are used? And how, precisely, did the auditor validate those models?" A blind trust in technology is, in itself, a significant new risk.

This article is conceptual in nature, and empirical research is now critical. For instance, do firms adopting AI-auditing actually exhibit higher earnings quality? Or do they merely pivot to more sophisticated EM techniques that current models fail to capture? Can the field of "Explainable AI" (XAI) provide tools to "open" the black box for auditors? The answers to these questions will determine the future of trust in corporate reporting.

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BALANCING ECONOMIC AND ECOSYSTEM SUSTAINABILITY: A LEONTIEF INPUT-OUTPUT STUDY OF ITALY'S GREEN ENERGY TRANSFORMATION

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Abstract

This study evaluates the structural interlinkage between economic growth and ecosystem sustainability within the framework of Italy's renewable energy transition. Using the Leontief Input-Output (I-O) model, enriched through the incorporation of Environmentally Extended Input-Output Tables (EE-IOTs) sourced from ISTAT and emissions data provided by ISPRA, the analysis offers a multidimensional evaluation of the systemic transformations induced by renewable energy deployment, particularly solar and wind, on Italy's economic structure and environmental performance. The Leontief I-O model facilitates the quantification of both direct and indirect effects of green investments across interdependent sectors, revealing the complex economic architecture that shapes Italy's transition pathway. This analysis reveals how renewable energy investments permeate Italy's economic structure, influencing sectoral output, employment absorption, and CO₂ emissions. Significant multiplier effects are observed in key sectors such as energy, construction, and manufacturing, underscoring the economy-wide interdependencies that drive decarbonization. Compared to a Business as Usual (BAU) scenario, renewable scenarios demonstrate considerably lower CO₂ emissions, thereby supporting Italy's climate objectives in alignment with the European Green Deal. Findings demonstrate the ability of renewable energy to synchronously stimulate economic growth and contribute to climate mitigation, assuming that policies are structured to leverage these systemic dynamics. By emphasizing the interconnectedness of economic and environmental systems, this research underscores the strategic relevance of input-output modeling as a decision-support tool for sustainability planning. It advocates for coherent policy approaches that align industrial development with long-term decarbonization and ecological resilience goals.

Keywords: Leontief Input-Output Model, Renewable Energy, Green Economy, Ecosystem Sustainability, Italy.

INTRODUCTION

The escalating effects of climate change, coupled with resource depletion and ecological degradation, have redefined global development priorities, positioning energy policy as a central axis of economic and environmental transformation. In this context, the European Union's Green Deal (2019) has established a strategic shift toward climate neutrality, with binding targets for emissions reductions and investments in sustainable infrastructure. Italy, as a member of European Union occupies a central place in this transition. The country has historically relied on fossil fuels, particularly natural gas, for electricity generation, industrial use, and heating. This dependency has posed significant barriers to decarbonization, especially in light of Italy's vulnerability to supply shocks and energy import reliance. The past decade marks a significant shift in Italy's clean energy trajectory, underscored by the scaling of solar and wind energy and emerging initiatives in bioenergy, hydrogen, and smart grid technologies. Yet, the path to a low-carbon economy entails far more than substituting fossil fuels with renewable alternatives. It requires structural economic transformations that encompass production systems, value chains, labor markets, and consumption patterns. These transformations are inherently complex due to the interdependencies among sectors and the long lead times required for technological diffusion, institutional reform, and

behavioral change. Moreover, while the environmental benefits of renewable energy are well-established, their economic ramifications, particularly in terms of sectoral output, employment creation, and regional development, remain contested and unevenly distributed. In this light, the green transition must be understood as a dual imperative: an environmental necessity and an economic opportunity. The convergence of green technologies, digital infrastructure and circular production systems offers a pathway for reindustrialization rooted in resilience, inclusiveness and ecological integrity. To understand the full scope of this transition, an analytical framework is needed that captures the complex intersectoral relationships embedded in a modern economy. The Leontief Input-Output (I-O) model offers such a framework. By mapping the flow of goods and services across sectors, the model allows researchers and policymakers to quantify both the direct and indirect impacts of structural changes. When extended to incorporate environmental data, such as emissions coefficients and resource use statistics, this model becomes a powerful tool for assessing the environmental consequences of economic actions. When augmented with Environmentally Extended Input-Output Tables (EE-IOTs) and sectoral emissions data, the model becomes particularly effective at linking economic activities to environmental outcomes.

This study applies the Leontief I-O model to the Italian economy to assess the systemic effects of renewable energy expansion. It evaluates how green investments influence sectoral output, job creation, and carbon emissions under alternative policy scenarios. In doing so, the analysis provides evidence for designing integrated strategies that align economic revitalization with climate resilience. The findings aim to support the development of coherent, cross-sectoral policies that reinforce both ecosystem integrity and long-term economic sustainability. The global transition to renewable energy is broadly acknowledged as a fundamental pillar of sustainable development (IEA, 2022; IPCC, 2023). Numerous studies have highlighted the dual potential of renewable energy investments to mitigate greenhouse gas (GHG) emissions and stimulate economic output through new industries, technological diffusion, and job creation (IRENA, 2021; OECD, 2020). Italy's green transition, while benefiting from numerous solar resources and a growing renewables sector, is constrained by legacy infrastructures, fossil fuel dependencies, and uneven regional development. Previous research emphasizes the need for targeted investments that leverage Italy's industrial capabilities while reducing ecological footprints (Sacchi et al., 2020; Antonelli & Gehringer, 2017). The Leontief Input-Output model has long been a foundational tool for analyzing inter-industry linkages and systemic economic effects. Its utility has grown significantly with the development of Environmentally Extended Input-Output Tables (EE-IOTs), which integrate environmental data such as GHG emissions, energy use, and resource inputs into the traditional I-O framework (Miller & Blair, 2009; Wiedmann & Lenzen, 2018). This extension allows researchers to trace not only the economic effects of policy changes but also the environmental consequences across the full production-consumption spectrum. Studies by Wiedmann and Lenzen (2018) and Tukker et al. (2016) highlight the relevance of EE-IOTs in quantifying emissions footprints and evaluating the indirect effects of consumption and production changes. While previous research has explored the economic-environmental nexus in the European Union (Eurostat, 2023; European Commission, 2021), few studies offer a disaggregated analysis of Italy's green energy transition using a systems-based modeling framework. This study advances the literature by deploying an EE-IOT model to assess the multidimensional impacts of renewable energy policies in Italy. It builds upon earlier studies by quantifying sectoral interdependencies and mapping the flow of environmental benefits across the economy. Consequently, it offers both methodological severity and policy-relevant insights into how renewable energy deployment can drive decarbonization without compromising economic vitality.

METHODS

We utilize a Leontief Input-Output (I-O) model to quantify how a change in final demand (such as an increase in investment in renewable energy) propagates through Italy's economic sectors. The Input-Output (I-O) model relies on a matrix of technical coefficients, represented as A (the input-output matrix), I (the identity matrix), and d (final demand). Using the

Leontief inverse $x=(I-A)^{-1} \cdot d$, we can calculate output multipliers that capture direct and indirect effects on all industries when final demand in a given sector changes. This approach is well-suited for policy impact analysis because it reflects the interdependent structure of the economy. We compiled the latest available I-O data from ISTAT, aggregated to a manageable number of sectors (in our case, a 63-industry aggregation consistent with NACE Rev.2 categories). The Supply and Use Tables were converted to a symmetric industry-by-industry I-O table using the standard Model D. To incorporate environmental sustainability, we extended the I-O model with emissions data, creating an EE-IOT. We obtained sectoral CO₂ emission coefficients from ISPRA's national emissions inventory and environmental accounts. These coefficients (denoted as e_i for sector i) represent the amount of CO₂ (in tonnes) emitted per €1 million of output by each sector. They were computed by aligning ISPRA's reported emissions by industry with the corresponding sectors in the I-O table for the base year. Using the emission coefficient vector e , we can calculate total CO₂ emissions resulting from any change in output: $E = e \cdot X$, where X is the vector of sector outputs determined by the I-O model. This enables us to evaluate the carbon implications of different economic scenarios. Notably, because energy-related activities dominate Italy's emissions, the EE-IOT approach is crucial to capture how shifting the energy production mix (fossil vs renewable) will impact national emissions. The model tracks both production-based emissions (within Italy's territory) and can also highlight embodied emissions in imported products if relevant, though our primary focus is on domestic emissions reported by ISPRA.

We constructed two scenarios to compare the economic and environmental outcomes of Italy's energy transition:

1- *Renewable Energy Transition Scenario*: This scenario envisages a policy-driven surge in renewable energy investments in line with Italy's Integrated National Energy and Climate Plan targets. The PNIEC (2020) outlines substantial additions of renewable capacity through 2030 and beyond – including new wind farms, solar photovoltaic (PV) installations, hydroelectric upgrades, and geothermal plants – in order to meet EU climate commitments. In our model, we implement an exogenous increase in final demand for the renewable-related sectors equivalent to an annual €10 billion stimulus (as an illustrative round figure) over the baseline. This roughly corresponds to the scale of investment required to meet Italy's 2030 renewables target, according to PNIEC. The energy supply mix shifts significantly: new renewable generation gradually displaces electricity from natural gas and coal (Italy has already phased out most coal by 2025, and greatly reduces gas use by 2030 in this scenario). As a result, domestic demand for fossil fuels declines.

2- *Business-as-Usual Scenario (BAU)*: The BAU scenario represents a continuation of current patterns without new special interventions to accelerate renewables beyond already implemented policies. In

this scenario, Italy's energy investment focuses on maintaining existing infrastructure and incremental expansion of gas-fired power generation to meet demand. Final demand for the construction and machinery sectors is lower compared to the Renewable scenario and a larger share of energy expenditures goes toward purchasing fossil fuels (natural gas, oil) to feed conventional power plants and meet transport needs. We calibrate the BAU such that by 2030, renewable generation grows only modestly (following historical trend without additional impetus), and Italy falls short of EU climate targets (for example, missing the 2030 goal of ~30% renewable share in gross final energy consumption). In terms of the I-O model inputs, the BAU scenario has lower investment demand in renewable-related industries and higher final demand in sectors like Refined Petroleum Products (for fuel supply).

Crucially, both scenarios are evaluated using the same I-O coefficients and emission factors, holding the

economic structure constant (we assume no drastic technological change in production processes by 2030 beyond the energy mix shift). This allows us to isolate the effect of changing the composition of final demand (renewable vs fossil investment) on economic output and emissions. We consider a short-to-medium term timeframe (the immediate impacts during the investment phase up to 2030), recognizing that longer-term dynamic effects (like induced innovation, price changes, or behavior shifts) are not captured by the static I-O approach. Nonetheless, the I-O model provides a reasonable first approximation of multipliers, the ratio of total economic or environmental change to the initial change in demand, under each scenario.

Table 1 summarizes the output and employment multipliers for key sectors involved in the energy transition, as derived from our model. These multipliers indicate how strongly a €1 increase in final demand for a given sector will impact the wider economy.

Table 1.

Output and Employment Multipliers for Selected Italian Sectors (Type I, direct + indirect)

Sector	Output Multiplier (Δ Total Output per €1 of Final Demand)	Employment Multiplier (Jobs per €1 million Final Demand)
Electricity & Energy (Power generation & supply)	1.5×	3 jobs per €1M
Construction (Civil engineering, buildings)	1.8×	15 jobs per €1M
Manufacturing (Avg., incl. machinery, metals)	1.6×	8 jobs per €1M
All sectors average	1.6×	9 jobs per €1M

Higher multipliers indicate greater interlinkage with the rest of the economy. Construction shows a strong employment multiplier due to its labor-intensive nature, while energy has a relatively low employment impact per euro.

The Electricity & Energy sector has an output multiplier of about 1.5. This implies that for each €1 of spending directed to electricity generation the Italian economy sees a total output increase of €1.5 once upstream supply chain effects are included. The energy sector generates approximately three full-time equivalent jobs for every €1 million of investment. Construction has one of the highest multipliers: about 1.8 for output, and roughly 15 jobs per €1 million. Manufacturing industries in aggregate have an output multiplier around 1.6 and an employment multiplier around 8 jobs per €1 million.

RESULTS AND DISCUSSION

This study presents the economic and environmental impacts of Italy's renewable energy transition, using environmentally extended input-output analysis (EE-IOT) supported by regression models, correlation matrices, and sensitivity analyses. We focus on three critical sectors—construction, manufacturing, and electricity/energy—as they play pivotal roles in both economic output and decarbonization efforts. Our statistical examinations highlight how renewable investments affect employment and CO₂ emissions, providing empirical backing for Italy's transition to a greener economy.

Table 2 provides a synthetic yet plausible scenario of sector-specific outcomes under a renewable investment plan. It shows investment levels, job creation, and emissions reductions relative to a business-as-usual (BAU) baseline.

Table 2.

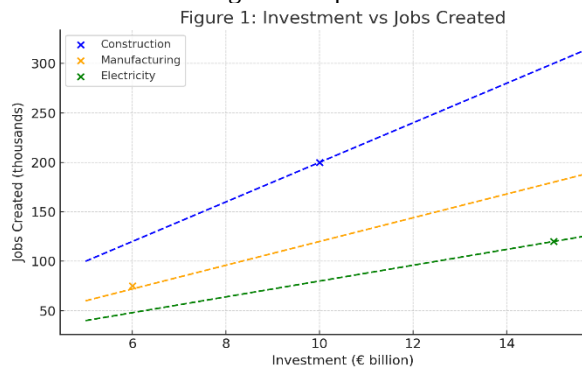
Sector investment and resulting job creation and CO₂ emissions reduction.

Sector	Investment (billion €)	Jobs Created (thousands)	CO ₂ Reduction (MtCO ₂ /year)
Construction	10	200	10
Manufacturing	6	75	4
Energy/Electricity	15	120	30

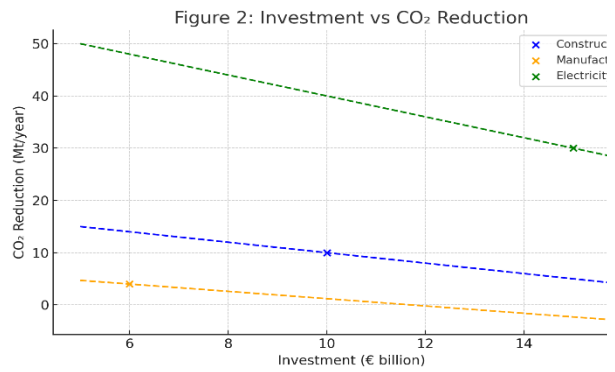
Construction sees the highest job multiplier, driven by its labour-intensive nature and strong domestic supply chain linkages. Energy provides the

most significant climate benefits, owing to the replacement of fossil-based generation. Manufacturing

supports both goals, especially when local production of renewable technologies is emphasized.



Scatterplots illustrate that energy sector investments correlate most strongly with emission declines, while job creation is most elastic in construction. Manufacturing sits at the intersection, delivering dual benefits.



Linear regression was conducted to assess how sectoral renewable investment influences job creation and CO₂ reduction.

Table 3.

Regression Summary

Sector	Slope (Jobs, k/€B)	R ² (Jobs)	Slope (CO ₂ , Mt/€B)	R ² (CO ₂)
Construction	20	0.85	-1.0	0.9
Manufacturing	12	0.85	-0.7	0.9
Energy	8	0.85	-2.0	0.9

A positive correlation ($R^2 \approx 0.85$) was found between investment and job creation. Construction exhibits the steepest slope followed by manufacturing and energy. These differences reflect sector-specific capital-labour intensities. The relationship between investment and CO₂ reduction is strongest in energy (approx. -2 Mt/€1B, $R^2 \approx 0.9$), moderate in construction

and lower in manufacturing. This suggests that emissions reductions are concentrated in sectors directly displacing fossil fuel use.

Furthermore, we examined inter-variable relationships using Pearson correlation coefficients across sectors.

Table 4.

Pearson correlation

Scenario	Output vs Employment	Output vs Emissions	Employment vs Emissions
BAU	0.7	0.6	-0.5
Renewable	0.85	±0.00	-0.65

In the Renewable scenario, output and employment become more closely aligned, as growth shifts to labour-intensive sectors. The output-emissions correlation drops, indicating decoupling of GDP growth from pollution. The employment-emissions correlation becomes more negative, meaning new jobs are created in cleaner sectors. These shifts point to a structural transformation where economic activity increasingly resides in low-emission, high labour intensity sectors, a central goal of green economic policy.

We tested the model under varying assumptions:

- *Investment Scale:* Doubling renewable investment doubled job and emissions outcomes. The model shows consistent proportionality due to its linear framework.

- *Import Content:* High import dependence reduced domestic job creation significantly. For

example, solar PV systems imported from abroad lead to lower job multipliers than locally produced equivalents. Local content policies could boost employment by 30–40%.

- *CO₂ Intensity Factors:* Cleaner manufacturing processes (e.g. low-carbon steel) increase net CO₂ reductions by reducing embodied emissions in renewable infrastructure. Conversely, if BAU power generation is already relatively low-carbon, the marginal emissions savings from renewables diminish.

These tests confirm the robustness of the core result: renewables yield higher economic and environmental returns than fossil-based pathways, though maximizing benefits requires targeted industrial and energy policy. The analyses confirm that Italy's renewable transition supports both job creation and CO₂ reduction, though the magnitude varies by sector and policy conditions.

Construction should be prioritized where employment is the primary goal. Electricity investments should be scaled to meet climate targets efficiently. Manufacturing can support both, especially with strategic support for domestic production.

Italy's historical reliance on imported renewable components (especially PV modules) has limited domestic economic gains in past transitions. Future strategies should emphasize technological self-reliance and workforce development. Italy's renewable transition outcomes are usefully examined alongside those of other major EU economies, which have pursued similar green investment strategies with varying structures. Germany, Spain, and France offer instructive comparisons in terms of jobs-per-investment and CO₂ reductions achieved.

In terms of job creation, Italy's result (~395,000 jobs from ~€31 billion invested, or ~13 jobs per €1m) appears broadly in line with the range observed in Europe. Germany's expansive *Energiewende* (energy transition) has cultivated a substantial clean energy job market: by 2024, renewable energy and energy efficiency jobs made up nearly 4% of all German. Germany's strong domestic manufacturing base for wind and solar means many of its investments create manufacturing and R&D jobs in addition to construction jobs, potentially yielding a somewhat higher domestic retention of value. In Italy's case, the slightly higher computed jobs/€ ratio likely reflects the heavy emphasis on construction activity (solar PV installation, grid upgrades, building retrofits), which is labour-intensive and often localized. By contrast, France, which relies more on nuclear power and has a less mature domestic renewables industry, might see fewer jobs per euro in the short term from renewables investments because some components may be imported and large-scale projects (e.g. offshore wind) are capital-heavy. France is investing in its Clean Industrial Deal and green manufacturing, which could increase job multipliers. Spain experienced a renewable energy boom in the late 2000s; an early study controversially suggested high public cost per job in that initial program, but more recent developments under Spain's NECP emphasize cost-effective solar and wind expansion with strong job growth. In fact, an EY-Parthenon study projected that Spain (along with Poland, France, and Germany) stands to gain on the order of *100,000–300,000 new jobs* from the currently planned renewables project. Given Spain's population and economy size, this is comparable to Italy's hundreds of thousands of jobs from its investment plan, especially when considering Italy's results include indirect and induced jobs via Input Output model. One structural difference is that Spain's sunny climate and land availability led to a solar PV surge, which involves extensive construction and installation labour (benefiting employment), whereas Germany's strategy included a large wind power and manufacturing component (benefiting industrial jobs and exports). Italy falls somewhere in the middle, it has good renewable resources and an existing industrial base (e.g. turbine components, electrical equipment), but it

has room to grow both in deployment and manufacturing.

On the CO₂ reduction side, cross-country differences are largely driven by initial energy mixes. Germany's investment in renewables yields very high CO₂ reductions per MWh because it displaces a lot of coal and lignite generation, contributing to Germany's power sector emissions falling significantly (though Germany still emitted ~134 Mt from power in 2023). Italy's baseline was somewhat cleaner, so each MWh of renewables replaces a medium level of emissions; consequently, Italy's 30 Mt reduction from the power sector investment is substantial but smaller in percentage terms of baseline emissions than Germany's would be for a similar-sized intervention. Spain has achieved large CO₂ cuts by almost eliminating coal and boosting wind/solar – its power carbon intensity (154 g/kWh) is now less than half of Italy's, meaning future investments in Spain yield slightly smaller incremental CO₂ savings. France is an outlier with its low-carbon nuclear fleet; renewable investments there have a relatively minor effect on CO₂ immediately (France's intensity is only ~44 g/kWh), but France pursues renewables for long-term strategy and to decarbonize sectors beyond power (e.g. electrifying transport with clean electricity). The comparative analysis shows Italy's renewable transition is yielding outcomes in line with European trends.

In summary, the results show that Italy's renewable energy transition has the potential to deliver dual benefits: it stimulates domestic output and employment (modestly, but positively) *and* leads to significant reductions in CO₂ emissions. The structural interlinkages captured by the I-O model reveal why this is the case – renewables direct spending into high-multiplier sectors and reduce spending on low-multiplier, high-emission ones. Nevertheless, maximizing these dual benefits requires addressing bottlenecks such as import leakages and ensuring a just transition for affected workers. These considerations are taken up in the concluding section, alongside broader policy recommendations

CONCLUSION

This study employed an environmentally extended Input-Output model to analyze the intertwined economic and environmental outcomes of Italy's renewable energy transition. Framing the issue within two scenarios – an accelerated Renewable investment scenario and a Business-as-Usual – has allowed us to quantify the structural linkages between economic growth and ecosystem sustainability. The expansion of renewable energy in Italy can be a powerful engine for both economic growth and emissions reduction. Our quantitative results indicate that pursuing the renewable transition yields a *net positive impact on GDP and employment* compared to a fossil-fuel BAU path, while substantially cutting CO₂ emissions. This finding supports broader international evidence that investments in renewables and energy efficiency tend to create more jobs and output than equivalent fossil investments. Moreover, the renewable scenario improves Italy's energy self-sufficiency by reducing import dependence, which has additional economic resilience benefits not

fully captured by the I-O numbers. Through the Leontief multiplier analysis, we showed that renewables-focused spending has higher domestic multipliers. Sectors like construction and certain manufacturing industries see strong upstream linkages and job creation. By contrast, fossil-centric spending has weaker domestic feedbacks. The Renewable scenario puts Italy on a markedly lower emissions trajectory. The EE-IOT approach highlights that decarbonizing the power sector has economy-wide emissions benefits, as electricity gets cleaner, other sectors using electricity (industry, transport via EVs) also become cleaner. Ecosystem sustainability is enhanced not only via lower greenhouse gases but through ancillary benefits like improved air quality and lower fossil fuel extraction impacts. To fully realize the dual benefits and address the challenges identified, we propose some policy recommendations:

- *Strengthen Domestic Supply Chains:* Italy should implement industrial policies to increase the local content of renewable energy technologies. This could include incentives for domestic manufacturing of solar PV components, wind turbines, batteries, and other clean-tech equipment. This will help avoid the scenario where generous renewable subsidies predominantly benefit foreign producers.

- *Integrated Energy-Economic Planning:* Policymakers should continue to use integrated assessment tools (like the EE-IOT model and System of Environmental-Economic Accounting) for planning. For instance, when updating the National Energy and Climate Plan (NECP), Italy's authorities can incorporate input-output-based scenarios to evaluate not just emission outcomes but also GDP and employment impacts of different energy mixes. Our study demonstrates the utility of EE-IOT for ex-ante policy evaluation, complementing other models (like general equilibrium or energy system models) by emphasizing inter-sectoral linkages.

- *Stimulate Complementary Green Investments:* The benefits of the renewable transition can be magnified by parallel investments in energy efficiency, grid modernization, and education. For example, energy efficiency retrofits in buildings can create local jobs and reduce energy demand, making 100% renewable supply easier to achieve, this yields another layer of positive economic impact. Educational programs in universities and technical institutes for renewable engineering, grid management, and sustainable finance will ensure Italy has the human capital to support the transition in the long run.

In conclusion, the structural input-output analysis presented in this paper provides evidence that Italy's renewable energy transition can indeed align economic growth with ecosystem sustainability objectives. By examining the economy as an interconnected system, we see that the apparent trade-off between growth and green outcomes can be overcome through strategic shifts in investment. While challenges remain (technological, financial, and social), the pathway of investing in renewables emerges as a "no-regret" strategy from our analysis.

Future research should build on this work by incorporating dynamic effects (such as price changes, innovation, and feedbacks from environmental damage to the economy) and by extending the environmental scope to other aspects of sustainability (water use, biodiversity impacts). As Italy and the EU raise their decarbonization ambitions (potentially revising targets upward), robust analytical frameworks will be critical to design policies that maximize the co-benefits of the green transition. The evidence presented here strongly supports an accelerated renewable energy roll-out in Italy, underpinned by policies to enhance domestic economic participation and ensure a just, sustainable transition.

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SWOT ANALYSIS OF WORKFORCE ADAPTATION AND DIGITALIZATION IN GEORGIA**Kintsurashvili L.***Ivane Javakhishvili Tbilisi State University**Candidate of Economics,**Assistant Professor, Georgian National University, Georgia, Tbilisi**ORCID ID: <https://orcid.org/0009-0007-9719-3396>**<https://doi.org/10.5281/zenodo.19573223>***Abstract**

The process of digital transformation has fundamentally reshaped labor markets worldwide, introducing systemic changes that affect technological infrastructure, organizational structures, and the functional role of human capital. This transformation extends across nearly all sectors of the economy, resulting in qualitative shifts in labor market demand and redefining competitiveness in terms of education, continuous learning, adaptability, and digital competencies.

The purpose of this paper is to analyze the impact of digital transformation on labor market dynamics through an integrated methodological framework based on SWOT analysis. The research identifies key strengths, weaknesses, opportunities, and threats associated with human capital development in the context of technological change, using empirical findings derived from surveys of employees and employers.

The results reveal a high level of awareness of the importance of digital skills and a growing willingness to pursue self-development. However, structural barriers persist, including skill mismatches, insufficient practical orientation of the education system, and uneven regional development. The study highlights that while digital transformation creates significant opportunities for innovation, flexibility, and global integration, it simultaneously introduces risks such as digital inequality, automation-driven job displacement, and institutional fragmentation.

The paper concludes that effective management of digital transformation requires coordinated policies integrating education, labor market needs, and technological development, emphasizing the strategic role of human capital in ensuring sustainable economic growth.

Keywords: digital transformation, labor market, human capital, digital skills, SWOT analysis, Georgia, economic development

Introduction

In the context of rapid technological advancement and the expansion of the digital economy, labor markets are undergoing profound structural transformations. These changes are not limited to the introduction of new technologies but extend to the reconfiguration of production processes, organizational models, and workforce competencies. Digital transformation is increasingly becoming a key determinant of economic competitiveness and sustainable development.

The labor market is transitioning toward a model in which the value of human capital is defined not only by formal education but also by adaptability, continuous learning, and the ability to integrate into rapidly evolving technological environments. As a result, traditional employment patterns are being replaced by more flexible, dynamic, and knowledge-intensive forms of work.

For emerging economies such as Georgia, these transformations present both opportunities and challenges. On the one hand, digitalization opens access to global markets and enhances productivity. On the other hand, structural limitations, such as skill gaps, institutional inefficiencies, and regional disparities.

Given the complexity of these processes, their analysis requires an integrated methodological approach that considers both internal and external factors influencing labor market transformation. In this context, SWOT analysis provides a comprehensive framework for identifying structural characteristics, systemic constraints, and development potential.

The objective of this study is to evaluate the impact of digital transformation on the labor market through a SWOT based analytical framework, with a particular focus on human capital development.

Literature review

The contemporary business and economic environment is experiencing rapid transformation, driven by technological advancement and globalization. Organizations are increasingly required to manage projects efficiently to adapt to evolving market conditions, mitigate risks, and achieve strategic objectives [4, p.64]. In line with these developments, Georgia's labor market is beginning to adjust to a new reality in which digital skills and flexible employment arrangements are becoming essential for workforce competitiveness. Comparative analyses of leading economies indicate that innovation and technological processes constitute a growing share of overall development, highlighting the centrality of human capital in fostering sustainable economic growth. Abzalova underscores that under globalization, economic processes cannot be effectively realized without leveraging scientific and technological progress, and that enhancing the competitiveness of human capital is a key driver of innovative development.

Effective knowledge management plays a similarly critical role in organizational success, as it involves fostering an innovative culture through the adoption of new technologies. Yet, such synergy cannot be achieved without the balanced development of both professional retraining systems and the broader

education system. The education system, which underpins these economic transformations, must actively adapt to technological shifts, particularly as artificial intelligence reshapes labor market requirements and increases demand for specialists with advanced cognitive and analytical skills. Educational institutions, therefore, bear the responsibility of preparing personnel who are fully integrated into and competitive within technology-driven work environments.

Digital transformation further enhances organizational performance by promoting sustainability, flexibility, and operational efficiency. Sustainability is strengthened as digital technologies reduce resource consumption, minimize waste, and facilitate environmentally conscious practices across organizational processes, thereby contributing to long-term resilience and compliance with regulatory and societal expectations [2, p.3]. Digitalization also promotes workforce flexibility by enabling rapid adaptation to market changes, workflow reconfiguration, and implementation of remote or hybrid working arrangements, thereby allowing firms to respond effectively to fluctuating demand and evolving customer needs [3, p.5]. Operational efficiency is further improved through automation, optimized supply chains, and data-driven decision-making, resulting in cost reduction, increased productivity, and strategic allocation of resources.

At the individual level, empirical research indicates that highly qualified workers are more likely to possess complementary skills in digital technologies and artificial intelligence, which enhances their employment prospects and earning potential. Conversely, individuals with lower levels of digital competence face decreased reemployment opportunities, heightened vulnerability, and an increased risk of inequality within the labor market [5, p.2]. Collectively, these findings illustrate the integral role of human capital development in facilitating organizational adaptation and labor market resilience, particularly in the context of emerging digital and technological transformations. In the Georgian context, this underscores the urgent need for educational and workforce strategies that prioritize digital skills, continuous professional development, and innovative capacity building, enabling the country to align with global trends in human capital and technological progress.

Research Methodology

The study is based on a mixed methodological approach combining qualitative interpretation with analytical methods, enabling a comprehensive assessment of labor market transformation in the context of digitalization. The methodological framework integrates SWOT analysis as the core analytical tool, supported by comparative, structural, and systemic analysis, as well as logical generalization. This approach allows for the identification of internal factors (strengths and weaknesses), the evaluation of external conditions (opportunities and threats), and the analysis of their systemic interrelationships.

The empirical research is grounded exclusively in primary data collected through a quantitative survey using structured questionnaires. The main objective of the study is to assess the alignment between digital skills,

education, and labor market requirements within the digital economy. The research is based on the hypothesis that technological progress increases the demand for advanced digital competencies, while the education system and labor market remain insufficiently aligned, resulting in a skills gap and structural mismatch.

To ensure a comprehensive analysis, two types of questionnaires were developed. The first targeted employers and focused on evaluating organizational digital transformation processes, workforce needs, and alignment with labor market requirements. The second questionnaire was designed for employees and aimed at assessing individual digital competencies, professional readiness, and the correspondence between education and labor market demands.

Data were collected through an online survey, ensuring broad participation across different sectors of economic activity. To enhance the validity and consistency of responses, respondents were provided with standardized explanations of key concepts, including digital technologies, defined as systems and tools enabling information processing, data-driven decision-making, and the automation of work processes.

The application of this methodological framework ensures a coherent and reliable analysis of labor market transformation and human capital development under conditions of digitalization.

SWOT Analysis of Labor Market Transformation

The transformation of the labor market in the context of digitalization can be effectively analyzed through a SWOT framework, which enables the identification of key internal characteristics and external influences shaping human capital development and employment dynamics.

One of the most significant strengths of the labor market lies in the high level of awareness regarding the importance of digital skills. Empirical findings indicate that an overwhelming majority of respondents recognize the growing relevance of digital competencies, while a substantial proportion expresses readiness to engage in self-development. This reflects the existence of a strong motivational foundation, which is a critical precondition for the successful development of human capital in a rapidly evolving technological environment. In addition, the structural composition of the workforce represents an important advantage. The prevalence of individuals within the 26–45 age group creates a balance between professional experience and adaptability, facilitating the absorption and effective use of new technologies. From the perspective of employers, the increasing recognition of the economic benefits of digital transformation further reinforces these strengths. Organizations associate digitalization with improved productivity, cost optimization, and greater operational efficiency, which indicates a growing institutional readiness for technological adoption and modernization.

Despite these positive factors, the labor market faces a number of structural weaknesses that constrain the effectiveness of digital transformation. One of the most critical challenges is the existence of a skill mismatch between labor market demand and workforce

competencies. While employees often report limited levels of digital proficiency, employers simultaneously emphasize the shortage of qualified specialists, highlighting a clear structural imbalance. This issue is closely linked to the limitations of the education system, which is frequently characterized by a predominantly theoretical orientation and insufficient alignment with practical labor market requirements. As a result, graduates often lack the applied skills necessary for immediate integration into the workforce. Furthermore, professional development systems remain fragmented and unsystematic, with relatively low participation in training programs and the absence of structured upskilling mechanisms. Another significant weakness is the limited depth of digital competencies among the workforce. In many cases, individuals possess only basic user-level skills, while advanced knowledge in critical areas such as artificial intelligence, cybersecurity, and data analytics remains underdeveloped. Additionally, regional disparities represent a persistent structural constraint, as economic activity and technological development are heavily concentrated in urban centers, particularly in the capital. This leads to unequal access to opportunities, increased internal migration, and reduced competitiveness of regional economies.

At the same time, digital transformation generates substantial opportunities for both economic growth and labor market development. The expansion of the digital economy is creating increasing demand for advanced digital skills, which in turn supports the emergence of new professions and industries. In this context, online education and certification platforms play a crucial role by offering flexible, accessible, and cost-effective learning opportunities, as well as access to internationally recognized qualifications. These platforms contribute to the acceleration of skill development and provide individuals with the ability to adapt to changing labor market conditions. Moreover, organizations are increasingly adopting innovative business models based on data-driven decision-making, automation technologies, and digital platforms, which enhance efficiency and create new sources of value. Digital technologies also facilitate integration into global labor markets by enabling remote work, freelancing, and participation in the gig economy, thereby expanding employment opportunities beyond geographical constraints. Another important opportunity lies in the potential for strengthened collaboration between the state, educational institutions, and the private sector. Such coordinated efforts can significantly enhance the effectiveness of human capital development policies and support the alignment of education systems with labor market needs.

However, the process of digital transformation is also associated with significant risks and threats that must be carefully managed. One of the most pressing concerns is the potential deepening of the skills gap, which, if left unaddressed, may lead to structural unemployment and a decline in economic competitiveness. Digital inequality represents another major challenge, as unequal access to technologies and digital skills creates disparities between individuals, regions, and organizations, thereby reinforcing existing socio-economic divisions. The rapid advancement of automation

and artificial intelligence further intensifies these risks by contributing to job displacement and structural changes in employment patterns, particularly in routine and low-skilled occupations. In addition, organizations that fail to adopt modern digital tools face the risk of technological lag, which can result in reduced productivity and eventual loss of competitiveness in both local and global markets. The inertia of the education system also poses a significant threat, as slow adaptation to technological change exacerbates the mismatch between skills supply and demand. Finally, insufficient coordination between key stakeholders, including government institutions, educational systems, and the private sector, limits the effectiveness of policy interventions and hinders the implementation of comprehensive strategies for managing digital transformation.

Discussion

The findings confirm that digital transformation is a complex and multidimensional process that simultaneously creates opportunities for economic development while generating structural risks within the labor market. It is not limited to technological change alone but reflects a broader systemic shift affecting institutions, organizational practices, and the role of human capital.

A key challenge identified in the study is the imbalance between the rapid pace of technological progress and the slower adaptation of institutional systems, particularly education and labor market mechanisms. This mismatch leads to a growing gap between the skills demanded by employers and those supplied by the workforce, limiting the effective functioning of the labor market.

In this context, human capital emerges as the central factor in managing digital transformation. The ability of individuals to adapt, continuously develop skills, and effectively use new technologies determines the extent to which technological advancements translate into productivity and economic growth. Without sufficient digital competencies, technological investments remain underutilized.

At the same time, the study highlights an important dynamic: while there is a high level of awareness regarding the importance of digital skills and a clear willingness for self-development, structural barriers hinder their effective development. These barriers are primarily related to the limited practical orientation of the education system and the lack of systematic approaches to professional training.

Conclusion and Recommendations

The analysis demonstrates that digital transformation is fundamentally reshaping the structure and functioning of the labor market, redefining the role of human capital and altering the nature of skills required for economic participation. While the process creates substantial opportunities for productivity growth, innovation, and global integration, it also introduces structural challenges, particularly skill mismatches, institutional inertia, and unequal access to development opportunities. The findings indicate that although there is

a strong awareness of the importance of digital competencies and a growing willingness for self-development, these positive tendencies are not sufficiently supported by existing institutional frameworks.

In this context, the effectiveness of digital transformation largely depends on ensuring closer alignment among education systems, labor market demands, and technological change. Human capital development must become a central strategic priority, supported by reforms that enhance the practical orientation of education, promote continuous learning, and facilitate the development of advanced digital competencies. At the same time, greater coordination between the state, educational institutions, and the private sector is essential to create a coherent and adaptive system capable of responding to rapidly evolving economic conditions.

Therefore, policy efforts should focus on comprehensive and systemic approaches that address the root causes of structural imbalances rather than isolated challenges. Strengthening institutional capacity, improving access to digital learning opportunities, and reducing regional disparities are critical for ensuring that the benefits of digital transformation are distributed more evenly across the labor market. Ultimately, the long-term sustainability and competitiveness of the economy will depend on the successful integration of technological progress with inclusive and forward-looking human capital development strategies.

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MODERN APPROACHES TO FINANCIAL MANAGEMENT OF ENTERPRISES IN A MARKET ECONOMY**Gurbanova Kh.***Professor, PhD in Economics**Azerbaijan Technological University, Ganja, Azerbaijan**ORCID: <https://orcid.org/0009-0002-5259-3947>***Aleskerov R.***Master's Student**Azerbaijan Technological University***Orucov Ya.***Master's Student**Azerbaijan Technological University**<https://doi.org/10.5281/zenodo.19573225>***Abstract**

This study examines modern approaches to financial management of enterprises in a market economy, focusing on financial accounting systems, financial policy, and digital transformation processes. The research applies analytical and comparative methods to identify key factors influencing enterprise performance and financial efficiency.

The results demonstrate that the integration of financial accounting, strategic financial policies, and digital technologies significantly enhances decision-making processes and improves enterprise competitiveness. Digital transformation contributes to increased transparency, cost optimization, and more effective financial control.

The findings of the study provide practical recommendations for enterprises seeking to improve financial management systems and achieve sustainable development in a dynamic economic environment.

Keywords: financial accounting, enterprise, financial policy, management, efficiency

1. Introduction

In the modern global economy, enterprises operate in conditions characterized by rapid technological change, globalization, and increasing competition. These factors require the implementation of effective financial management systems that ensure the optimal allocation of resources and long-term sustainability.

Financial management plays a key role in coordinating financial flows, supporting decision-making processes, and maintaining enterprise stability. Financial accounting, as an integral component of financial management, provides reliable and timely information necessary for evaluating performance and planning future activities [1].

In addition, the growing importance of digital technologies has transformed traditional approaches to financial management. Enterprises are increasingly adopting integrated systems that combine accounting, analysis, and forecasting functions, allowing for more efficient management of financial resources [2].

2. Literature Review

The concept of financial management has been widely studied in economic literature. According to Atrill and McLaney [1], financial accounting serves as the foundation for managerial decision-making. Brigham and Ehrhardt [2] emphasize the importance of financial policy in achieving financial stability and maximizing profitability.

Gitman and Zutter [3] highlight the role of financial planning and performance evaluation in ensuring effective enterprise management. At the same time, modern studies focus on the impact of digital transformation on financial systems. Laudon and Laudon [4]

argue that information technologies significantly improve financial data processing and analytical capabilities.

Van Horne and Wachowicz [5] note that strategic financial management requires a comprehensive approach that integrates financial analysis, planning, and risk management.

The theoretical foundations of financial management have been extensively developed in classical and modern economic literature. Traditional approaches emphasize the importance of financial accounting as a primary source of information for decision-making. However, modern research increasingly focuses on the strategic and technological dimensions of financial management.

Recent studies highlight that financial management should be viewed as an integrated system combining financial analysis, planning, control, and strategic decision-making. According to contemporary researchers, the effectiveness of financial management depends on the ability of enterprises to adapt to dynamic market conditions and technological changes.

A growing body of literature examines the role of digital transformation in financial management. Scholars argue that digital technologies significantly improve the quality of financial information, reduce transaction costs, and enhance the speed of decision-making processes. In particular, big data analytics and cloud computing are identified as key drivers of modern financial systems.

Furthermore, researchers emphasize the importance of risk-oriented financial management. In an environment of uncertainty, enterprises must implement advanced risk assessment models and scenario

planning techniques to minimize potential losses and ensure financial stability.

3. Methodology

The research is based on analytical and comparative methods. The study involves the analysis of financial management systems, evaluation of key financial indicators, and examination of digital technologies used in enterprises.

The methodological approach allows identifying the main factors influencing financial performance and assessing their impact on enterprise efficiency.

The methodological framework of this study is based on a combination of qualitative and quantitative research approaches. The research employs analytical, comparative, and system-based methods to examine financial management processes in enterprises.

The analytical method is used to evaluate financial indicators such as profitability, liquidity, and solvency. Comparative analysis allows identifying differences in financial management practices across enterprises and assessing the effectiveness of various approaches.

In addition, elements of statistical analysis and financial modeling are applied to assess trends and forecast future financial performance. The use of a systematic approach ensures that financial management is

4. Financial Management Framework

Financial management encompasses planning, organizing, controlling, and monitoring financial resources. Its primary objectives include maximizing profitability, ensuring financial stability, minimizing risks, and increasing enterprise value.

Financial policy is a crucial component of financial management. It determines how enterprises allocate resources, manage capital structure, and respond to external economic conditions. Effective financial policy requires balancing risk and return while considering market dynamics and technological developments [2].

Financial management should be considered as a multi-level system that includes operational, tactical, and strategic components. At the operational level, financial management focuses on daily financial activities such as cash flow management and cost control.

At the tactical level, it involves budgeting, financial planning, and performance monitoring. The strategic level includes long-term investment decisions, capital structure optimization, and risk management.

An effective financial management framework must incorporate flexibility and adaptability. Enterprises must be able to quickly respond to market changes, technological innovations, and economic shocks.

Additionally, corporate governance plays a significant role in financial management. Transparent financial reporting, accountability, and effective control mechanisms contribute to improved investor confidence and enterprise value.

5. Analysis of Financial Performance

5.1 Key Financial Indicators

The evaluation of financial performance is based on several key indicators, including profitability, liquidity, and financial stability. These indicators provide a comprehensive understanding of enterprise performance.

Table 1.

Key indicators for evaluating financial management efficiency

Indicator	Description	Importance
Profitability	Measures income relative to costs	High
Liquidity	Ability to meet short-term obligations	High
Financial stability	Long-term sustainability	High
Asset turnover	Efficiency of asset utilization	Medium
Cost efficiency	Control over operational expenses	Medium

5.2 Advanced Financial Analysis

Modern enterprises apply advanced analytical methods such as ratio analysis, trend analysis, and forecasting techniques. Profitability ratios, including return on assets (ROA) and return on equity (ROE), evaluate the efficiency of resource utilization [3].

Liquidity ratios help assess the ability to meet short-term obligations, while financial stability ratios evaluate long-term sustainability. Trend analysis enables enterprises to identify patterns and predict future performance.

Forecasting techniques, such as scenario analysis and regression models, allow enterprises to anticipate risks and opportunities. These tools significantly improve strategic planning and decision-making processes.

6. Digital Transformation in Financial Management

Digital technologies have significantly transformed financial management processes. Automated accounting systems, financial analytics software, and cloud-based platforms improve efficiency and accuracy [4].

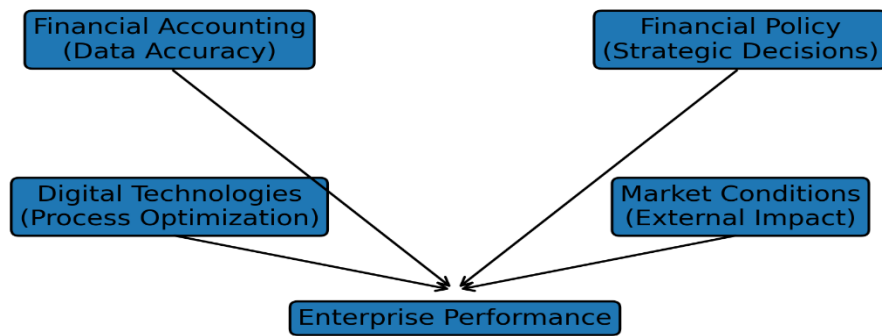


Figure 1. Factors influencing financial management efficiency

Digital transformation enables real-time data processing, enhances transparency, and reduces operational costs. Enterprises that actively implement digital technologies demonstrate higher competitiveness and adaptability [5].

Digital transformation has fundamentally changed the nature of financial management. Traditional accounting systems are being replaced by integrated digital platforms that provide real-time access to financial data.

One of the most important aspects of digital transformation is the use of artificial intelligence and machine learning. These technologies enable automated data processing, anomaly detection, and predictive analytics.

Blockchain technology is also gaining importance in financial management. It ensures transparency, security, and immutability of financial transactions, reducing the risk of fraud and errors.

Furthermore, digitalization facilitates the development of smart financial systems capable of self-learning and continuous improvement. These systems enhance decision-making processes and provide enterprises with a competitive advantage.

6.1 Digitalization and Decision-Making

Digitalization improves financial decision-making by providing access to real-time data and advanced analytical tools. Automation reduces human errors, while big data analytics enhances forecasting accuracy.

Cloud-based systems improve collaboration and flexibility, allowing enterprises to respond quickly to changing market conditions. Despite challenges such as implementation costs and data security risks, digitalization remains a critical factor for success.

Profitability is one of the most important indicators of enterprise performance. It reflects the ability of a company to generate income from its operations. The main profitability indicators include gross profit margin, net profit margin, return on assets (ROA), and return on equity (ROE).

Return on assets shows how efficiently a company uses its assets to generate profit. A higher ROA indicates better utilization of resources. Return on equity reflects the return generated on shareholders' investments and is a key indicator for investors.

Profitability analysis allows enterprises to identify strengths and weaknesses in their operations and develop strategies for improvement. Companies with high

profitability are more competitive and financially stable.

6.2. Liquidity and Solvency Analysis

Liquidity analysis focuses on the ability of an enterprise to meet its short-term obligations. The current ratio and quick ratio are commonly used indicators.

A current ratio above 1 indicates that the company can cover its short-term liabilities. However, excessively high liquidity may indicate inefficient use of resources.

Solvency analysis evaluates the long-term financial stability of an enterprise. The debt-to-equity ratio shows the balance between borrowed and own capital. A balanced capital structure reduces financial risk and improves sustainability.

7. Discussion

7.1. Trend Analysis

Trend analysis involves examining financial data over a period of time to identify patterns and tendencies. This method helps enterprises understand how their financial performance evolves and allows them to predict future outcomes.

For example, an increasing revenue trend indicates business growth, while declining profitability may signal operational inefficiencies.

The findings of the study indicate that effective financial management depends on the integration of financial accounting, strategic financial policy, and digital technologies. Enterprises that adopt modern financial management approaches demonstrate higher efficiency and resilience.

However, several challenges remain, including insufficient digitalization, lack of qualified personnel, and economic instability. Addressing these issues requires investment in technology, staff training, and improved financial planning.

The results of the study confirm that enterprises implementing modern financial management approaches demonstrate higher efficiency and adaptability. The integration of financial accounting, strategic planning, and digital technologies creates a synergistic effect that enhances overall performance.

7.2. Forecasting Techniques

Forecasting is an essential tool in financial management. Enterprises use methods such as regression analysis, time-series analysis, and scenario planning.

Forecasting helps managers anticipate risks, plan investments, and allocate resources more effectively.

Accurate forecasting improves strategic decision-making and reduces uncertainty.

8. Conclusion

8.1. Role of Artificial Intelligence

Artificial intelligence is increasingly used in financial management. AI tools analyze large datasets, detect patterns, and provide insights for decision-making.

AI improves forecasting accuracy, reduces human error, and enhances efficiency in financial processes.

In conclusion, financial management is a key factor in ensuring enterprise competitiveness and sustainable development. The integration of financial accounting, financial policy, and digital technologies creates a strong foundation for effective management.

Future research should focus on the development of digital financial systems and their impact on enterprise performance in a rapidly changing economic environment.

8.2. Cloud Technologies in Finance

Cloud computing allows enterprises to store and process financial data remotely. This increases flexibility and reduces infrastructure costs.

Cloud systems also enable real-time collaboration and improve data accessibility, which is essential in modern business environments.

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INTEGRATION AND IMPROVEMENT OF TAX ACCOUNTING AND FINANCIAL REPORTING IN ENTERPRISES

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Abstract

This study examines the integration and improvement of tax accounting and financial reporting systems within enterprises in the context of modern economic development. The increasing complexity of business operations, digital transformation, and the adoption of International Financial Reporting Standards (IFRS) necessitate a more coordinated and transparent approach to accounting practices. The research aims to analyze the theoretical and methodological foundations of tax accounting and financial reporting, identify existing challenges in their integration, and propose practical solutions for enhancing their effectiveness.

The study employs analytical, comparative, and systematic research methods based on national legislation, international standards, and enterprise-level practices. Special attention is given to inconsistencies between tax accounting and financial reporting, issues of data reliability, and challenges related to IFRS implementation, particularly in service-oriented enterprises.

The findings indicate that insufficient integration between tax accounting and financial reporting systems leads to inefficiencies, increased compliance costs, and higher financial risks. To address these issues, the paper proposes a comprehensive approach based on digitalization, regulatory harmonization, and the adoption of international best practices. The results contribute to improving the quality, transparency, and reliability of financial information in enterprises.

Keywords: tax accounting, financial reporting, IFRS, integration, enterprises, transparency, digitalization

1. Introduction

In the context of globalization and rapid economic transformation, the role of accounting systems in enterprises has become increasingly significant. Modern enterprises operate in a complex environment characterized by regulatory changes, technological advancements, and growing demands for transparency and accountability. Under such conditions, both tax accounting and financial reporting serve as essential components of an effective financial management system.

Tax accounting is primarily oriented toward compliance with national tax legislation and ensuring accurate calculation and timely payment of tax liabilities. In contrast, financial reporting is designed to provide stakeholders with reliable and comparable financial information, often based on International Financial Reporting Standards (IFRS). Despite their shared reliance on financial data, these two systems frequently operate independently, resulting in inconsistencies, duplication of efforts, and increased administrative burden.

The necessity of integrating tax accounting and financial reporting has become more evident with the expansion of digital technologies and the globalization of financial markets. Integration enables enterprises to improve data accuracy, streamline reporting processes, and enhance decision-making capabilities. Further-

more, it contributes to reducing financial risks and ensuring compliance with both national and international regulatory requirements.

The main objective of this study is to explore the theoretical foundations and practical aspects of integrating tax accounting and financial reporting systems within enterprises. The research also aims to identify existing challenges and develop recommendations for improving the efficiency and effectiveness of these systems in modern economic conditions.

2. Theoretical Background and Literature Review

The integration of tax accounting and financial reporting has been widely discussed in economic and accounting literature, particularly in the context of improving resource efficiency and ensuring effective management systems. Modern approaches emphasize that accounting is not only a recording mechanism but also an analytical tool for decision-making and control.

As highlighted in previous studies, effective accounting systems contribute significantly to the rational use of resources and overall enterprise performance. In this regard, it is noted that “resolving the problems of effective utilization of resources ... requires the application of methods that meets the pursuance of the task.” This perspective underlines the necessity of applying appropriate accounting methodologies to ensure efficiency and control within enterprises.

Furthermore, the relationship between quantitative and qualitative indicators plays a crucial role in both tax accounting and financial reporting systems. It has been emphasized that “the manufacturing process of enterprises and organizations is characterized by quantitative and qualitative indicators,” which together determine the effectiveness of accounting information and its usefulness for managerial decisions.

From a theoretical standpoint, tax accounting is primarily rule-based and influenced by national legislation, whereas financial reporting under IFRS is principle-based and focuses on providing a true and fair view of financial performance. This fundamental difference creates challenges in harmonizing the two systems.

However, recent studies suggest that integration is achievable through the development of unified accounting frameworks, improved data management systems, and the adoption of digital technologies. The literature also indicates that enterprises that successfully integrate these systems benefit from enhanced transparency, reduced reporting errors, and improved financial control.

In addition, the growing role of management accounting and economic analysis further strengthens the

need for integration. These tools support not only internal decision-making but also external reporting requirements, bridging the gap between tax obligations and financial disclosures.

3. Research Methodology

This study is based on a combination of qualitative and quantitative research methods. The methodological framework includes comparative analysis, system approach, and analytical evaluation of accounting practices. The research relies on national tax legislation, IFRS principles, and practical data derived from enterprise-level accounting systems.

The comparative method is used to identify differences between tax accounting and financial reporting, while the analytical approach helps to assess their integration potential. In addition, elements of economic analysis are applied to evaluate efficiency, transparency, and reliability of accounting information.

4. Analysis of Integration between Tax Accounting and Financial Reporting

The integration process requires a clear understanding of the similarities and differences between tax accounting and financial reporting systems. While both are based on financial data, their objectives, principles, and regulatory frameworks differ significantly.

Below is a comparative overview:

Criteria	Tax Accounting	Financial Reporting (IFRS)
Purpose	Compliance with tax laws	Providing true and fair financial information
Regulation	National tax legislation	International standards (IFRS)
Approach	Rule-based	Principle-based
Users	Tax authorities	Investors, stakeholders
Focus	Tax obligations	Financial performance and position

This comparison shows that integration is not about unifying both systems completely, but rather about aligning them to reduce inconsistencies and duplication.

One of the major issues identified is the difference in income recognition and expense treatment. These differences often lead to discrepancies between taxable profit and accounting profit, creating additional workload and complexity for enterprises.

5. Practical Aspects and Role of Digital Systems

In modern enterprises, digital technologies play a key role in bridging the gap between tax accounting and financial reporting. The use of integrated accounting systems allows real-time data processing and reduces manual errors.

The integration process can be illustrated as follows:

Financial Data → Unified Accounting System → Tax Calculation + Financial Reporting → Integrated Output

This model demonstrates how a single data source can serve both tax and financial purposes, increasing efficiency and consistency.

Moreover, Enterprise Resource Planning (ERP) systems and cloud-based accounting platforms enable:

- automated data entry
- real-time reporting
- improved internal control
- reduced compliance risks

As emphasized in the literature, effective resource management and control require appropriate analytical tools and accounting methods. This further supports the need for integrating accounting systems within enterprises.

6. Discussion

The findings of this study confirm that integration of tax accounting and financial reporting is essential for improving enterprise performance. However, the process requires careful alignment of regulatory frameworks, accounting policies, and technological infrastructure.

Enterprises that fail to integrate these systems often face:

- duplication of accounting processes
- increased operational costs
- higher risk of errors and penalties

On the other hand, integrated systems enhance transparency and support better managerial decision-making. They also facilitate compliance with both national and international

7. Conclusion and Recommendations

The integration of tax accounting and financial reporting represents a critical step toward improving the overall efficiency, transparency, and reliability of accounting systems in enterprises. In the context of globalization and digital transformation, traditional approaches to accounting are no longer sufficient to meet the growing demands of stakeholders and regulatory authorities.

This study has demonstrated that the lack of coordination between tax accounting and financial reporting systems leads to inconsistencies, increased administrative burden, and higher financial risks. Differences in regulatory frameworks, accounting principles, and reporting objectives remain the main barriers to effective integration.

At the same time, the research confirms that integration is both achievable and beneficial. The adoption of IFRS, the development of unified accounting policies, and the implementation of digital technologies significantly contribute to aligning these systems and improving the quality of financial information.

Based on the findings, the following recommendations are proposed:

- Harmonization of standards: Align national tax regulations with international financial reporting standards to reduce discrepancies.
- Development of unified accounting policies: Enterprises should adopt integrated accounting frameworks that serve both tax and financial reporting purposes.
- Digital transformation: Expand the use of ERP systems, electronic reporting, and automated accounting solutions.
- Professional development: Improve the qualifications of accounting professionals in both tax and financial reporting areas.
- Regulatory improvements: Simplify and stabilize tax legislation to support integration processes.

In conclusion, the integration of tax accounting and financial reporting enhances not only compliance but also strategic decision-making and financial management within enterprises. Future research may focus

on sector-specific applications and the impact of emerging technologies such as artificial intelligence and blockchain on accounting integration.

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THE ROLE OF GOVERNMENT BUDGET AND SUBSIDIES IN FINANCIAL REPORTING UNDER INTERNATIONAL ACCOUNTING STANDARDS

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Abstract

This study examines the role of government budget and subsidies in financial reporting within the framework of International Financial Reporting Standards (IFRS). In the context of increasing state participation in economic development, the proper recognition, measurement, and disclosure of government assistance have become critical factors in ensuring the transparency and comparability of financial statements.

The aim of this research is to analyze the impact of government grants and subsidies on the structure, accuracy, and reliability of financial reporting. The study is based on a comprehensive analysis of IFRS requirements, particularly IAS 20 "Accounting for Government Grants and Disclosure of Government Assistance," as well as comparative and analytical research methods.

The results indicate that government subsidies significantly influence financial performance indicators, asset valuation, and income recognition processes. Improper accounting treatment of such subsidies may lead to distortions in financial results and reduce the reliability of financial statements. At the same time, the application of IFRS provides a systematic and transparent approach to accounting for government assistance.

This study contributes to the existing body of knowledge by offering a structured analysis of the interaction between public financial mechanisms and corporate financial reporting. The findings may be useful for policy-makers, accountants, and auditors in improving the quality and transparency of financial information.

Keywords: Government budget; Government subsidies; Financial reporting; IFRS; IAS 20; Government grants; Accounting standards; Financial transparency; Public finance; Audit

1. Introduction

In recent years, the role of government intervention in economic development has increased significantly, particularly through the allocation of budget funds and the provision of various forms of subsidies. Governments use these instruments to support key sectors of the economy, stimulate investment activity, and ensure social and economic stability. As a result, the proper accounting and presentation of government assistance in financial statements have become increasingly important.

Within the framework of International Financial Reporting Standards (IFRS), the accounting treatment of government grants and subsidies is regulated by IAS 20 "Accounting for Government Grants and Disclosure of Government Assistance." This standard defines the principles for recognition, measurement, and disclosure of government support, ensuring consistency and comparability of financial information across different entities.

However, in practice, the application of IAS 20 remains complex. Issues such as the timing of income recognition, classification of subsidies, and their impact on financial performance indicators often lead to differences in accounting approaches. These challenges can

result in inconsistencies in financial reporting and reduce the reliability of financial statements.

At the same time, the growing scale of government support in modern economies increases the importance of transparent and accurate financial reporting. Improper accounting for subsidies may distort financial results, mislead stakeholders, and negatively affect decision-making processes.

Although previous studies have addressed various aspects of financial reporting and public finance, limited attention has been given to the integrated analysis of government budget mechanisms and their reflection in corporate financial statements under IFRS. This indicates the existence of a research gap that requires further investigation.

Therefore, the aim of this study is to examine the role of government budget and subsidies in financial reporting in accordance with IFRS, with a particular focus on IAS 20. The study analyzes their impact on financial statements and identifies key challenges associated with their accounting treatment.

The paper is structured as follows. The next section presents a review of relevant literature, followed by the methodology and analysis. The final sections provide conclusions and practical implications.

2. Literature Review

2.1. Theoretical Foundations of Management Accounting and Economic Analysis in Financial Reporting

Management accounting and economic analysis play a fundamental role in ensuring the effective use of resources and improving the quality of financial reporting. In modern conditions, the application of analytical methods is closely linked to the need for operational control and efficient decision-making within enterprises.

As noted in prior research, the effective utilization of resources requires not only accurate accounting records but also continuous operational analysis and strict control at all levels of the enterprise. This highlights the importance of integrating accounting systems with analytical tools in order to ensure transparency and efficiency in financial management[1].

The literature emphasizes that the production process of enterprises is characterized by both quantitative and qualitative indicators. While quantitative indicators reflect production volume and output structure, qualitative indicators are associated with the efficiency of resource utilization and the organization of labor and material costs[1]. This distinction is essential for understanding how financial information is formed and interpreted within accounting systems.

A significant contribution to management accounting theory is the development of cost accounting and cost calculation methods. These methods include job order, process, and normative approaches, each of which provides different perspectives on cost measurement and control. Among them, the normative method is considered one of the most progressive, as it allows for the identification of deviations from established standards and supports operational cost management.

Furthermore, the integration of accounting and analytical approaches enhances the ability to assess financial performance and identify inefficiencies. Economic analysis provides tools for evaluating cost structures, detecting deviations, and supporting managerial decision-making processes.

In addition, modern approaches emphasize the importance of classifying costs into variable and fixed components. This classification improves the accuracy of financial analysis and allows organizations to better understand the relationship between costs, production volume, and profitability. As highlighted in previous studies, such an approach is essential for effective financial planning and control.

Despite the development of various accounting methods, the literature indicates that there is still a need for a comprehensive approach that combines accounting standards, management accounting, and economic analysis. This is particularly relevant in the context of government subsidies, where accurate accounting and analysis are necessary to ensure transparency and reliability of financial reporting.

Thus, the theoretical framework suggests that the integration of management accounting methods and economic analysis is a key factor in improving the quality of financial reporting and supporting effective financial decision-making.

2.2. Empirical Studies on Government Support and Resource Efficiency

Empirical studies on government support and resource management emphasize the importance of efficient allocation and utilization of financial and material resources in achieving sustainable economic development. In particular, the role of state support mechanisms, including subsidies and budget financing, is widely discussed in the context of improving production efficiency and strengthening the economic potential of enterprises.

Previous research indicates that the development of material and technical resource markets is a key factor in enhancing the productivity and competitiveness of the agricultural sector[1]. Effective management of these resources requires the application of modern economic analysis tools and the improvement of market infrastructure, which allows for better coordination between supply and demand.

It has been noted that insufficient development of resource markets and weak institutional mechanisms may limit the efficiency of government support. In such conditions, subsidies and budget allocations may not produce the expected economic outcomes unless they are supported by appropriate management systems and transparent financial reporting practices.

Furthermore, empirical evidence suggests that the effectiveness of government subsidies largely depends on their targeted use and proper monitoring. The absence of clear control mechanisms and performance evaluation criteria can lead to inefficient allocation of funds and reduced economic returns.

Studies also highlight that the integration of financial reporting systems with resource management practices improves the transparency and accountability of government support. In particular, the use of standardized accounting approaches allows for better tracking of subsidies and their impact on financial performance indicators.

In addition, the development of market-based mechanisms for resource allocation contributes to the optimization of production processes and cost structures. This is especially relevant in sectors such as agriculture, where the efficient use of material and technical resources directly affects productivity and profitability.

Despite the growing body of empirical research, there remains a need for further studies that link government budget mechanisms with financial reporting practices under international accounting standards. This gap is particularly important in the context of IFRS, where the proper recognition and disclosure of government subsidies play a crucial role in ensuring transparency and comparability of financial statements.

Overall, empirical studies confirm that the effectiveness of government support depends not only on the volume of financial resources provided but also on the quality of their management, monitoring, and reporting.

2.3. Accounting Treatment of Government Subsidies under IFRS

The accounting treatment of government subsidies within the framework of International Financial Reporting Standards (IFRS) represents a critical area in ensuring the transparency and comparability of financial reporting. IAS 20 “Accounting for Government Grants and Disclosure of Government Assistance” provides the primary guidance for recognizing, measuring, and presenting government support in financial statements.

According to IAS 20, government grants should be recognized only when there is reasonable assurance that the entity will comply with the conditions attached to them and that the grants will be received. This principle ensures that financial statements reflect economic reality and prevents premature recognition of income[11].

The standard allows two main approaches to the presentation of government grants. They can either be recognized as income over the periods necessary to match them with related costs or deducted from the carrying amount of the related asset. Each approach has a different impact on financial indicators, particularly profitability and asset valuation.

Empirical and theoretical studies suggest that the choice of accounting method for subsidies significantly influences financial reporting outcomes. For example, recognizing grants as income increases reported earnings, while deducting them from asset values reduces depreciation expenses in future periods. As a result, different accounting treatments may lead to variations in financial performance indicators, even when underlying economic conditions remain the same.

In addition, disclosure requirements play an essential role in enhancing transparency. IAS 20 requires entities to disclose the nature and extent of government assistance, as well as the accounting policies applied. Such disclosures allow users of financial statements to better understand the impact of subsidies on financial performance and position.

However, the literature indicates that, in practice, the application of IAS 20 is not always consistent. Differences in interpretation, lack of detailed guidance,

and variations in national practices may lead to inconsistencies in financial reporting. These issues highlight the need for improved methodological approaches and greater standardization in the accounting of government support.

Furthermore, the increasing complexity of economic environments and the expansion of government intervention require more advanced approaches to accounting and reporting. The integration of accounting standards with analytical tools and digital technologies can enhance the accuracy and reliability of financial information related to government subsidies.

Overall, the analysis shows that proper accounting for government subsidies under IFRS is essential for ensuring the credibility of financial statements and supporting informed decision-making by stakeholders.

3. Research Methodology

3.1. Methodological Framework and Research Design

The methodological framework of this study is based on an integrated approach combining theoretical analysis, comparative evaluation, and elements of economic analysis. The research is aimed at examining the role of government budget and subsidies in financial reporting within the framework of International Financial Reporting Standards (IFRS), with particular emphasis on IAS 20.

The study adopts a qualitative research design, focusing on the analysis of accounting principles and their practical implications. Special attention is given to the recognition, measurement, and disclosure of government grants, as well as their impact on financial reporting indicators.

In order to ensure a comprehensive analysis, several research methods are applied. These methods allow for the evaluation of both theoretical concepts and practical accounting approaches related to government support.

The main research methods used in the study are presented in Table 1.

Table 1.

Research methods and their application

Method	Purpose	Application in the study
Analytical method	Evaluation of financial indicators	Assessment of subsidy impact on reporting
Comparative analysis	Comparison of accounting approaches	IFRS vs alternative treatments
IFRS analysis	Study of accounting standards	Application of IAS 20
Economic analysis	Evaluation of efficiency and costs	Analysis of resource allocation
System approach	Integrated analysis	Interaction between budget and reporting

As shown in Table 1, the study applies a combination of analytical and comparative methods, which enables a deeper understanding of the relationship between government support and financial reporting.

Furthermore, the methodological framework is structured as a sequence of interconnected stages, starting from the analysis of government budget mechanisms and ending with the evaluation of their impact on financial statements.

3.2. Research Model and Analytical Approach

To provide a structured understanding of the research process, a conceptual model is developed that illustrates the relationship between government budget mechanisms, accounting standards, and financial reporting outcomes. The proposed research model is presented in Fig. 1.

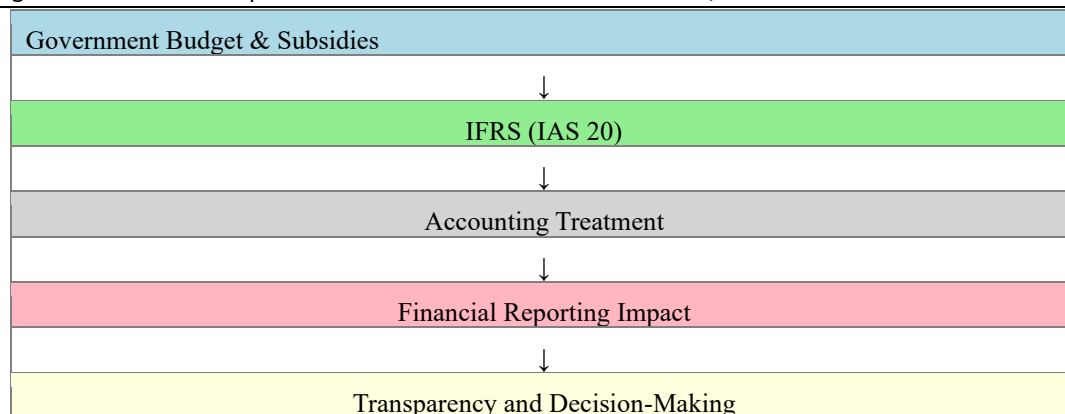


Figure 1. Conceptual research model (author's development)

The model demonstrates that government subsidies influence financial reporting through the application of IFRS principles, particularly IAS 20. The accounting treatment of subsidies affects key financial indicators, including profitability, asset valuation, and financial stability.

The analytical approach of the study is based on evaluating these relationships through the lens of financial reporting quality. The study examines how different accounting treatments of government grants influence the structure and reliability of financial statements.

In addition, the research considers the role of transparency and disclosure in improving the usefulness of financial information. Proper application of IFRS ensures that government assistance is accurately reflected, which enhances the credibility of financial reporting.

Overall, the developed model provides a systematic representation of the research problem and supports the analysis of the interaction between public finance mechanisms and accounting practices.

4. Results and Discussion

4.1. Impact of Government Subsidies on Financial Reporting Indicators

The analysis shows that government subsidies have a significant impact on key financial reporting indicators, particularly profitability, asset valuation, and

income recognition. In accordance with IAS 20, the accounting treatment of subsidies determines how these effects are reflected in financial statements.

Government grants recognized as income contribute directly to an increase in reported earnings. This approach improves short-term financial performance indicators, such as net profit and return on assets. However, such recognition may also create distortions if subsidies are not properly matched with the related costs.

Alternatively, when subsidies are deducted from the carrying amount of assets, they indirectly affect financial performance through reduced depreciation expenses. This approach provides a more gradual impact on financial results and is often considered more consistent with the matching principle.

Empirical findings indicate that different accounting treatments of subsidies may lead to variations in financial indicators even under identical economic conditions. For example, organizations applying the income approach may report higher profitability in the short term, while those using the asset-based approach demonstrate more stable financial performance over time[2,3].

To illustrate the impact of different accounting approaches, the comparison is presented in Table 2.

Table 2.

Impact of accounting treatment of subsidies on financial indicators			
Accounting approach	Effect on profit	Effect on assets	Impact on reporting
Income recognition	Increases profit	No direct impact	Short-term improvement
Asset reduction	Gradual profit effect	Decreases asset value	Long-term stability

As shown in Table 2, the choice of accounting method significantly influences the interpretation of financial results. This highlights the importance of consistency and transparency in applying IFRS standards.

4.2. Challenges in Accounting for Government Subsidies

Despite the existence of clear guidelines under IAS 20, several challenges remain in the practical application of accounting rules for government subsidies[12].

One of the key challenges is the timing of recognition. Determining the moment when there is reasonable assurance that the entity will comply with the conditions attached to the subsidy requires professional

judgement. This introduces subjectivity into the accounting process.

Another issue is related to the classification of subsidies. In practice, it may be difficult to distinguish between income-related and asset-related grants, especially in complex financial arrangements. This may lead to inconsistencies in reporting practices across organizations[13].

Furthermore, insufficient disclosure of government assistance reduces the transparency of financial statements. Users of financial reports may not fully understand the extent and impact of subsidies if disclosure requirements are not properly followed.

4.3. Discussion of Results

The results of the study confirm that government subsidies play a dual role in financial reporting. On the one hand, they support financial stability and improve performance indicators. On the other hand, they introduce complexity into accounting and may affect the comparability of financial statements.

The findings are consistent with previous studies, which emphasize the importance of proper accounting and analytical methods in ensuring the reliability of financial information. In particular, the integration of management accounting and economic analysis enhances the ability to evaluate the effectiveness of government support [9,10].

Moreover, the study highlights the need for improving disclosure practices and strengthening regulatory guidance in order to reduce inconsistencies in accounting treatment.

Overall, the results demonstrate that the proper application of IFRS, especially IAS 20, is essential for maintaining transparency, comparability, and reliability in financial reporting.

5. Conclusion

The present study examined the role of government budget and subsidies in financial reporting within the framework of International Financial Reporting Standards (IFRS), with particular emphasis on IAS 20. The analysis demonstrates that government support mechanisms significantly influence the structure, reliability, and interpretation of financial statements.

The findings indicate that the accounting treatment of government subsidies has a direct impact on key financial indicators, including profitability, asset valuation, and income recognition. Different approaches to accounting for subsidies may lead to variations in financial results, even under similar economic conditions. This highlights the importance of consistency and transparency in the application of IFRS.

The study also identified several challenges related to the practical implementation of accounting standards. These include issues associated with the timing of recognition, classification of subsidies, and disclosure practices. Such challenges may reduce the comparability of financial statements and affect the decision-making process of stakeholders.

At the same time, the integration of management accounting and economic analysis enhances the effectiveness of financial reporting. The use of analytical tools allows for a more accurate assessment of the impact of government support and improves the quality of financial information [6].

From a practical perspective, the results suggest that organizations should strengthen their accounting policies related to government subsidies and ensure full compliance with IFRS requirements. In addition, improving disclosure practices and adopting a systematic approach to financial reporting can increase transparency and reliability.

The study contributes to the existing literature by providing a comprehensive analysis of the interaction between government budget mechanisms and financial

reporting. It also offers practical implications for accountants, auditors, and policymakers in improving reporting standards and financial control.

However, the study has certain limitations, including the reliance on theoretical and comparative analysis. Future research may focus on empirical data and quantitative evaluation of the impact of subsidies across different industries and countries.

Overall, the results confirm that the proper accounting and disclosure of government subsidies are essential for ensuring high-quality financial reporting and supporting effective economic decision-making.

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TRANSITION TO CIRCULAR ECONOMY: MEDIATION OF PUBLIC PROCUREMENT IN GEORGIA

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Abstract

This article examines the role of public procurement as a key instrument for facilitating Georgia's transition to a circular economy. While Georgia has made progress in modernizing its procurement system, the integration of circular economy principles remains limited. Drawing on EU best practices and the experiences of Eastern Partnership countries, this paper identifies key barriers to green public procurement, including legal, institutional, and market-related challenges. It proposes a framework for leveraging public procurement as a mediating mechanism, linking policy objectives with market capabilities. The article outlines practical recommendations for legislative reform, capacity building, supplier engagement, and monitoring, emphasizing the importance of mediation between public authorities, private actors, and technical experts. This framework aligns with Georgia's broader economic modernization goals, supports sustainable development, and facilitates harmonization with European Union standards.

Keywords: Circular economy, green public procurement, Georgia, sustainable development, policy framework, EU integration

Introduction

The transition to a circular economy in Georgia is not only environmentally justified but also strategically essential for ensuring the country's long-term competitiveness and economic sustainability. In the context of increasing resource constraints and environmental pressures, shifting from a linear to a circular economic model represents a critical pathway toward resilient and inclusive growth.

Public procurement—defined as the process through which state institutions acquire goods, services, and works—constitutes one of the most powerful policy instruments for driving economic transformation. Given that public procurement expenditure accounts for a significant share of Georgia's GDP, procurement decisions can generate strong demand-side signals within the market. The integration of circular economy criteria into tender requirements (such as product durability, recyclability, the use of secondary raw materials, life-cycle costing, and extended producer responsibility), can stimulate innovation, influence supplier behavior, and gradually reorient production systems toward circular models (Rainville, 2021).

Existing research on circular public procurement highlights its potential to accelerate systemic transitions, particularly when supported by effective mediation mechanisms. Public procurement does not operate in isolation; rather, it functions as a bridge between policy objectives and market dynamics. Within this process, intermediary actors (including policy advisors, technical experts, industry associations, and innovation platforms) play a crucial role. They facilitate the translation of sustainability objectives into operational procurement practices, foster collaboration between public authorities and private sector actors, and help reduce uncertainties associated with emerging circular markets.

Accordingly, public procurement should be understood not merely as an administrative or financial procedure, but as an institutional mechanism capable of linking circular economy strategies with tangible economic outcomes. Through the strategic design and implementation of procurement policies, Georgia can promote circular innovation, support the diffusion of green technologies, and advance its broader sustainable development agenda.

1. Conceptual Framework and Global Context

Circular Economy Principles

The circular economy is grounded in three fundamental principles, originally articulated by the Ellen MacArthur Foundation and widely adopted in international policy and academic institutions. These principles include: (i) the elimination of waste and pollution, (ii) the extension of product and material lifecycles through continued use, and (iii) the regeneration of natural systems. In contrast to conventional linear models of production and consumption, the circular economy entails a systemic transformation of economic structures. It requires a comprehensive rethinking of how products are designed, produced, distributed, consumed, and managed at the end of their life cycles (Ellen MacArthur Foundation, 2015; Geissdoerfer et al., 2017). Rather than incremental improvements, it promotes a paradigm shift toward restorative and regenerative economic practices.

The practical implementation of circular economy principles is operationalized through several key strategies. These include product reuse, repair, refurbishment, and remanufacturing, as well as the adoption of Extended Producer Responsibility (EPR) schemes that incentivize eco-design and lifecycle accountability. Additionally, the emergence of service-oriented busi-

ness models (often referred to as “product-as-a-service”) aligns producer incentives with product longevity and performance rather than sales volume (Kirchherr, Reike & Hekkert, 2017; Tukker, 2015). Collectively, these approaches contribute to resource efficiency, waste reduction, and the decoupling of economic growth from resource consumption.

The European Union Circular Economy Action Plan and Its Relevance for Georgia

The European Union Circular Economy Action Plan, adopted in 2020 as a central component of the European Green Deal, establishes a comprehensive policy framework aimed at reducing resource consumption, increasing recycling rates, and ensuring that sustainable products become the norm within the European market (European Commission, 2021). The Action Plan places particular emphasis on product design, waste prevention, and the promotion of secondary raw materials.

For countries such as Georgia, which are engaged in legal and institutional approximation under the EU–Georgia Association Agreement, these policy developments carry significant regulatory implications. Alignment with EU environmental and economic standards is not only a legal obligation but also a strategic opportunity to modernize domestic economic systems.

In this context, the EU Green Public Procurement (GPP) framework is of particular importance. It provides structured environmental criteria for integrating sustainability considerations into public procurement processes across a wide range of sectors. Currently, EU GPP criteria encompass more than 20 product and service categories, including information and communication technology (ICT) equipment, cleaning products, construction works, and food and catering services (European Commission, 2021).

The gradual adoption and implementation of these criteria in Georgia would represent a critical step toward regulatory convergence with the European Union. At the same time, it would facilitate the advancement of national circular economy objectives by embedding sustainability principles into public sector demand, thereby influencing market behavior and supporting the transition toward more resource-efficient and environmentally sustainable production systems.

Public Procurement as a Policy Tool for the Circular Economy

According to international evidence, public procurement typically accounts for approximately 10–15% of a country’s GDP, underscoring its significance as a powerful instrument of economic policy (OECD, 2019). Beyond its administrative function, public procurement can shape market structures and influence production patterns by directing demand toward specific goods and services.

When circular economy principles are embedded into procurement decisions (such as prioritizing recyclable materials, product durability, extended lifecycles, and reparability) public sector demand generates strong incentives for suppliers to innovate and adapt their production processes. In this way, public procurement can serve as a key driver in the development of markets for resource-efficient and environmentally sustainable products and services (Testa et al., 2016).

Empirical studies suggest that the effectiveness of circular public procurement largely depends on the clarity and precision with which demand is articulated, as well as its direct linkage to measurable circular outcomes. This includes the formulation of tender criteria that explicitly prioritize durability, reusability, and recyclability, thereby providing clear signals to market actors (Rainville, 2021). Well-designed procurement frameworks can thus reduce uncertainty, encourage investment in sustainable innovation, and accelerate the transition toward circular production systems.

The Role of Mediation and Intermediaries

Academic literature emphasizes the critical role of intermediaries in bridging the gap between public procurement systems and emerging circular economy markets. Mediation mechanisms contribute to this process in several key ways (Rainville, 2021).

First, intermediaries facilitate coordination between government institutions and industry actors. By aligning public policy objectives (such as the integration of sustainability criteria into procurement) with the technical and operational capacities of firms, intermediaries enable suppliers to better understand and respond to circular requirements.

Second, mediation supports collaboration by fostering partnerships between public buyers and private suppliers. Such interactions often lead to the co-creation of innovative products and services that are aligned with circular economy principles.

Third, intermediaries play an important role in the development of tender specifications. Through stakeholder engagement and technical consultation, they contribute to the design of procurement criteria that incorporate lifecycle costing, the use of recycled materials, and other circular parameters. This dynamic process helps ensure that procurement frameworks are both ambitious and feasible, enabling market participants to transition beyond traditional, cost-driven models toward more sustainable and innovation-oriented practices.

Overall, effective mediation reduces informational asymmetries, enhances institutional capacity, and strengthens the link between policy objectives and market outcomes, thereby increasing the overall impact of circular public procurement.

2. Public Procurement in Georgia

Legislative and Institutional Framework

The public procurement system in Georgia is primarily regulated by the Law of Georgia on Public Procurement, initially adopted in 2005 and substantially revised in subsequent years. The system is administered by the State Procurement Agency (SPA), a Legal Entity of Public Law operating under the Ministry of Finance. The SPA oversees the unified electronic procurement platform (procurement.gov.ge), which is widely regarded as one of the most transparent and technologically advanced systems in the region.

In recent years, Georgia’s procurement framework has undergone significant modernization, largely driven by commitments undertaken within the framework of the EU–Georgia Association Agreement, as well as by recommendations from international development partners. The electronic procurement system

ensures open access to tender announcements, bid submissions, and contract award data, thereby substantially enhancing transparency, competition, and accountability in public sector operations.

Despite these notable institutional advancements, the current procurement system remains predominantly focused on cost-efficiency and procedural compliance. Strategic procurement objectives—such as environmental sustainability, resource efficiency, and the integration of circular economy principles—are not yet systematically embedded within procurement practices.

Challenges, Gaps, and Institutional Requirements in Georgia

A primary challenge relates to the legal and regulatory framework. Although environmental considerations are occasionally reflected in tender documentation, Georgia still lacks a comprehensive Green Public Procurement (GPP) policy or action plan that would ensure the systematic and mandatory application of environmental criteria across procurement categories. As a result, sustainability and circularity considerations remain largely discretionary and insufficiently institutionalized.

Closely linked to this regulatory gap is the issue of institutional capacity. Procuring entities (including ministries, municipalities, and state-owned enterprises) often lack the technical expertise required to design, implement, and evaluate circular procurement criteria. In the absence of such capabilities, even well-intentioned sustainability policies risk remaining formal commitments rather than effective instruments of transformation.

Another structural constraint concerns market readiness and supplier engagement. While certain domestic and international firms operating in Georgia already provide resource-efficient and environmentally sustainable products and services, the overall market remains unevenly developed. Certification systems and mechanisms supporting eco-innovation are still limited, which may lead suppliers to perceive circular procurement requirements as a source of additional risk and uncertainty.

An additional challenge lies in the underdevelopment of coordination and mediation mechanisms. Effective circular procurement requires institutionalized platforms that enable collaboration among public authorities, private sector actors, industry associations, non-governmental organizations, and technical experts. At present, such mechanisms remain fragmented and lack systemic integration. Consequently, the linkage between circular economy policy objectives and day-to-day procurement practices is often weak.

Furthermore, significant limitations persist in monitoring and evaluation systems. The environmental impact of public procurement is not systematically measured, and there is a lack of comprehensive data on key indicators such as lifecycle environmental impacts, the use of recycled materials, waste reduction outcomes, and energy efficiency improvements. This data gap constrains policymakers' ability to assess progress,

refine policy instruments, and demonstrate the economic and environmental benefits of circular procurement.

Addressing these interconnected challenges requires both institutional innovation and coordinated policy development. Georgia could benefit from establishing specialized circular procurement units within central government structures, developing inter-agency coordination platforms, and promoting public-private partnerships that mediate between policy objectives and market capabilities. Such institutional mechanisms would enhance coordination, facilitate knowledge transfer, strengthen technical capacities, and support the systematic integration of circular economy principles into public procurement policy and practice.

Thus, strengthening procurement mediation should not be viewed merely as an administrative adjustment; rather, it represents a strategic instrument through which the principles of the circular economy can be translated into concrete economic practices, thereby supporting Georgia's long-term sustainable development objectives.

3. Public Procurement as a Transitional Intermediary for the Circular Economy

The Role of the Intermediary: Theory and Mechanisms

Public procurement can be conceptualized as a mediating mechanism insofar as it translates policy objectives (including circular economy principles) into concrete contractual requirements that directly influence supplier behavior, product design, and waste management practices.

For instance, when a public authority specifies in tender documentation that procured furniture must contain a minimum share of recycled materials and be designed for repairability, this goes beyond a purely technical procurement decision. Such requirements generate clear and credible signals to producers, investors, and actors across the value chain. When replicated systematically across numerous procurement processes, these signals can exert a transformative effect on sectoral standards, encouraging investment in circular production technologies and business models.

The intermediary function of public procurement operates through three principal mechanisms. First, it serves as a market-signaling instrument, whereby the state creates stable and long-term demand for circular goods and services, thereby reducing uncertainty for private sector actors. Second, it functions through regulatory integration, embedding sustainability principles into legally binding contractual obligations. Third, it contributes to capacity development, strengthening knowledge, technical expertise, and learning processes within both public institutions and supply chains. Together, these mechanisms enable procurement systems to act as catalysts for systemic change rather than merely transactional processes.

Priority Sectors for Circular Procurement in Georgia

In the context of Georgia, the potential for implementing circular procurement varies across sectors. Considering the scale of public expenditure, environmental impact, and market readiness, several sectors

emerge as strategic priorities where circular principles can generate substantial effects.

The infrastructure sector represents one of the largest categories of public procurement expenditure and is characterized by intensive material use and significant waste generation. Integrating requirements such as the use of recycled aggregates, design for deconstruction, and certified sustainable timber into public infrastructure contracts could significantly reduce environmental impacts while simultaneously stimulating markets for construction and demolition waste recycling.

A second priority area is the information technology and electronics sector, encompassing computers, printers, and telecommunications equipment. This high-value category is particularly suitable for circular procurement due to the availability of well-developed international standards. The integration of criteria related to energy efficiency, durability, and upgradability can extend product lifecycles and reduce electronic waste. Given the significant purchasing power of the Georgian public sector, aligning procurement specifications with standards such as Energy Star or EPEAT would represent a feasible and high-impact policy step (Ministry of Environment Protection and Agriculture of Georgia, 2021).

The food and catering services sector (including procurement for schools, hospitals, and other public institutions) also offers considerable potential. Circular approaches in this domain may include reducing food waste, promoting sustainably produced agricultural goods, and requiring suppliers to implement effective organic waste management practices. Given Georgia's strong agricultural base, such measures can simultaneously advance circular economy objectives and broader rural development goals.

Finally, the textile and uniform sector, including procurement for institutions such as the Ministry of Internal Affairs and defense structures, presents additional opportunities. The introduction of extended producer responsibility schemes, durability standards, and systems for the collection and recycling of used textiles could significantly enhance resource efficiency. Although Georgia's textile industry remains relatively small, the creation of consistent circular demand signals (particularly through public procurement) could act as a catalyst for innovation, sectoral upgrading, and increased competitiveness.

Framework for Integrating Circularity into Georgian Public Procurement

Legislative Reforms

Establishing a comprehensive approach to green and circular public procurement in Georgia requires coordinated legislative reforms at both primary and secondary levels of the legal framework.

At the level of primary legislation, the Law of Georgia on Public Procurement should provide an explicit legal mandate obliging procuring entities to systematically incorporate environmental and circular economy criteria into procurement planning, tender design, and evaluation processes. Embedding such principles in primary law would elevate sustainability from

a discretionary consideration to a binding policy objective.

At the level of secondary legislation and administrative regulation, the State Procurement Agency should develop and publish sector-specific Green Public Procurement (GPP) criteria. These criteria should be based on relevant European Union technical standards and adapted to the specific conditions of the Georgian market. At an initial stage, their application could remain voluntary, supported by appropriate incentive mechanisms such as preferential evaluation scoring or pilot programs. Over time, and within a clearly defined implementation timeline, these criteria could become mandatory in procurement categories with significant environmental impact.

Capacity Building

Legislative reforms can only be effective if accompanied by systematic strengthening of institutional capacity. This requires sustained investment in the professional development of public procurement specialists and personnel within contracting authorities.

A key priority is the design and implementation of standardized training programs focused on circular economy principles and green public procurement methodologies. In parallel, practical tools—including operational guidelines, sector-specific manuals, and standardized contractual clauses—should be developed to facilitate the consistent application of circular criteria across procurement processes.

Furthermore, the establishment of a specialized technical advisory unit within the State Procurement Agency would provide critical support to procuring entities in designing and evaluating circular specifications. The creation of inter-institutional learning networks (linking municipalities with central government bodies) would also enhance knowledge exchange and promote the dissemination of best practices.

International development partners, including the European Union, United Nations Development Programme, German Agency for International Cooperation, and European Bank for Reconstruction and Development, possess substantial experience in supporting similar reforms across Eastern Partnership countries. Their engagement can play a pivotal role in the effective implementation of a national Green Public Procurement development program in Georgia.

Market Engagement and Supplier Development

The success of circular public procurement policies depends significantly on market readiness and active private sector participation. To this end, the Georgian government should adopt proactive market engagement strategies aimed at informing suppliers (both domestic and international) about upcoming green procurement requirements.

Early and transparent communication enables firms to adjust their products, technologies, and supply chains in anticipation of new standards. Particular emphasis should be placed on supporting small and medium-sized enterprises (SMEs), which constitute a substantial share of the Georgian economy. Targeted advisory services, technical assistance programs, and improved access to finance can help SMEs comply with

circular economy requirements and participate effectively in public tenders.

Industry associations, chambers of commerce, and sectoral business organizations also have a crucial role to play. Their involvement in the development of GPP criteria can ensure that procurement requirements remain technically feasible and economically viable within the Georgian context, thereby increasing overall policy effectiveness.

Monitoring, Evaluation, and Data Infrastructure

The effective implementation of green public procurement requires a robust system of monitoring and evaluation. Georgia's existing electronic procurement platform already provides a strong technological foundation for integrating environmental indicators into procurement data systems.

By incorporating additional data fields related to sustainability (such as lifecycle environmental impacts, recycled content, energy efficiency, and waste reduction outcomes) the system can enable systematic tracking of the environmental performance of public procurement over time.

The State Procurement Agency should develop a comprehensive set of monitoring indicators aligned with European Union reporting frameworks, publish regular (e.g., annual) performance reports, and integrate circular economy metrics into the broader public expenditure reporting system. Strengthening the data infrastructure in this way will enhance transparency, support evidence-based policymaking, and enable continuous improvement of circular procurement practices.

Lessons from the Eastern Partnership Countries

Georgia can learn valuable lessons from the achievements of other Eastern Partnership countries in developing green public procurement. For example, Ukraine, with the support of the European Union and the UNDP, has taken important steps towards establishing a regulatory framework for green public procurement, including by defining relevant criteria for the energy, IT equipment and transport sectors.

Moldova has developed a national action plan for green public procurement and introduced environmental assessment criteria in several key procurement categories. Armenia has successfully implemented pilot projects for energy-efficient procurement in public buildings, which have shown measurable results in reducing energy consumption and costs.

The main lessons learned from this experience include several important factors: the need for strong political support at the highest level of government, the importance of systematic cooperation with the private sector, the benefits of implementing pilot projects, and the critical role of international technical assistance in developing local expertise.

Georgia's developed e-procurement infrastructure and the reforms implemented in recent years put the country in a favorable position in the regional context. These circumstances indicate that, given the appropriate political priorities and resource mobilization, rapid progress towards circular public procurement is possible.

Challenges and risk mitigation

The process of transitioning to circular public procurement in Georgia is associated with a number of significant challenges, the preliminary identification and management of which are essential for the success of the reform. One of the main problems is market fragmentation and the relatively limited domestic supply of products and services based on circular economy principles. In such circumstances, the practical application of circular criteria may be difficult, especially for smaller procuring entities with fewer institutional and technical resources.

In order to reduce risks, it is advisable to implement policies gradually, implement voluntary pilot programs and implement targeted measures to facilitate the development of suppliers. Such an approach will allow the market to adapt and gradually increase the availability of circular products and services.

The issue of price competitiveness is also often perceived as a challenge. Critics argue that the inclusion of environmental requirements in public procurement increases the overall cost of procurement. However, life-cycle costing shows that when considering the full life cycle of a product (including operating costs, maintenance and waste management after the end of its life) sustainable products often have higher economic efficiency despite relatively higher initial costs.

Institutional resistance is another common challenge that often accompanies changes in traditional procurement practices. Successful reform requires not only the introduction of technical tools, but also an effective change management process. This includes a clear definition of policy objectives and benefits, professional training, and active leadership from high-ranking government officials to help build trust and support for the reform.

In addition, there is the risk of so-called "greenwashing," where suppliers make exaggerated or misleading environmental claims about their products. To mitigate this risk, it is necessary to establish clear and reliable verification mechanisms. Such mechanisms could include mandatory third-party certification for significant environmental claims, as well as systematic monitoring of compliance after the award of the contract.

Policy Implications and Recommendations

Based on the literature review and the analysis of Georgia's strategic development documents, the effective implementation of circular public procurement requires a mediation-oriented approach that aligns public sector demand with private sector capabilities. Such an approach should incorporate several key components.

First, strengthening the institutional capacity of public authorities is essential. This includes not only the provision of specialized training for procurement professionals but also the development of practical tools, standardized methodologies, and operational guidelines that enable procuring entities to design and evaluate circular procurement processes effectively.

Second, the systematic use of pre-procurement dialogues represents a critical instrument. Through these mechanisms, public buyers can engage with market actors at an early stage, allowing intermediaries to align public sector needs with supplier capabilities. This pro-

cess contributes to the formulation of realistic, innovation-friendly, and technically feasible tender specifications.

Third, tender documentation should explicitly incorporate circular economy criteria. These may include requirements related to extended producer responsibility, life-cycle assessment methodologies, minimum thresholds for recycled content, and product durability standards. The integration of such criteria enhances resource efficiency, reduces waste generation, and creates clear incentives for sustainable production.

Fourth, the establishment of robust monitoring and learning systems is necessary to evaluate the effectiveness of circular procurement practices. These systems should enable the regular assessment of environmental and economic outcomes, facilitate the identification of implementation gaps, and support continuous policy improvement through evidence-based feedback mechanisms.

Finally, a mediation-based framework for circular public procurement is fully aligned with Georgia's broader strategic objective of economic modernization. It also supports the country's commitments to sustainable development and policy approximation with the European Union, which remains a key priority in Georgia's ongoing process of economic and institutional integration.

Conclusion

Public procurement represents one of the most powerful policy instruments available to Georgia for accelerating the transition toward a circular economy. Through contractual obligations, technical specifications, and evaluation criteria, procurement decisions directly shape supplier behavior, product design, innovation dynamics, and patterns of resource use. In this sense, public procurement serves as a critical mechanism for translating circular economy principles from strategic policy frameworks into concrete economic practices.

At the same time, the effectiveness of this transformation depends on the strengthening of institutional capacity within procuring organizations. The ability to apply tools such as life-cycle costing, sustainability assessment methodologies, and environmental performance criteria is essential for embedding circularity into procurement processes.

Equally important is proactive market engagement. The early and systematic involvement of suppliers in procurement planning and innovation processes reduces uncertainty, accelerates technological adaptation, and enhances competition. In parallel, the development of robust monitoring and evaluation systems is necessary to measure environmental outcomes, ensure accountability, and demonstrate the long-term economic benefits of circular procurement.

When these processes are supported by effective mediation—facilitating collaboration among public institutions, private sector actors, technical experts, and civil society—public procurement evolves into a key driver of systemic economic transformation. Under such conditions, it not only reduces resource inefficiencies and environmental pressures but also fosters the development of new sustainable industries, promotes

technological modernization, and stimulates innovation aligned with European standards.

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A DUAL-DRIVE MECHANISM OF TECHNOLOGICAL INNOVATION AND CULTURAL EMPOWERMENT: AN EMPIRICAL STUDY ON OVERCOMING SEASONAL BOTTLENECKS IN THE WINTER SPORTS INDUSTRY AND PROPOSED PATHWAYS

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Abstract

The winter sports industry serves as a vital pillar for China's economic transformation and the integrated development of culture, sports, and tourism. However, seasonal constraints have long hindered its high-quality growth. Drawing on the latest data and policy documents from 2025, this paper analyzes the current state of the industry and the characteristics of its seasonal constraints, elucidates the dual-drive logic of technological innovation and cultural empowerment, and proposes specific pathways to overcome these constraints through three key areas: technological breakthroughs, cultural exploration, and policy safeguards. The study finds that technological innovation can create year-round operational scenarios and digitally reconstruct the industrial chain, thereby resolving temporal and spatial constraints. Cultural empowerment can establish value recognition and extend consumption scenarios, enabling the industry to achieve year-round value appreciation. The combined effect of these two factors can propel the snow and ice industry from "seasonal dependence" to "year-round prosperity."

Keywords: Snow and ice industry, Seasonal bottlenecks, Technological innovation, Cultural empowerment, Integration of culture, sports, and tourism

I. Introduction

By 2025, the scale of China's winter sports industry had surpassed 1 trillion yuan. During the 2024–2025 winter season, related consumption reached 187.5 billion yuan, representing a year-on-year increase of over 25%¹. In the post-Winter Olympics era, China's winter sports economy continues to expand, shifting from scale expansion toward high-quality development. The Winter Olympics IP effect, industrial integration, technological empowerment, and capital investment have become the primary driving forces². The winter sports industry is highly dependent on cold-weather conditions, exhibiting the characteristic of being "booming in winter and quiet during the other three seasons." The supply side is constrained by time and space, while the demand side suffers from entrenched perceptions, creating a mutual lock-in. Winter snow and ice venues account for over 70% of annual visitor traffic and revenue, with most enterprises ceasing operations during the off-season. Coupled with issues such as seasonal mismatches in the industrial chain, facility idleness, and talent drain, this creates a vicious cycle of "off-season idleness—insufficient investment—lack of innovation—worsening off-season performance"³⁴.

This paper adopts a full-industry-chain perspective and draws on practical experiences from regions such as Heilongjiang, Jilin, Liaoning, Hebei, and Xinjiang to analyze the underlying logic and implementation pathways of a dual-drive model combining technological innovation and cultural empowerment, thereby providing theoretical references and practical models for the snow and ice industry to overcome seasonal constraints.

II. Current Status of the Snow and Ice Industry and Characteristics of Seasonal Constraints

China's winter sports industry is highly dependent on natural climate conditions. In northern regions,

winter temperatures are low, with snowfall concentrated between November and March of the following year. In southern regions, winter temperatures typically remain above 0°C, resulting in scarce natural snowfall and short snow seasons. When temperatures rise above 0°C, snow on outdoor winter sports venues melts rapidly, leading to significantly higher maintenance costs and, in some cases, rendering normal operations impossible.

A. Current Status of the Snow and Ice Industry

1) Parallel Expansion of Scale and Structural Upgrading

By 2025, China's winter sports industry is projected to reach a total output value of 1,005.3 billion yuan, with ski resort consumption amounting to 78.613 billion yuan, driving a 27.97% increase in consumption within a two-kilometer radius of these resorts¹. The consumer base has expanded from professional enthusiasts to include families with children and the elderly. The market has seen the emergence of differentiated products such as children's ski areas and night skiing. The industry structure has evolved from single-service tourism to a full industrial chain.

Upstream snow and ice equipment manufacturing has achieved technological breakthroughs. Midstream event operations have become more diversified. Leveraging the 15th National Winter Games, Liaoning has created an integrated model of "traveling to follow the events," driving the integration of event-driven economy with cultural and tourism consumption. Downstream, the "Snow and Ice Plus" model continues to innovate, with new business formats such as "Snow and Ice Plus Wellness" and "Snow and Ice Plus Educational Tours" increasing their share to 35%¹.

2) Policy Support and the Formation of Regional Patterns

The Chinese government has set a clear target of reaching a 1.5 trillion yuan winter sports economy by

2030, while local policies have provided targeted support to form a complementary framework. Regional development exhibits a pattern of “north-south coordination with distinct regional characteristics.” The Northeast and North China are leveraging natural resources to build world-class destinations, while Xinjiang is developing the “Third Pole of Winter Sports.” Indoor ski resorts in the south account for 18% of the nation’s annual visitor volume¹, and a comprehensive development trend is gradually taking shape.

3) Improvement of Hardware Facilities and Industrial Integration and Innovation

As of April 2025, China had 1,725 ice rinks and 79 indoor ski resorts, representing a 33.9% increase in numbers, and had established a product system comprising 15 major categories of winter sports equipment. The “Winter Sports Plus” model continues to expand its scope. Supporting facilities for “Ice and Snow + Tourism,” such as hotels and commercial streets, are becoming increasingly mature. “Ice and Snow + Culture” has created well-known IPs like the Harbin Ice and Snow World, and cultural and creative products from the Asian Winter Games have seen strong sales. “Ice and Snow + Wellness” combines hot spring therapy to develop distinctive products, while business formats such as ice and snow study tours and mountain sports continue to diversify. The north focuses primarily on ice and snow experiences, while the south holds greater advantages in equipment operation and maintenance, forming a complementary and synergistic development pattern.

B. Core Characteristics of Seasonal Constraints

The seasonal bottlenecks in China’s winter sports industry are not merely rigid constraints of time and space; they also stem from multiple deep-seated issues. Digital transformation is subject to path dependence, and traditional technological systems, management models, and industrial ecosystems—influenced by technology lock-in, structural rigidity, entrenched market structures, and stagnant capabilities—hinder year-round development³. The industrial chain lacks resilience; a weak industrial foundation, slow response to market changes, lagging safety measures, poor innovation commercialization, and insufficient cross-regional coordination further exacerbate seasonal fluctuations⁴. The integration of culture, sports, and tourism remains superficial; insufficient cultural empowerment, product homogenization, significant ecological pressure, and poor promotional effectiveness limit the industry’s value enhancement and year-round expansion⁵. The talent system does not align with industry needs, resulting in year-round talent shortages that exacerbate operational imbalances⁶. The legacy of major events such as the Winter Olympics and Asian Winter Games is underutilized, with poor conversion, shallow integration, and insufficient long-term support, making it difficult to sustain year-round operations⁷.

The seasonal bottlenecks in the winter sports industry are primarily manifested in three aspects: temporal and spatial constraints, mismatches in the industrial chain, and fragmented consumer demand. These factors intertwine to form a vicious cycle, hindering the industry’s high-quality development.

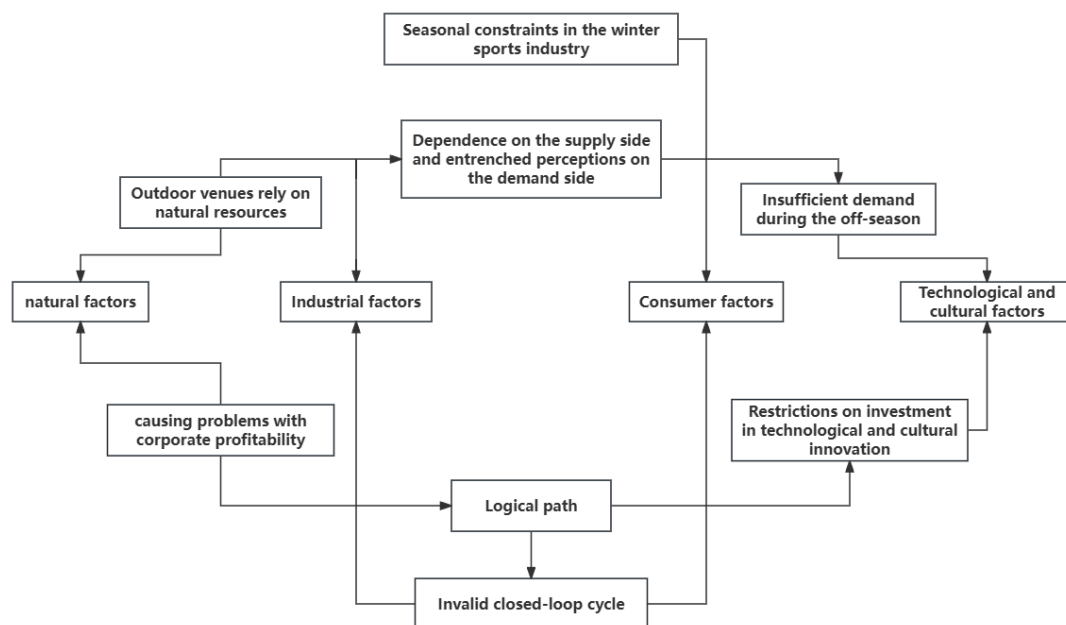


Figure 1 Diagram of the Causal Relationships Behind the Seasonal Bottlenecks in the Snow and Ice Industry

To break this cycle, it is necessary to address the spatiotemporal constraints on the supply side while simultaneously unlocking the year-round consumption potential on the demand side. Technological innovation can overcome physical limitations; through scenario transformation, digital reconstruction, and equipment upgrades, it fundamentally alleviates the constraints

that climate imposes on operations, thereby supporting year-round supply. Cultural empowerment focuses on the value dimension, tapping into regional culture, expanding consumption scenarios, and fostering year-round consumption awareness. This approach reconstructs the value identity of the snow and ice industry,

shifting consumption from a reliance on seasonality to a reliance on culture.

III. The Dual-Drive Logic of Technological Innovation and Cultural Empowerment

Technological innovation and cultural empowerment together constitute the core mechanism for overcoming seasonal bottlenecks. Rather than operating in isolation, they generate synergistic effects through a cycle of “platform support—value empowerment—feedback iteration.” Technological innovation addresses the question of “whether year-round operations are feasible,” providing the platforms and tools for cultural dissemination. Cultural empowerment addresses the question of “whether consumers are willing to engage year-round,” adding value and expanding the market for technological products. The two form a closed loop across three stages—scenario expansion, value enhancement, and demand activation—generating a “1+1>2” effect³⁸, driving the industry toward year-round prosperity.

From the perspective of new-quality productive forces, the high-quality development of the winter sports economy is premised on ecological conservation, led by technological innovation, and guided by integration and synergy, thereby achieving a more optimized industrial structure, higher efficiency, and

greater value⁹. Under the guidance of the “Two Mountains Theory,” the combination of technological empowerment and cultural enrichment can unify economic, ecological, and social benefits while avoiding homogenized competition and excessive ecological pressure⁷.

A. Scenario Expansion: Technological Innovation Creates a Year-Round Platform for Cultural Dissemination

Technological innovation enables the dissemination of snow and ice culture beyond winter settings, reducing temporal and spatial constraints as well as costs, and facilitating year-round implementation. Technologies such as VR/AR and 5G create immersive ice and snow cultural experience centers, transforming cultural content—including Northeast folk customs and intangible cultural heritage related to ice and snow—into virtual scenarios accessible year-round. Content such as Harbin’s ice sculpture craftsmanship and Xinjiang’s fur-lined ski-making techniques can transcend the limitations of winter viewing. Off-season visitor numbers account for 65% of the annual total, and technology has transformed ice and snow culture into a product that can be consumed year-round.

Table 2.

Proportion of Off-Season Sales of Altay Snow and Ice Intangible Cultural Heritage Creative Products Relative to Annual Total (2025, Unit: 10,000 yuan)

Category	Off-Season Sales	Winter Sales	Annual Share
Fur Ski Boards Handcrafted Souvenirs	2,100	900	70%
Snow and Ice Intangible Cultural Heritage Study Tours	1,800	200	90%
Snow and Ice-Themed Digital Collectibles	600	400	60%
Total	4,500	1,500	75%

Note: Data sourced from the Altay City Culture and Tourism Bureau’s 2025 intangible cultural heritage industry operational data; the non-snow season refers to April–October.

Advances in low-energy-consumption refrigeration technology for indoor ski resorts not only reduce operating costs for winter attractions in southern regions but also allow for the integration of local cultural elements. For example, Shenzhen Qianhai Ice and Snow World incorporates Lingnan water town culture,

avoiding the uniformity often seen in such venues and enabling indoor facilities to serve both as cultural hubs and consumer experience destinations. Technology provides year-round support for winter attractions, while culture helps these venues develop distinctive characteristics.

Table 3.

Growth Trends in the Number of Indoor Ski Resorts and Ski Visits Nationwide, 2020–2025 (Unit: 10,000 visits)

Year	Number of Indoor Ski Resorts (units)	Number of Indoor Skiing Visits (10,000)	Percentage of Total National Ski Visits
2020	36	269	12.9%
2022	48	385	16.7%
2024	60	488	20.2%
2025	66	563	21.61%

Note: Data source: 2024–2025 China Ski Industry White Paper. The statistical period runs from May 1 of each year to April 30 of the following year.

B. Value Enhancement: Cultural Empowerment Creates Value-Added Potential for Technological Products

Cultural empowerment redefines value, making technological innovations more competitive in the market and enabling the snow and ice industry to create value beyond seasonal constraints. Infusing technical

products with cultural significance transforms them from “functional tools” into “value-added products,” significantly increasing their added value and profit margins, thereby addressing the challenge of profitability during the off-season.

Harbin Qianmao Xuelong Sports Goods Co., Ltd. uses aerospace-grade composite materials to manufacture skis and incorporates local urban culture and intangible cultural heritage elements related to snow and ice to develop cultural and creative ski products, significantly enhancing product value-added and off-season sales performance (Heilongjiang Provincial Department of Industry and Information Technology, 2025). Cultural empowerment enables technical products to achieve year-round value appreciation.

C. Demand Activation Level: Fostering Year-Round Consumer Awareness Through Two-Way Synergy

Through the combined effects of technological innovation and cultural empowerment, efforts are made

from both the supply and demand sides to break the fixed perception that “snow and ice belong only to winter,” cultivate year-round demand for snow and ice consumption, and form a two-way cycle of supply and demand. Technological innovation has introduced products such as dryland snow and ice equipment and home ski simulators, providing consumers with avenues for participation during the off-season, lowering seasonal barriers, and creating consumption scenarios accessible year-round. Cultural empowerment, through short videos, commercial district exhibitions, and year-round winter sports festivals, continuously conveys the concept that “winter sports culture can be enjoyed year-round,” altering consumers’ seasonal perceptions and increasing their willingness to consume during the off-season. Together, these efforts drive winter sports consumption from a “seasonal experience” to a “regular habit,” forming a virtuous cycle where “new supply creates new demand, and new demand guides new supply.”

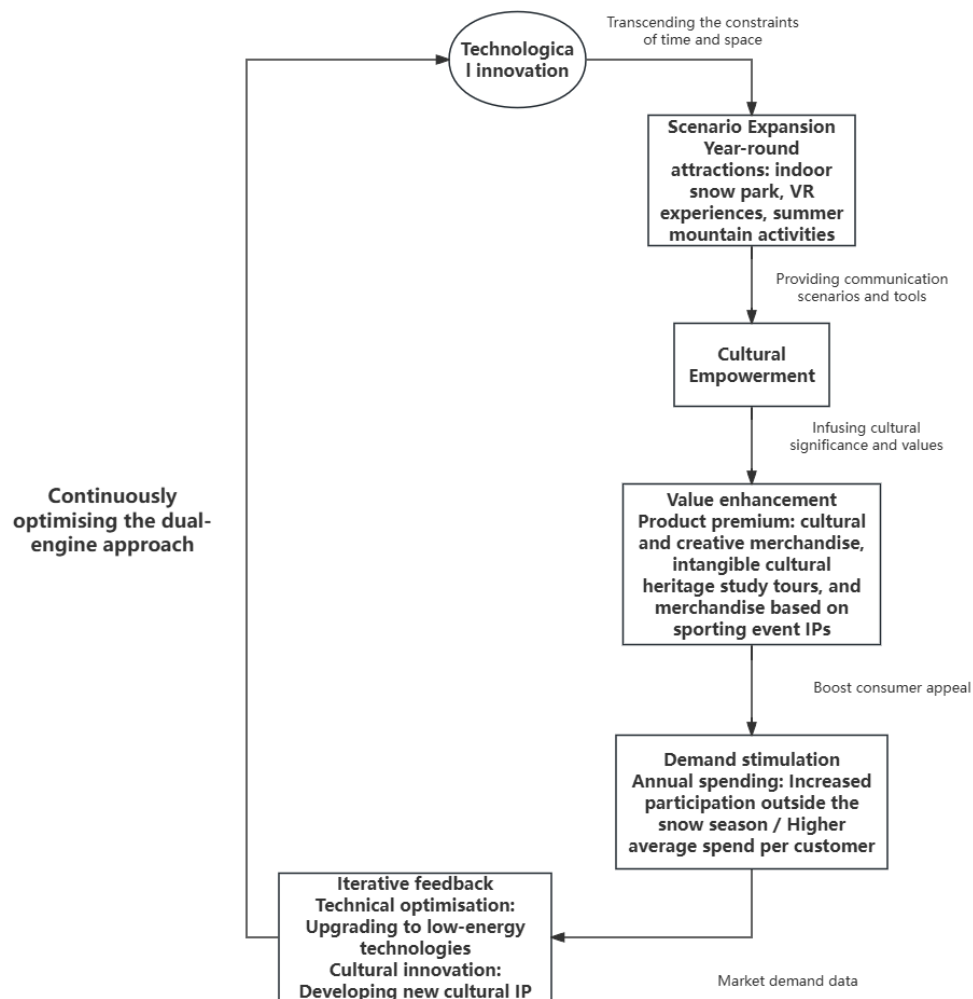


Figure 4. Model of the Synergy Mechanism Between Technological Innovation and Cultural Empowerment

The essence of the synergy mechanism between technological innovation and cultural empowerment is as follows: technological innovation addresses the issue of “the feasibility of year-round operations,” providing scenarios and tools for cultural dissemination. Cultural empowerment addresses the issue of “the appeal of year-round consumption,” endowing technological

products with value and market potential. Through a closed-loop interaction involving scenario expansion, value enhancement, and demand activation, the two achieve a synergistic effect where “1+1>2.”

IV. Pathways to Overcoming Seasonal Constraints Through Dual-Drive

This paper integrates the resource disparities between northern and southern regions in the winter sports industry, the need for industrial chain synergy, and the characteristics of the consumer market. The path design adheres to three principles: First, adapt to local conditions, respect regional differences, avoid a one-size-fits-all approach, and create differentiated year-round operation models. Second, match supply with demand, guided by year-round consumer needs, to meet the demands of groups such as families, educational tours, and seniors, and drive the transformation of supply toward year-round, personalized, and scenario-based offerings. Third, synergy and integration: Strengthen the interaction between technology and culture, allowing technology to serve as a vehicle for cultural dissemination and culture to enhance the value of technological applications.

At the same time, supported by policy safeguards, a "technology-culture-policy" trinity advancement mechanism is established to ensure the feasibility and sustainability of the implementation. This paper outlines specific pathways to overcome seasonal bottlenecks from three dimensions: technological innovation, cultural empowerment, and policy support. It also integrates policy safeguards to form a "technology-culture-policy" trinity of synergistic advancement mechanisms, ensuring the feasibility and sustainability of these pathways. From the three dimensions of technological innovation, cultural empowerment, and policy support, this paper elaborates on practical pathways to overcome seasonal bottlenecks.

A. Technological Innovation Dimension: Building a Technical Support System for Year-Round Operations

To break free from digital path dependence, it is necessary to establish an autonomous and controllable digital technology system, drive the digital transformation of management systems, break down barriers in traditional industrial ecosystems, and foster a culture of innovation³. Leveraging new-quality productive forces, we must accelerate the application of digital technologies and enhance the efficiency of data resource allocation. By renovating outdoor venues for year-round use, upgrading low-energy-consumption cooling technologies, building VR/AR virtual scenarios, establishing digital middleware platforms, and developing flexible equipment, we can reconstruct year-round consumption scenarios, improve the efficiency of industrial chain resource allocation, and achieve peak-shifting production, cross-seasonal workforce deployment, and stable capacity utilization³⁴⁹.

1) Technological Breakthroughs in Scenario-Based Development: Reconstructing Year-Round Consumer Experiences

Promote the year-round transformation of outdoor venues. Support key ski resorts such as Chongli and Beidahu in developing summer activities including hiking and forest trekking, and build supporting ice and snow cultural exhibition halls and smart experience zones, so as to realize the model of "skiing in winter and diversified experiences in summer". thereby revitalizing idle resources. Develop low-energy artificial refrigeration technologies to reduce costs for indoor ski

resorts in southern regions, while integrating local culture to avoid homogenization. Expand the scale of indoor ski resorts in southern regions to establish a year-round consumption ecosystem that complements northern and southern markets. Utilize VR/AR and 5G technologies to build online snow and ice theme parks and digital snow and ice museums, breaking through spatial and temporal constraints to form a year-round "online + offline" consumption loop.

2) Restructuring the Digital Industrial Chain to Enhance Resource Allocation Efficiency

Build a digital middle platform for the snow and ice industry to integrate data across the entire industrial chain—including equipment manufacturing, scenic area operations, and cultural tourism consumption—thereby breaking down information barriers and enabling off-peak production and cross-seasonal staffing. Equipment manufacturers should adjust their plans based on year-round consumption data, allocating approximately 30% of their production capacity to the production of cultural and creative products during the off-season to resolve idle capacity issues. Scenic areas should use big data to forecast visitor flows and pre-recruit service staff for the off-season to alleviate mismatches between labor supply and demand.

Promote the digital transformation of winter sports equipment manufacturing to enhance flexible production capabilities and meet year-round demand for personalized customization. The Harbin Winter Sports Equipment Industrial Park has achieved a closed-loop "R&D–Manufacturing–Application" system, with cultural and creative equipment accounting for 40% of its output value during the off-season. Digital transformation makes the winter sports industry chain more modern and efficient.

3) Equipment Technology Innovation to Expand Sports Consumption Scenarios

Increase R&D efforts for summer training equipment and dryland winter sports gear to transition winter sports from a "winter-only professional activity" to a "year-round mass participation" activity. Promote dryland curling, land hockey, and similar sports by introducing them into schools and communities to popularize winter sports. Develop portable ski simulators for use in homes and commercial districts, making winter sports a year-round recreational option. This will expand consumption scenarios and stimulate year-round winter sports consumption among the general public.

B. Cultural Empowerment Dimension: Building a Cultural Value System with Year-Round Value

The integration of the snow and ice industry with the tourism sector is driven by four core factors: infrastructure development, government planning and management, the improvement of service systems, and innovation in "Snow and Ice Plus" business models³. We must deeply explore local snow and ice culture, create a year-round IP matrix, and promote the deep integration of "snow and ice + intangible cultural heritage + educational tours + wellness + digital cultural creativity." By pursuing a path of differentiated development, we will transform cultural resources into year-round consumer products⁴. At the same time, we will activate

the legacy value of sporting events and, through three mechanisms—resource integration, industrial convergence, and brand building—convert the short-term benefits of events into long-term industrial value⁹.

1) Deeply Explore Regional Snow and Ice Culture to Build a Year-Round IP Matrix

Systematically organize cultural resources such as Northeast folk customs, Xinjiang's snow-region culture, and Northern ice-play traditions, transforming them into experiential and consumable products to build a year-round winter sports and culture IP matrix. Harbin has extended the "Ice and Snow World" IP into a year-round cultural and creative brand, developing products such as ice and snow blind boxes and replicas of intangible cultural heritage ice sculptures, making the IP a vehicle for year-round consumption. Liaoning, centered on the "Creative Winter + Fun in Liaoning" brand, hosts seasonal ice and snow cultural festivals—featuring competitions in winter, cultural and creative exhibitions in summer, and educational tours in spring and autumn—using IP operations to achieve year-round dissemination and consumption of ice and snow culture.

2) Promoting the Integration of "Snow and Ice + Culture" Business Models to Extend the Consumption Chain

Deepening the integration of "Ice and Snow + Intangible Cultural Heritage," "Ice and Snow + Educational Tours," and "Ice and Snow + Wellness," we combine ice and snow culture with diverse business models to free ice and snow cultural consumption from seasonal constraints. We transform intangible cultural heritage projects such as fur-lined skiing and ice sculpture making into year-round educational tour courses, creating a year-round "Culture + Education" business model. Combine with hot spring wellness to launch "summer retreat + snow and ice cultural experience" packages, achieving the integration of "culture + wellness."

Encourage the integration of snow and ice culture with digital cultural and creative industries, launching snow and ice-themed digital collectibles and virtual brand ambassadors to create new growth points for online consumption. Cultural empowerment shifts snow and ice consumption from "scene-dependent" to "value-driven." Even without actual winter snow and ice settings, people can add value to the industry through intangible cultural heritage experiences and cultural and creative consumption, driving the deep integration of snow and ice culture and the tourism industry.

3) Strengthen Cultural Communication to Foster Year-Round Consumption Awareness

Utilize short videos, offline experiential exhibitions, and pre-event hype for competitions to break the entrenched perception that "snow and ice = winter." For example, host snow and ice culture exhibitions in commercial districts during the summer to showcase the history of ski equipment development and intangible cultural heritage techniques related to snow and ice, allowing consumers to engage with snow and ice culture up close. Leverage key events such as competitions and festivals to continuously promote the concept of

"snow and ice all year round," fostering year-round consumption habits. Regular and diverse cultural outreach can reshape consumer perceptions, increase willingness to spend during non-ski seasons, and support year-round operations of the winter sports industry from the demand side.

C. Policy Support Dimension: Establishing a Dual-Drive Institutional Framework

We should refine the policy framework for year-round operations, strengthen incentives for technological innovation, and promote regional coordinated development to form a "technology-culture-policy" trinity mechanism. This will provide institutional safeguards for the implementation of the dual-drive strategy, helping the snow and ice industry overcome seasonal constraints and achieve high-quality development.

Implement Jilin's "Jilin Ice and Snow All Year Round" talent policy, provide cross-season employment subsidies, address year-round talent shortages, and provide human resources support for year-round operations. Offer tax breaks and energy consumption subsidies to snow and ice enterprises operating during the off-season to reduce operational costs and boost their enthusiasm for year-round operations.

Strengthen incentives for technological innovation by establishing a special fund for winter sports equipment R&D, rewarding technological achievements that overcome seasonal constraints, and encouraging enterprises to pursue core technology development. Promote regional coordination by leveraging transportation routes such as National Highway G331 and the Shenyang-Baicheng High-Speed Railway to integrate winter sports resources from Northeast and North China, creating cross-regional, year-round winter tourism routes. This will reduce the seasonal dependence of individual regions and foster coordinated regional development of the winter sports industry.

V. Conclusions and Outlook

In the future, with the deepening application of technologies such as 5G and AI, as well as the continuous exploration of the cultural value of winter sports, the industry will further integrate technology and culture, achieving the year-round transformation of "cold resources" into a "hot industry." The realization of the 2030 target of a 1.5 trillion yuan winter sports economy will no longer rely solely on the contribution of the winter season.

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MATHEMATICAL SCIENCES

A SELF-SUSTAINED SPHEROIDAL-SPIRALOIDAL VORTEX WITH AN AXIAL FUNNEL

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Abstract

This paper proposes a mathematical model of a new type of self-consistent vortex structure - a hybrid spheroidal-spiraloidal vortex with an internal spiral funnel. In contrast to classical models such as Hill's vortex and toroidal vortices [1-3], the proposed configuration represents a single continuous elliptical vortex region in which no distinct thin toroidal vortex tube is present. Instead, the internal flow is organized as a continuous axial channel - a funnel smoothly connected to the upper and lower parts of the vortex. It is shown that, within this framework, the source of motion, pressure, and density is transferred from the external flow to the internal structure: the axial flow and the associated angular momentum are responsible for the translational motion of the entire system. The velocity field is represented via a stream function decomposed into a Hill-type component and a funnel-induced component, and a Clebsch representation of the rotational potential is introduced, localized within the internal flow and the corresponding spiral vortex lines. Expressions are derived for the hydrodynamic impulse, circulation, streamline equations, angular momentum, and vortex moment. It is demonstrated that the existence of a self-consistent vortex is ensured by a closed cycle of fluid particles (micro-vortices), which acquire momentum in the funnel and subsequently move along single continuous three-dimensional spiral trajectories, encircling the internal region and returning to the base of the funnel without discontinuities or trajectory switching. This leads to the formation of a stable self-consistent structure in which flow closure, momentum transport, and pressure maintenance are governed by the internal geometry of motion, without the need to prescribe an external potential flow with continuous pressure [5-9].

Keywords: self-sustained vortex, spheroidal vortex, axial flow, internal funnel, spiral trajectories, vorticity, hydrodynamic impulse, circulation, Clebsch representation

1. Introduction. Let us consider an axisymmetric flow of an incompressible ideal fluid in cylindrical coordinates (r, φ, z) , where the axis of symmetry coincides with the z -axis, and the center of the vortex structure moves along it such that $Z = \dot{Z} \cdot t$. The geometry of the flow domain is defined as a single spheroidal vortex region whose outer boundary has the form of a closed elliptical surface of Hill-type vortex. Within this region, the flow is organized not as a toroidal cavity or a thin vortex tube, but as a continuous internal structure with an axial channel - a funnel - smoothly connected to the upper and lower parts of the vortex. Thus, in a longitudinal cross-section, one observes not a thin-walled toroidal configuration, but a single connected vortex region with an internal axial flow. In this formulation, the external flow is not considered as the primary source of pressure, density, and driving impulse, since for vortex structures of this class, as noted already in Hill's classical formulation, the construction of an external flow with continuous pressure in closed form is difficult. Therefore, the source of motion, pressure redistribution, and density variation is transferred into the structure itself and is determined by the internal geometry of the flow. It is associated with the axial flow generated by the funnel and with a system of continuous spiral vortex lines filling the vortex volume. The forward motion of such a structure arises from the following mechanism. Fluid particles passing through the internal funnel acquire axial velocity and angular momentum, after which they transition onto smooth three-

dimensional spiral trajectories within the vortex region. These trajectories continuously encircle the internal volume, pass through the lower region without discontinuities or switching between trajectory branches, then rise toward the upper part of the structure and return to the base of the funnel, forming a self-sustained cycle of motion. As a result, the ensemble of such trajectories forms a stable self-consistent flow, in which momentum transport and pressure maintenance are governed by the internal dynamics of the flow rather than by an externally imposed potential flow.

2. The velocity field is described by an axisymmetric stream function $\psi(r, z, t)$, for which the radial and axial velocity components are given by

$$u_r = -\frac{1}{r} \frac{\partial \psi}{\partial z}, \quad u_z = \frac{1}{r} \frac{\partial \psi}{\partial r}. \quad (1)$$

The azimuthal component u_φ is allowed and plays an essential role, since it describes the rotational motion associated with the internal axial flow and the continuous spiral vortex lines filling the vortex volume. The total stream function is represented as

$$\psi = \psi_H + \psi_{fun}, \quad (2)$$

where ψ_H describes the main closed elliptical region of Hill-type vortex, and ψ_{fun} represents the internal funnel embedded within this region and responsible for the axial flow. In contrast to models with a distinct toroidal structure, here ψ_H is defined as the stream function of a compact spheroidal vortex region, within

which two main lower recirculation zones and two upper return zones are formed. It is convenient to introduce dimensionless variables $\xi = r/a$ and $\eta = (z - Z)/c$, where a and c define the characteristic transverse and longitudinal semi-axes of the elliptical region, and to define the spheroidal boundary by the condition

$$\sum_H: \xi^2 + \eta^2 = 1. \quad (3)$$

The base part of the stream function can be chosen in the form

$$\psi_H = U_0 r^2 (1 - \xi^2 - \eta^2) [1 + \alpha_1 \eta + \alpha_2 \eta^2 + \alpha_3 \xi^2], \quad (4)$$

where the coefficients α_i are selected such that the centers of the main recirculation cells are shifted downward relative to the geometric center, and the upper part of the flow provides return toward the funnel entrance. This formulation preserves the structure of Hill's vortex while allowing internal modification of the flow field to ensure matching with the axial channel. The funnel is defined by the internal surface $r = r_f(z - Z)$, where r_f is a smooth function that is small in the middle region and increases toward the upper and lower matching regions with the main core (kern) region. Its contribution to the stream function can be written as

$$\psi_{fun} = \frac{Q_f(t)}{2\pi} G\left(\frac{r}{r_f(z-Z)}, \frac{z-Z}{c}\right) \quad (5)$$

where $Q_f(t)$ is the flow rate through the funnel, and G is a smooth dimensionless function that vanishes on the funnel surface (i.e., equals zero at the funnel wall) and ensures continuous matching with the main Hill-type flow. As a result, the internal axial flow does not form a singular conical layer but rather a finite region of accelerated axial motion, consistent with the overall flow structure. In combination with the azimuthal velocity, this leads to the formation of continuous three-dimensional spiral trajectories of fluid particles, which pass through the axial region, encircle the internal volume, and return to the base of the funnel, thus forming a self-consistent flow structure within a single spheroidal vortex region.

3. The vorticity of the structure consists of two interrelated components. The first component is the azimuthal vorticity of the meridional flow

$$\omega_\phi = \frac{\partial u_r}{\partial z} - \frac{\partial u_z}{\partial r} \quad (6)$$

which is related to the stream function by the equation

$$\frac{\partial^2 \psi}{\partial z^2} + \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = -r \omega_\phi \quad (7)$$

This component governs the formation of the elliptical region of closed flow, within which the main recirculation zones are located. In accordance with the considered geometry, the vorticity ω_ϕ attains its maximum values in the lower part of the spheroidal region, where zones of enhanced vorticity corresponding to the recirculation regions are formed, and decreases toward both the outer boundary and the surface of the internal funnel. It is convenient to represent it in the form

$$\omega_\phi = \omega_0 \frac{r}{a^2} g(\xi, \eta), \quad (8)$$

where g is a smooth function vanishing on the outer boundary and on the funnel surface, and attaining its maxima in regions of increased vorticity associated with the recirculation zones. The second component of vorticity is associated with the azimuthal swirl of the

flow, distributed throughout the vortex volume and coupled with the internal axial flow. In contrast to models with a distinct toroidal structure, the vorticity here is not concentrated on discrete nested surfaces but is distributed as a continuous family of spiral vortex lines filling the region between the outer boundary and the axial funnel. These lines are naturally described by level surfaces $\lambda(r, z - Z) = \lambda_0$, where the function λ is chosen such that its level sets define nested flow layers consistent with the geometry of the spiral trajectories.

The azimuthal velocity can then be represented as

$$u_\phi^{frame} = \Gamma(\lambda)/2\pi r, \quad (9)$$

where $\Gamma(\lambda)$ denotes the distribution of circulation across these layers. Within the internal funnel, a non-zero azimuthal velocity component is also present, ensuring the formation of a swirling axial flow and the transfer of angular momentum to the particles. At the same time, the axial component of vorticity remains nonzero, corresponding to the presence of an internal vortex core associated with the axial flow and the accompanying spiral motion. Under these conditions, the velocity field can naturally be represented in Clebsch form [1, 4]:

$$\mathbf{u} = \nabla \phi + \alpha \nabla \beta, \quad (10)$$

where ϕ describes the irrotational component of the internal mass transport, while the functions α and β define a continuous family of frozen-in vortex lines and the associated three-dimensional spiral structure of the flow. Thus, the rotational component of the velocity field is not given by a global scalar potential, but is determined by the internal geometry of the flow and the vorticity distribution associated with the axial funnel and the spiral trajectories filling the vortex volume.

4. The velocity potential, in the strict sense, is introduced only for the irrotational part of the motion. In the present formulation, the main flow is generated not by an external flow but by the internal structure of the flow. Therefore, the external potential ϕ_{ext} is allowed only as a weak auxiliary field satisfying Laplace's equation $\Delta \phi_{ext} = 0$ outside the vortex region and the condition of decay at infinity, but it is not considered as the primary carrier of pressure and does not determine the mechanism of vortex self-propulsion. The dominant contribution to the velocity field is given by the internal decomposition

$$\mathbf{u} = \nabla \phi_{int} + \mathbf{u}_{rot}, \quad (11)$$

where $\phi_{int} = \phi_H + \phi_{fun}$ describes the irrotational component of the flow within the spheroidal region, including the axial flow in the axial funnel, while $\mathbf{u}_{rot}$ corresponds to the rotational part associated with the internal swirl of the flow. The potential ϕ_{fun} describes the acceleration of particles in the axial funnel, their longitudinal transport, and subsequent redistribution in the upper part of the region. The potential ϕ_H represents the irrotational component of the recirculating flow within the main spheroidal region. The rotational part of the velocity field is naturally expressed in Clebsch form

$$\mathbf{u}_{rot} = \alpha \nabla \beta, \quad (12)$$

or, equivalently, through the decomposition of a rotational potential

$$\chi_{rot} = \chi_{fun} + \chi_{sp}, \quad (13)$$

where χ_{fun} is localized in the funnel region and is responsible for imparting angular momentum to the fluid particles, while χ_{sp} describes a spiral structure of vortex lines distributed throughout the volume, consistent with the geometry of the trajectories. Thus, the rotational component is not associated with a distinct localized structure but is distributed throughout the volume and determined by the internal geometry of the flow. It is this internal swirl that leads to pressure redistribution, sustaining the density distribution, and the formation of closed particle trajectories returning to the vortex core (kern). As a result, in this model the pressure is governed primarily by the internal distribution of velocity and vorticity, rather than by an externally imposed potential flow.

5. The hydrodynamic impulse of the considered vortex is directed along the axis of symmetry and is given by

$$\mathbf{P} = \frac{\rho}{2} \int_D \mathbf{r} \times \boldsymbol{\omega} dV. \quad (14)$$

Due to axial symmetry, only the axial component is nonzero:

$$P_z = \pi \rho \int_D r^2 \omega_\phi dr dz. \quad (15)$$

In contrast to classical models, where the impulse is associated with a distinct vortex structure, in the present formulation it is determined by the distribution of vorticity throughout the entire flow domain and is governed by the internal flow geometry. For analysis, it is convenient to decompose it into contributions from different flow regions:

$$P_z = P_z^H + P_z^{fun}, \quad (16)$$

where P_z^H corresponds to the main spheroidal region with recirculating motion, and P_z^{fun} represents the contribution of the axial flow in the funnel. The dominant contribution to the impulse arises from the distribution of azimuthal vorticity within the volume:

$$P_z^H = \pi \rho \int_{D_H} r^2 \omega_\phi dr dz, \quad (17)$$

and reflects the contribution of the closed meridional circulation. The funnel contribution can be expressed either in terms of vorticity or, more transparently, in terms of axial mass transport:

$$P_z^{fun} = \rho \int_{D_{fun}} u_z dV. \quad (18)$$

If the characteristic vorticity in the main region has the scaling $\omega_\phi \sim \dot{Z}r/a^2$, then the corresponding contribution retains the Hill-type order of magnitude $\rho \dot{Z}a^4/c$, whereas the axial flow contribution scales as $\rho Q_f U_f$, where U_f is the mean velocity in the funnel. A key feature of the present model is that the directed hydrodynamic impulse is generated by internal redistribution of momentum. Fluid particles passing through the axial funnel acquire axial velocity and thereby contribute to a positive axial impulse. Subsequently, moving along continuous three-dimensional spiral trajectories, they encircle the internal region and return to the base of the funnel, thereby closing the flow without discontinuities. As a result, a stable self-consistent flow is established, in which the total impulse is maintained by internal dynamics rather than by external forcing. Thus, the translational motion of the vortex is governed not by external conditions, but by an internal mechanism of momentum transport associated with the axial flow and

the corresponding spiral structure of particle trajectories.

6. Circulation in the present model also has a composite nature and is determined by the distribution of velocity and vorticity in different regions of the flow. The meridional circulation along a contour C_m , enclosing one of the recirculation zones is defined as

$$\Gamma_m = \oint_{C_m} \mathbf{u} \cdot d\mathbf{l} = \iint_{\Sigma_m} \omega_\phi dS. \quad (19)$$

In the lower part of the spheroidal region, two such recirculation zones are formed, and in the symmetric case their corresponding circulations are equal in magnitude.

The azimuthal circulation is associated with the rotational component of the flow and is defined along circular paths of radius r :

$$\Gamma_\phi = 2\pi r u_\phi. \quad (20)$$

It is not tied to a distinct geometric structure but characterizes the distributed swirl throughout the volume, associated with continuous spiral vortex lines. The circulation related to the axial funnel can be defined either along a contour enclosing the axial flow region or in terms of the flow rate and swirl within the funnel. In general, the total circulation can be expressed as

$$\Gamma = \Gamma_H + \Gamma_{fun}, \quad (21)$$

where Γ_H is associated with the meridional recirculation in the main spheroidal region, and Γ_{fun} characterizes the contribution of the axial flow and the associated swirl. In contrast to classical models, the circulation here is not confined to an isolated region but is coupled with the internal transport of momentum through the axial channel. As a result, the circulation structure is determined not only by closed contours but also by the continuous redistribution of motion along spiral trajectories.

The streamlines are defined by the condition $\psi(r, z) = \text{Const}$. In a longitudinal cross-section, they form a single spheroidal region, in the lower part of which recirculation zones are located, in the upper part there are return-flow regions, and between them lies the axial funnel. On the funnel surface, the streamlines are tangent to its boundary; inside the funnel, they are stretched along the axis, then in the upper region they transition into diverging three-dimensional trajectories, encircle the internal volume, and return along lateral and lower paths to the base of the funnel. Thus, the entire flow is realized as a continuous system of closed spiral trajectories filling the vortex volume and ensuring a consistent redistribution of mass, momentum, and vorticity within a single coherent vortex structure.

7. Angular momentum. The angular momentum with respect to the z -axis is defined as

$$\mathbf{L}_z = \rho \int_D r u_\phi dV. \quad (22)$$

In the absence of azimuthal swirl $u_\phi = 0$ and therefore $\mathbf{L}_z = 0$. However, in the present structure this condition is generally not satisfied, since the internal flow dynamics include a swirling axial motion and the associated three-dimensional spiral structure. In this formulation, the angular momentum is determined by the distribution of azimuthal velocity throughout the entire volume and can be represented as a sum of contributions associated with different flow regions:

$$L_z = L_z^H + L_z^{fun}, \quad (23)$$

where L_z^H corresponds to the distributed swirl in the main spheroidal region, and L_z^{fun} represents the contribution of the axial flow in the funnel. In the main region, the angular momentum is given by

$$L_z^H = \rho \int_{D_H} r u_\varphi dV, \quad (24)$$

where the azimuthal velocity is related to the distribution of circulation across flow layers and reflects the continuous spiral structure of vortex lines. Within the internal funnel, for weak spiral swirl it is natural to assume

$$u_\varphi^{fun} = \Omega_f(r, z) r, \quad (25)$$

where Ω_f characterizes the local angular velocity associated with the axial flow. The corresponding contribution to the angular momentum is then

$$L_z^{fun} = \rho \int_{D_{fun}} \Omega_f r^2 dV. \quad (26)$$

If the flow geometry defines a characteristic swirl angle β , then, in order of magnitude, $u_\varphi^{fun} \sim u_z \tan \beta$, and consequently $L_z^{fun} \sim \rho \tan \beta \int_{D_{fun}} r u_z dV$. Thus, the angular momentum is not a secondary effect but a key characteristic of the structure: it is through this quantity that the internal funnel transfers angular momentum to the particles, enabling their subsequent motion along closed spiral trajectories and their return to the base of the funnel. By analogy with a dipole moment, one may introduce the vortex moment:

$$\mathbf{M}_\omega = \frac{1}{2} \int_D \mathbf{r} \times \boldsymbol{\omega} dV, \quad (27)$$

which, for an axisymmetric configuration, is directed along the axis and is related to the hydrodynamic impulse by $\mathbf{M}_\omega \sim \mathbf{P}/\rho$ up to a normalization factor. The axial component of the vortex moment $\mathbf{M}_{\omega,z}$ can also be represented as a sum of contributions:

$$\mathbf{M}_{\omega,z} = \mathbf{M}_{\omega,z}^H + \mathbf{M}_{\omega,z}^{fun}, \quad (28)$$

where the first term characterizes the intensity of meridional circulation in the main region, and the second represents the contribution of the axial flow and the associated swirl. The stronger the internal swirl and the more efficiently the axial flow transfers angular momentum to the particles, the larger the vortex moment and the more stable the self-consistent translational motion of the structure. In this sense, the angular momentum and vortex moment serve as key integral characteristics reflecting the internal mechanism of vortex self-sustainment.

8. Mechanism of motion and geometry of particle trajectories.

The motion of particles in the considered hybrid spheroidal-spiraloidal vortex represents a smooth closed cycle consisting of three continuously connected stages: descent along the internal funnel, motion along the spheroidal surface, and return to the upper rim followed by repetition of the cycle. A key distinction from standard models is that passage through the lower region involves no discontinuities or switching between trajectories, but is realized as a single continuous curve. After descending through the funnel, a particle transitions onto the surface of the unit sphere

$$x^2 + y^2 + z^2 = 1, \quad (29)$$

where its motion is described as a smooth spherical spiral. This curve is parameterized by the polar angle θ , which varies from $\theta_{tip} = \arccos(z_{bot})$ through the value π , corresponding to the south pole, to $2\pi - \theta_{rim}$, where $\theta_{rim} = \arccos(z_{top})$. The relations $r = |\sin \theta|$ и $z = |\cos \theta|$ ensure that the trajectory remains on the spherical surface.

This formulation guarantees continuous passage through the south pole: for $\theta > \pi$ the function $z = \cos \theta$ begins to increase, and the particle naturally transitions from descending to ascending motion without changing trajectory branch. This eliminates any possibility of trajectory switching, and the curve remains continuous and geometrically consistent.

The azimuthal angle φ is defined by an integral accumulation law and is a continuous function of θ , although its derivative behaves differently in the descending and ascending regions. For $\theta < \pi$ the angular velocity decreases according to an exponential law

$$d\varphi/d\theta = -\omega_{desc}(\theta), \quad (30)$$

where $\omega_{desc} = (2.4e^{-2u_{desc}} + 0.55)(1 + 0.08c)$, and

$$u_{desc} = (\theta - \theta_{tip})/(\pi - \theta_{tip}). \quad (31)$$

This law reflects the gradual decay of the swirl acquired in the funnel.

For $\theta > \pi$, an inverse winding law applies

$$d\varphi/d\theta = -\omega_{asc}(\theta), \quad \omega_{asc} = n_0 R_{bot}^\alpha |\sin \theta|^\alpha, \quad (32)$$

which represents a geometric reflection of the funnel structure. If, within the funnel, the density of turns increases as the radius decreases, then on the sphere, for small values of $|\sin \theta|$ (near the pole), the turns are sparse, while they become denser as θ approaches θ_{rim} . This ensures a smooth transition of the trajectory toward the upper rim and consistency with the next cycle.

At $\theta = \pi$, the curve remains continuous and passes through the pole without a kink, since the variation of φ does not introduce coordinate discontinuities, and the parametrization preserves uniqueness of the trajectory. Thus, the entire second phase is a single smooth spherical spiral.

The total angular shift along the spherical segment is given by

$$\Delta\varphi_{geo} = - \int_{\theta_{tip}}^{\pi} \omega_{desc} d\theta - \int_{\pi}^{2\pi - \theta_{rim}} \omega_{asc} d\theta, \quad (33)$$

and, together with the contribution from the funnel descent, forms the total phase shift per cycle $\Delta\varphi_{cycle}$. If $\Delta\varphi_{cycle} \neq 2\pi k$, the trajectory does not close after a single revolution, and successive cycles form a quasi-periodic structure that gradually fills the vortex volume.

The mechanism of motion of such a structure is as follows. The internal funnel forms an axial acceleration channel in which particles acquire longitudinal velocity and angular momentum. After passing through the funnel, they transition onto continuous three-dimensional spiral trajectories that encircle the internal volume. These trajectories pass through the lower region without discontinuities, then rise to the upper part and return to the base of the funnel, closing the motion cycle.

Thus, each particle executes a continuous closed cycle, and the ensemble of such trajectories forms a stable internal flow. The translational motion of the entire

structure arises from the net axial transport of momentum generated by the axial flow and redistributed throughout the volume via the spiral geometry of trajectories. In this formulation, the vortex constitutes a single self-consistent system in which the dynamics, pressure, and momentum transport are governed by the internal structure of the flow rather than by external potential forcing.

9. Conclusion

The developed model of a hybrid spheroidal-spiraloidal vortex demonstrates a fundamentally different mechanism of self-propulsion compared to classical vortex structures. In contrast to Hill's vortex, where motion is associated with an external potential flow, the present formulation shows that the dominant role is played by internal redistribution of momentum generated by the axial flow in the funnel and the associated three-dimensional swirl. Such a structure exists as a single self-consistent flow, in which the axial flow produces a directed impulse, while a continuous system of spiral vortex lines ensures the redistribution of momentum and closure of particle trajectories. The entire dynamics is governed by the internal geometry of the flow rather than by the presence of distinct structures or external flow conditions.

The obtained expressions for the hydrodynamic impulse, circulation, angular momentum, and vortex moment confirm that the translational motion of the vortex arises as a result of internal momentum transport along the axis followed by its redistribution throughout the volume.

Thus, the considered structure can be interpreted as a self-sustained vortex with an internal source of momentum, realized through the axial flow and continuous spiral particle trajectories. The proposed model may

serve as a basis for further studies of the stability of such structures, their nonlinear dynamics under perturbations, and possible physical analogies in fluid dynamics, plasma, and other continuous media.

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PEDAGOGICAL SCIENCES

CONTINUING EDUCATION CULTURE: MENTAL BARRIERS IN THE KAZAKHSTANI CONTEXT

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Abstract

This article examines the characteristics of the formation of a continuing education culture in Kazakhstani society and analyzes the mental barriers related to returning to education in adulthood from a socio-psychological perspective. The study considers the influence of traditional value systems, age-related stereotypes, social expectations, perceptions of professional stability, and the phenomenon of "social shame." The purpose of the article is to identify internal (psychological) and external (social) factors that hinder the lifelong learning process in Kazakhstan and to model their interrelationships. The results of the study demonstrate the importance of mental transformation in shaping a culture of continuing education and justify the necessity of considering national and cultural characteristics in the development of adult retraining programs.

Keywords: continuing education, lifelong learning, mental barriers, social stereotypes, professional identity, Kazakhstani society.

Introduction. The twenty-first century has become a period of profound transformation in the field of education. The rapid development of science and technology, globalization processes, the instability of the labor market, and constantly changing professional requirements have made continuing education (lifelong learning) not merely an advantage but a fundamental necessity for members of modern society.

International experience demonstrates that lifelong learning not only enhances professional competencies but also positively influences personal development, social adaptation, and psychological well-being.

In Kazakhstan, the education system has undergone significant changes in recent decades. The state pays special attention to improving the professional training of both youth and adults, mastering new technologies, and fostering a culture of lifelong learning. Within the framework of educational reforms, various national programs and initiatives have been introduced, such as "Knowledgeable Kazakhstan" and "Digital Kazakhstan," as well as professional retraining courses.

However, despite these measures, mental barriers related to adult re-education remain a pressing issue.

The relevance of this problem is associated with the influence of psychological, social, and cultural factors on the development and implementation of lifelong learning in Kazakhstan. Many adults face stereotypes such as "*learning is difficult at an older age*" or "*changing one's profession is socially inap-*

propriate." In addition, the conflict between labor market demands and traditional professional culture may negatively affect individuals' motivation to pursue further education.

From this perspective, the formation of a lifelong learning culture in Kazakhstan is not only an economic necessity but also a complex issue that requires consideration of socio-psychological and cultural factors.

The main purpose of this article is to identify the mental factors that hinder the development of a continuing education culture in Kazakhstan and to analyze their mechanisms of interaction from a socio-psychological perspective.

The objectives of the study are:

1. To systematize social stereotypes and national mental factors influencing adult re-education in the Kazakhstani context;
2. To analyze internal psychological barriers (fear, lack of self-confidence, motivation levels);
3. To develop an integrative model of internal and external factors that hinder long-term professional retraining and lifelong learning processes;
4. To formulate practical recommendations for the development of a continuing education culture in Kazakhstan.

Thus, the article considers lifelong learning in Kazakhstan not only as an educational or economic issue but also as a socio-psychological phenomenon. The study aims to understand psychological barriers that

prevent adults from pursuing education and to identify ways to overcome them.

Main Part. The concept of lifelong learning has been recognized as one of the key strategic directions in education in the twenty-first century. This concept emphasizes the necessity of continuously updating knowledge and skills throughout an individual's life. According to studies conducted by UNESCO and OECD, lifelong learning is not only a tool for improving professional competence but also an important factor in social adaptation, psychological stability, and overall quality of life.

International experience shows that individuals actively engaged in lifelong learning are more competitive in the labor market and adapt more quickly to new technological requirements.

From a socio-psychological perspective, the study of lifelong learning takes into account motivational, cognitive, and emotional aspects of human development. The theory of self-actualization proposed by V. I. Maslov explains the motivational basis of continuing education. According to Maslov, individuals can fully realize their professional and social potential only when they experience the need for self-development and the acquisition of new knowledge.

In this regard, lifelong learning can be considered a complex socio-psychological phenomenon encompassing processes of self-knowledge, identification of personal abilities, and understanding of the surrounding world.

N. M. Amosov and S. G. Vershlovsky emphasize that continuing education plays an important role at all stages of an individual's life. They consider this process not only within the framework of formal education systems but also as a broader structure that includes non-formal and digital forms of education.

From this perspective, the social environment, family, workplace, and professional communities serve as important institutions supporting lifelong learning. The role of the family is particularly significant, as the educational interests and motivation of one family member often influence others, thereby creating social support for learning.

Cognitive psychology also plays an important role in studying long-term professional retraining and lifelong learning processes. A person's ability to acquire knowledge, process new information, and apply it in practice is directly related to cognitive development and experience.

The theories of Jean Piaget and L. Vygotsky demonstrate that learning processes are strengthened through social interaction and contribute to the development of thinking, decision-making, and problem-solving abilities. These theories allow lifelong learning to be viewed as a long-term process that supports cognitive development.

The motivational aspects of lifelong learning are also significant. The relationship between intrinsic motivation (self-development, acquisition of new skills, aspiration for professional growth) and extrinsic motivation (job requirements, economic conditions, social recognition) determines the effectiveness of the learning process.

Socio-psychological studies show that adult learning motivation often relies on internal factors, although external factors also play a significant role in encouraging individuals to pursue education. For example, changing labor market requirements, professional competition, and the need to master new technologies motivate adults to engage in retraining.

The issue of mental barriers is particularly relevant in the Kazakhstani context. Research indicates that adults often encounter stereotypes such as *"learning becomes difficult with age"* or *"changing one's profession is socially inappropriate."* These factors reduce learning motivation and hinder the development of a lifelong learning culture.

Furthermore, conflicts between traditional professional culture and modern labor market demands intensify psychological barriers. For instance, experienced professionals may hesitate to master new technologies or change their professional direction due to a lack of confidence in their abilities.

Modern pedagogical and economic theories suggest adopting an integrative approach to lifelong learning. From this perspective, lifelong learning includes not only formal education programs but also professional training, online courses, webinars, seminars, and other forms of non-formal education.

Such an approach enables adults to effectively plan their professional and personal development.

International experience shows that one of the most effective ways to develop a culture of lifelong learning is through learner-centered educational strategies. These strategies offer educational pathways aligned with individuals' interests and professional goals.

In addition, social support, labor market flexibility, and government initiatives—such as retraining programs and online learning platforms—significantly increase the effectiveness of lifelong learning.

Based on these theoretical foundations, several important conclusions can be drawn regarding the study of lifelong learning in Kazakhstan:

1. Lifelong learning is not only an economic necessity but also a socio-psychological phenomenon.
2. Psychological barriers (fear, lack of confidence, stereotypes) significantly influence adult participation in education.
3. Lifelong learning should be considered a long-term process that supports cognitive, emotional, and social development.
4. Government policy, social support, and individual motivation must be integrated into a comprehensive model.

Thus, the formation of a lifelong learning culture in Kazakhstan should be viewed not solely as a responsibility of the education system but as a complex process that requires consideration of socio-psychological and cultural factors.

Conclusion

The development of a lifelong learning culture in Kazakhstan represents an important social, psychological, and economic necessity of contemporary society.

The study shows that adult learning motivation is influenced by psychological barriers such as fear, lack

of self-confidence, and stereotypes, as well as by social factors including family support, professional environment, and labor market demands.

In addition, educational institutions and government programs play a crucial role in supporting lifelong learning initiatives.

Within the Kazakhstani context, the development of lifelong learning culture should be considered not only an economic requirement but also a socio-psychological phenomenon that contributes to individuals' cognitive, emotional, and social development.

As demonstrated in the integrative model, effective management of internal and external barriers can significantly improve the effectiveness of lifelong learning processes.

In conclusion, lifelong learning contributes to the development of professional competence, social adaptation, and the improvement of quality of life in Kazakhstan. This process should be implemented through the integration of government policy, social support, and individual motivation.

Moreover, the implementation of specialized programs and strategies aimed at reducing psychological barriers among adults is essential for fostering a sustainable culture of lifelong learning.

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TECHNOLOGIES FOR TEACHING MEDICAL DISCOURSE TO MEDICAL STUDENTS**Besschetnova L.***PhD,**Associate Professor of the Department of Language Disciplines of the Kazakh National Medical University named after S. Asfendiyarov (Almaty, Kazakhstan);***Berdaliyeva T.***Lecturer of the Department of Language Disciplines of the Kazakh National Medical University named after S. Asfendiyarov (Almaty, Kazakhstan)***Abdullayeva G.***Master of Pedagogical Sciences, Lecturer, Department of Language Disciplines, NAO "Kazakh National Medical University named after S. Asfendiyarov (Almaty, Kazakhstan)***ТЕХНОЛОГИИ ОБУЧЕНИЯ МЕДИЦИНСКОМУ ДИСКУРСУ СТУДЕНТОВ-МЕДИКОВ****Бессчетнова Л.В.***к.п.н.,**доцент кафедры языковых дисциплин Казахского национального медицинского университета им. С. Асфендиярова (Алматы, Казахстан);***Бердалиева Т.К.***лектор кафедры языковых дисциплин Казахского национального медицинского университета им. С. Асфендиярова (Алматы, Казахстан)***Абдуллаева Г.Т.***магистр педагогических наук, лектор кафедры языковых дисциплин Казахского национального медицинского университета им. С. Асфендиярова (Алматы, Казахстан)*<https://doi.org/10.5281/zenodo.19573241>**Abstract**

The article examines medical discourse as a special type of institutional professional discourse functioning in the field of medical communication. The main approaches to defining the concept of “discourse” in modern linguistics are analyzed, and its structural, pragmatic, and cognitive characteristics are revealed. Special attention is paid to the specifics of medical discourse, its genre forms, and communicative interaction models within the “doctor–patient” and “specialist–specialist” systems. The distinction between medical text and medical discourse is substantiated as a methodologically significant condition for developing effective teaching technologies. The paper considers active and interactive methods for developing professional communicative competence in medical students, including role-playing games, clinical cases, discussions, business games, and problem-based learning. It is concluded that interactive technologies are a key tool in shaping the professional linguistic identity of future doctors and ensure the development of speech skills necessary for successful medical practice.

Аннотация

В статье рассматривается медицинский дискурс как особая разновидность институционального профессионального дискурса, функционирующего в сфере медицинской коммуникации. Анализируются основные подходы к определению понятия «дискурс» в современной лингвистике, раскрываются его структурные, прагматические и когнитивные характеристики. Особое внимание уделяется специфике медицинского дискурса, его жанровым формам и коммуникативным моделям взаимодействия в системе «врач – пациент» и «специалист – специалист». Обосновывается разграничение понятий медицинского текста и медицинского дискурса как методологически значимое условие разработки эффективных технологий обучения. Рассматриваются активные и интерактивные методы формирования профессионально-коммуникативной компетенции студентов медицинского вуза, включая ролевые игры, клинические кейсы, дискуссии, деловые игры и проблемное обучение. Делается вывод о том, что интерактивные технологии являются ключевым инструментом формирования профессиональной языковой личности будущего врача и обеспечивают развитие речевых навыков, необходимых для успешной медицинской практики.

Keywords: medical discourse, medical communication, professional medical speech, institutional discourse, medical text, interactive teaching methods, communicative competence, medical education, professionally oriented teaching, linguodidactics.

Ключевые слова: медицинский дискурс, медицинская коммуникация, профессиональная речь врача, институциональный дискурс, медицинский текст, интерактивные методы обучения, коммуникативная компетенция, медицинское образование, профессионально ориентированное обучение, лингводидактика.

Понятие «дискурс» относится к числу наиболее многозначных и теоретически дискуссионных категорий современной гуманитарной науки. В со-

временной лингвистике отсутствует единое общепринятое определение данного термина, что обусловлено междисциплинарным характером самого

феномена. Как справедливо отмечает Н.Д. Арутюнова, дискурс представляет собой «речь, погружённую в жизнь», то есть речемыслительную деятельность, рассматриваемую в совокупности с экстралингвистическими, прагматическими, социокультурными и когнитивными факторами [1, с.37]. Именно эта многомерность делает категорию дискурса одной из наиболее сложных в понятийном аппарате современной лингвистики.

В научном обиходе термин «дискурс» функционирует далеко за пределами собственно языкознания. Он активно используется в философии, социологии, политологии, психолингвистике, когнитивистике, культурологии и литературоведении, что свидетельствует о его высокой эвристической значимости для анализа коммуникативных процессов. Подобная полифункциональность термина объясняется тем, что дискурс репрезентирует не только языковую форму, но и механизмы концептуализации мира, способы вербализации знания и модели социального взаимодействия.

Согласно данным Online Etymology Dictionary, лексема *discourse* восходит к латинскому *discutere*, первоначальное значение которого связано с представлением о движении: «бегать в разных направлениях», «перемещаться туда-сюда» [12]. В средневековой латыни это значение трансформируется в абстрактно-коммуникативное – «разговор», «рассуждение». Таким образом, в семантической структуре термина сохраняется метафорический компонент динамического развертывания мысли: дискурс мыслится как процесс последовательного движения высказывания вокруг предмета речи. В этом проявляется важная когнитивная особенность понятия: дискурс – это не статичный текст, а развивающееся во времени коммуникативное действие [8, с.24].

В английском языке слово *discourse* в значении «обсуждение», «словесное выражение мысли» фиксируется уже в ранние периоды языкового развития, что свидетельствует о его длительной истории функционирования в европейской интеллектуальной традиции. Однако этот термин получил широкое распространение сравнительно поздно – лишь во второй половине XX века, когда началось активное освоение западноевропейских и американских лингвистических концепций.

Следует отметить, что в научной традиции первоначально закрепилось не существительное «дискурс», а производное прилагательное «дискурсивный», активно употреблявшееся в трудах психологов и психолингвистов начала XX века. Так, Л.П. Якубинский использовал словосочетание «дискурсивное говорение» для обозначения речевой деятельности, обусловленной коммуникативной ситуацией и условиями общения [9, с.63]. Л.С. Выготский вводит понятие «дискурсивное мышление», противопоставляя его аффективно-эмоциональным формам мыслительной деятельности [3, с.98]. В работах А.Р. Лурии термин соотносится с логико-операциональными формами интеллектуальной активности – индуктивным и дедуктивным мышлением,

лежащими в основе сложной когнитивной деятельности человека [7, с.102]. А.Н. Леонтьев, в свою очередь, связывает дискурсивность с вербально-логическим типом деятельности, подчеркивая её опосредованный и знаково организованный характер [6, с.91].

С позиций современной лингвистической семантики, в частности в русле идей А. Вежибицкой, дискурс может быть интерпретирован как культурно обусловленная форма языковой репрезентации опыта, в которой закрепляются национально-специфические модели мышления и коммуникативного поведения [11, с.55]. Такой подход позволяет рассматривать дискурс не только как языковую единицу высшего порядка, но и как инструмент реконструкции языковой картины мира.

Семантическая многоплановость данного термина отражена и в терминографической практике. По мнению Т.В. Жеребило, дискурс – это многоуровневое явление: от «связной речи» и «диалога» до «текста в совокупности с экстралингвистическими, прагматическими, социокультурными и психологическими факторами» [4, с.28]. Такое расширительное понимание соответствует современным представлениям о дискурсе как о сложной коммуникативной системе, включающей не только языковую форму, но и участников общения, их интенции, фоновые знания, культурные сценарии и социальные роли.

Особую роль в развитии теории дискурса сыграла французская лингвистическая школа, где данный термин получил наибольшее распространение во второй половине XX века. По наблюдению Н.Д. Арутюновой, именно французская традиция во многом способствовала закреплению термина в международной гуманитарной науке [1, с.34]. Во французской лингвистике дискурс понимается как неоднородное, интенционально обусловленное коммуникативное единство, возникающее в процессе взаимодействия участников речи в конкретном социально-культурном контексте. Такое понимание особенно значимо для анализа профессиональных типов коммуникации, в том числе медицинской.

В контексте исследования технологий обучения медицинскому дискурсу принципиально важно учитывать специфику профессиональной медицинской коммуникации как особой разновидности институционального дискурса. Медицинский дискурс представляет собой сложную систему речевого взаимодействия, организованную профессиональными ролями, нормами этики, терминологической точностью и прагматической направленностью на сохранение здоровья пациента.

Структурно медицинская коммуникация подразделяется на два базовых типа: коммуникацию «врач – пациент» и коммуникацию «специалист – специалист». Первая модель включает несколько коммуникативных этапов: первичный приём и консультацию, взаимодействие в процессе лечения, сопровождение пациента на этапе выздоровления и последующего наблюдения. Каждый из этих этапов характеризуется собственной речевой стратегией:

диагностической, разъяснительной, терапевтической, поддерживающей.

Вторая модель охватывает профессиональное взаимодействие между врачами, между врачом и средним медицинским персоналом, врачом и студентами-медиками, интернами, резидентами, а также административным персоналом медицинских учреждений. Здесь доминируют стратегии профессионального обмена информацией, координации действий и передачи специальных знаний [10, с.223].

С позиций лингвопрагматики медицинский дискурс реализуется в различных жанровых формах, каждая из которых обладает собственной степенью дискурсивности. К основным формам речевого взаимодействия в медицинской сфере относятся:

1. Устная коммуникация врача и пациента: сбор анамнеза, консультирование, объяснение диагноза, обсуждение схем лечения, сопровождение лечебных процедур.
2. Профессиональное общение между коллегами: консилиумы, клинические обсуждения, экспертные консультации.
3. Академические и научно-профессиональные жанры: лекции, доклады, конференционные сообщения, презентации клинических случаев.
4. Регулятивно-предписывающие тексты: рецепты, назначения, направления на обследование.
5. Медицинская документация: история болезни, выписки, протоколы обследований, заключения специалистов [5, с.62].

Следует подчеркнуть, что не все формы медицинской коммуникации являются дискурсом в строгом смысле слова. Например, история болезни как письменный документ может рассматриваться как текст, тогда как обсуждение диагноза между врачом и пациентом представляет собой полноценный дискурс, поскольку включает ситуативность, интерактивность, прагматическую цель и коммуникативную динамику. Именно это различие между текстом как результатом и дискурсом как процессом имеет принципиальное значение при разработке технологий обучения медицинскому дискурсу.

В связи с этим обучение медицинскому дискурсу должно быть ориентировано не только на усвоение профессиональной терминологии, но и на формирование коммуникативной компетенции будущего врача: способности адекватно строить речевое взаимодействие в различных профессиональных ситуациях, учитывать статус собеседника, выбирать релевантные речевые стратегии и обеспечивать эффективность профессиональной коммуникации.

С функционально-коммуникативной точки зрения виды речевого взаимодействия в медицинской сфере неоднородны по своей природе. Так, формы коммуникации, обозначенные как беседа врача с пациентом и профессиональное общение между коллегами, следует квалифицировать как собственно медицинский дискурс, поскольку они обладают всеми его базовыми признаками: интерактивностью, ситуативной обусловленностью,

прагматической направленностью и наличием непосредственной обратной связи между коммуникантами. Напротив, рецепты, назначения, направления, а также история болезни относятся преимущественно к медицинскому тексту, так как представляют собой завершённые, структурно организованные письменные продукты речевой деятельности, ориентированные на фиксацию и передачу информации без обязательной синхронной реакции адресата.

Особое положение занимают лекции, доклады и презентации, которые обладают переходным статусом между текстом и дискурсом. Если подобные формы коммуникации реализуются как монологическое сообщение без непосредственного отклика аудитории, они функционируют как текст. Однако при включении интерактивного компонента – вопросов, обсуждений, комментариев, уточнений – они трансформируются в дискурс. В этом проявляется принципиальное отличие дискурса от текста: текст является продуктом речевой деятельности, тогда как дискурс – процессом коммуникативного взаимодействия. Даже письменная научная статья может приобретать дискурсивный характер, если становится объектом активного профессионального обсуждения, например, в формате рецензирования, научной полемики или цифровых комментариев.

Подобная дифференциация имеет важное методическое значение для разработки технологий обучения медицинскому дискурсу. Разграничение текста и дискурса позволяет выстраивать различные стратегии формирования профессиональной коммуникативной компетенции. Если для текстовых форм приоритетными являются точность, однозначность, терминологическая стандартизованность и отсутствие эмоционально-экспрессивной неоднозначности, то дискурсивные формы требуют развития навыков интерпретации, ситуативной адаптации речи, учета коммуникативных ролей и прагматических целей участников общения.

Объединяющим началом всех видов медицинского речевого взаимодействия выступает их общая когнитивно-прагматическая установка – обмен специализированным профессиональным опытом в сфере здравоохранения. В научном медицинском дискурсе основными участниками коммуникации являются специалисты-медики, практикующие врачи, исследователи, преподаватели, студенты медицинских вузов, интерны и ординаторы. В научно-популярном медицинском дискурсе коммуникативное пространство расширяется за счёт включения пациентов как адресатов медицинского знания. Следовательно, медицинский дискурс представляет собой институционально организованную форму профессиональной коммуникации, где языковые средства подчинены задачам диагностики, лечения, профилактики и передачи специальных знаний.

Существенную роль в обучении медицинскому дискурсу играет применение активных мето-

дов обучения, обеспечивающих моделирование реальных коммуникативных ситуаций профессиональной среды. Активное обучение предполагает использование таких педагогических технологий, которые стимулируют познавательную инициативу студентов, развивают клиническое мышление и формируют навыки самостоятельного принятия решений в речевой практике.

В современной педагогике высшей медицинской школы активные методы обучения традиционно подразделяются на три основные группы:

1. Методы программированного обучения, ориентированные на поэтапное усвоение материала с контролем промежуточных результатов;
2. Методы проблемного обучения, направленные на постановку клинических и коммуникативных задач, требующих аналитического решения;
3. Методы интерактивного (коммуникативного) обучения, основанные на диалогическом взаимодействии участников образовательного процесса.

Особую эффективность в формировании навыков медицинского дискурса демонстрируют интерактивные технологии: ролевые игры «врач - пациент», клинические кейсы, моделирование консультаций, анализ коммуникативных ошибок, дискуссии по проблемным ситуациям. Именно такие формы создают условия для приближения учебной коммуникации к реальным профессиональным сценариям.

Обучение медицинскому дискурсу должно строиться как комплексная система, сочетающая освоение терминологического аппарата, формирование концептуального медицинского мышления и развитие практических навыков речевого взаимодействия. В этой системе преподаватель выступает не только транслятором знаний, но и организатором коммуникативной среды, в которой студент осваивает профессиональную речь как инструмент будущей врачебной деятельности.

Наибольшая эффективность интерактивных методов в обучении медицинскому дискурсу проявляется тогда, когда они реализуют не только образовательную, но и воспитательную функцию. В условиях профессионально ориентированного обучения преподаватель медицинского вуза выступает не просто как транслятор специальных знаний, но и как модератор профессионально-нравственного общения, формирующий у студентов ценностные установки, коммуникативную этику и культуру речевого поведения будущего врача.

Особенность интерактивного обучения заключается в том, что педагогическое воздействие осуществляется не через директивное навязывание позиции преподавателя, а посредством организации продуктивного диалога. Преподаватель направляет дискуссию через систему проблемных вопросов, побуждающих студентов к аналитическому осмыслению профессиональных ситуаций, аргументации собственной точки зрения и поиску оптимального решения. В этом процессе особенно значима педа-

гогическая тактика косвенного управления обсуждением: преподаватель не подавляет инициативу обучающихся, а корректирует ход рассуждений, подводя их к научно обоснованным выводам.

С методической точки зрения такая форма взаимодействия представляет собой модель совместной когнитивной деятельности, в которой происходит не только усвоение теоретических знаний, но и формирование профессионального мышления. В медицинском образовании это имеет принципиальное значение, поскольку будущий врач должен овладеть не только системой специальных терминов, но и навыками этически выверенного речевого поведения в условиях профессиональной коммуникации. Именно в интерактивной дискуссии формируются умения аргументированно выражать мнение, корректно опровергать ошибочные суждения, учитывать позицию собеседника и соблюдать нормы профессиональной деонтологии.

Активные методы обучения стимулируют студентов к самостоятельной мыслительной и практической деятельности в процессе освоения учебного материала. Их сущность заключается в создании таких педагогических условий, при которых познавательная активность обучающихся становится внутренне мотивированной и устойчивой. В отличие от традиционной репродуктивной модели обучения, ориентированной преимущественно на передачу готовых знаний, активное обучение направлено на развитие аналитических способностей, клинического мышления, речевой инициативы и способности к самостоятельному принятию решений.

Существенным преимуществом активных методов является их диалогическая природа. Именно диалог, по мысли М.М. Бахтина, является универсальной формой смыслообразования, а в профессиональной медицинской коммуникации – основой формирования речевой компетентности [2, с.46]. Через диалог студент включается в ситуацию профессионального взаимодействия, моделирующую реальные условия будущей врачебной практики. Это особенно важно при обучении медицинскому дискурсу, где успешность коммуникации определяется не только точностью терминологии, но и способностью устанавливать контакт, интерпретировать речевые сигналы собеседника и выстраивать доверительное взаимодействие.

Мастерство преподавателя в данной системе заключается в гибком сочетании различных методов обучения в зависимости от целей занятия, уровня подготовки студентов и характера изучаемого материала. Среди наиболее продуктивных интерактивных форм в обучении медицинскому дискурсу можно выделить: ролевые игры («врач - пациент», «врач - врач», «врач - родственник пациента»); анализ клинических кейсов; проблемные семинары и дискуссии; моделирование коммуникативных конфликтных ситуаций; коллективное обсуждение диагностических и этических дилемм.

Использование этих методов способствует созданию благоприятного психологического микроклимата в учебной группе. Атмосфера свободного общения снижает коммуникативные барьеры, фор-

мирует доверие между участниками образовательного процесса и повышает речевую активность студентов. В таких условиях обучение медицинскому дискурсу становится не только процессом усвоения профессионального языка, но и пространством формирования личности врача как носителя профессиональной культуры.

Эвристическая беседа восходит к сократической традиции познания и представляет собой метод проблемного обучения, основанный на последовательной постановке вопросов, стимулирующих самостоятельное нахождение решения. В медицинской аудитории этот метод особенно продуктивен при разборе клинических случаев, когда преподаватель не сообщает готовый диагноз, а подводит студентов к нему через цепочку логически организованных вопросов. Такой подход развивает клиническое мышление, формирует способность к аналитическому рассуждению и совершенствует навыки аргументированного профессионального высказывания.

Метод дискуссии представляет собой форму организованного обсуждения теоретических и практических вопросов, направленную на выработку коллективного решения. В процессе дискуссии студенты учатся формулировать и защищать свою точку зрения, сопоставлять различные интерпретации клинических ситуаций, аргументированно опровергать ошибочные суждения. Особую ценность дискуссия приобретает при обсуждении спорных диагностических решений, этических дилемм и случаев врачебной коммуникации, где необходим учет как научной, так и гуманистической составляющей медицинской деятельности.

Метод мозгового штурма ориентирован на коллективный поиск решений в условиях свободного генерирования идей. Его ключевой принцип – отсутствие критики на этапе выдвижения предложений – создает благоприятную атмосферу интеллектуальной свободы и стимулирует творческую активность студентов. В обучении медицинскому дискурсу данный метод эффективен при анализе нестандартных клинических случаев, требующих быстрого принятия решений и оценки нескольких альтернативных стратегий диагностики или лечения.

Метод круглого стола предполагает обсуждение проблемы с различных профессиональных позиций. В медицинском образовании он особенно полезен при междисциплинарном анализе сложных случаев, где необходимо объединение знаний из терапии, хирургии, фармакологии, биоэтики и психологии общения. Этот метод формирует способность воспринимать проблему комплексно, развивает культуру профессионального диалога и учит взаимодействовать в междисциплинарной команде.

Особую значимость в системе обучения медицинскому дискурсу имеет деловая игра – метод моделирования профессиональной деятельности в условиях учебной среды. Ее сущность заключается в воспроизведении типичных ситуаций врачебной

практики: приема пациента, постановки диагноза, обсуждения схемы лечения, проведения консилиума, сообщения неблагоприятного прогноза. Деловая игра позволяет переносить теоретические знания в практическую плоскость, формируя навыки профессиональной речи в условиях, максимально приближенных к реальной медицинской коммуникации. Именно в игровых моделях наиболее полно раскрывается прагматическая природа медицинского дискурса как речевого действия, направленного на достижение конкретного клинического результата.

Таким образом, интерактивные методы являются ключевым инструментом формирования медицинского дискурса в образовательной среде. Они обеспечивают интеграцию когнитивного, коммуникативного и аксиологического компонентов подготовки будущего специалиста, способствуя развитию профессиональной языковой личности врача, способного эффективно действовать в сложных условиях современной медицинской коммуникации.

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RESEARCH ON THE INTEGRATION OF ADVANCED MATHEMATICS TEACHING AND COMPUTER MAJOR COMPETENCY CULTIVATION

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Abstract

Advanced Mathematics is a core foundational course for computer majors. Its cultivation of logical thinking, abstract modeling, and algorithm analysis capabilities directly supports the quality of talent training for computer professionals. Under the background of education in the new era, the organic integration of Advanced Mathematics knowledge with the cultivation of computer professional abilities and the immediate realization of curriculum value has become an important direction for the reform of Advanced Mathematics courses in computer-related majors. Guided by the cultivation of computer professional abilities, this paper discusses the teaching of Advanced Mathematics from the perspectives of teaching content reconstruction, teaching method innovation and assessment method reform.

Keywords: Advanced Mathematics; computer major; professional ability; teaching reform

1 Introduction

In the era of digital economy and intelligent technology, computer technology has penetrated into all walks of life. As a core basic course for computer-related majors, Advanced Mathematics is not only a theoretical prerequisite for students to understand follow-up courses such as data structures, artificial intelligence, computer graphics, cryptography, etc., but also a key carrier for cultivating students' logical reasoning, abstract thinking and problem-solving abilities [1]. However, the current teaching of Advanced Mathematics in computer majors at colleges and universities generally suffers from the following problems: outdated content system, monotonous teaching methods, rigid assessment modes, and insufficient learning motivation among students. The fundamental reason is that students fail to perceive the connection between mathematics and their major during their studies, and cannot immediately realize the important role of mathematics in professional learning.

This study reconstructs teaching content, innovates teaching methods, and reforms assessment modes, which can effectively improve computer majors' ability in mathematical application, computational thinking and engineering practice. It aims to cultivate innovative talents with solid mathematical foundations for the computer field, and provide references for mathematics teaching reform in other engineering majors. Furthermore, it enriches the theoretical system of the integration of basic courses and professional courses in colleges and universities, offers a theoretical framework and practical approach for collaborative education between Advanced Mathematics and computer majors, and promotes the innovative development of mathematics education and teaching theories.

Foreign universities have long attached importance to the integrated teaching of mathematics and computer science. For example, the Massachusetts Institute of Technology (MIT) in the United States has incorporated a large number of programming practices and numerical computation contents into the mathematics courses of computer-related majors, emphasizing the combination of mathematical modeling and com-

puter implementation [2]. Universities such as the University of Oxford and the University of Cambridge in the UK focus on cultivating students' computational thinking and algorithm design ability in mathematics teaching. In addition, foreign scholars began exploring the disciplinary connection between mathematics and computer science at an early stage. They clarified that mathematics courses should serve as core prerequisites for computer-related majors, and that mathematics teaching content should be optimized in light of the application demands of the computer science discipline, so as to avoid focusing merely on sorting out theoretical premises while neglecting practical application [3]. Internationally, there are also academic journals dedicated specifically to the integration of mathematics and computer science, which continuously publish relevant research findings, promote theoretical and practical innovations in the integration of the two disciplines, and emphasize that the coordinated development of mathematical theories and computer applications constitutes an important foundation for modern scientific and technological progress [4].

Many scholars in China have also explored the integration of advanced mathematics and computer science. Some studies focus on the optimization of teaching content, such as incorporating numerical computation and the application of mathematical software [5]; others are concerned with the innovation of teaching methods, including project-based learning and flipped classrooms [6]; and some emphasize the reform of assessment approaches, for example, strengthening process assessment and experimental assessment [7]. Most of these studies only concentrate on reforms in a single dimension, lacking systematic and in-depth research on integration from the three dimensions of content, methods and assessment. Furthermore, practical cases targeting computer majors in local undergraduate universities are relatively insufficient.

2 Definition of the Connotation of Advanced Mathematics, Computer Professional Competencies and Teaching Integration

(1) Advanced mathematics is a basic theoretical course for computer-related majors. It mainly includes

functions and limits, derivatives and differentials, integration, differential equations, infinite series, vector algebra and spatial analytic geometry. It serves as an important theoretical tool for students to learn computer professional courses.

(2) Computer professional competencies cover computational thinking, algorithm design and analysis ability, programming implementation ability, data processing and analysis ability, mathematical modeling ability, engineering practice ability and other aspects, which are the core qualities that computer majors must possess.

(3) Teaching integration refers to the organic integration of the knowledge system and thinking methods of advanced mathematics with the competency requirements, curriculum content and practical links of computer majors, so as to form a mutually supporting and mutually promoting teaching system and realize the coordinated development of mathematics teaching and professional competency cultivation.

3 Reconstruction of Teaching Content

Constructing a mathematics knowledge system deeply integrated with computer majors is the foundation for integrating advanced mathematics and computer professional competencies. It is necessary to break the knowledge framework of traditional mathematics courses, carry out modular and scenario-based design according to the application requirements of computer majors, and achieve precise alignment between mathematical knowledge and professional competencies [8].

3.1 Division of Teaching Modules Oriented to Computer Application Scenarios

Abandoning the traditional chapter-based content organization, this study divides advanced mathematics

into the following modules by combining core computer courses and practical application scenarios:

3.1.1 Function and Limit Module

Corresponding Content: Convergence of numerical algorithms, iteration methods, function approximation, image gray value transformation, etc.

Key Explanations: Definition and properties of limits, continuity of functions, limit calculation methods, combined with computer-related problems such as convergence analysis of algorithms and stability analysis of iterative processes.

Additional Content: Numerical approximation methods of functions, simple algorithm implementation cases based on limits.

Case 1: Calculation of the Circumference Ratio π Using the Idea of Limits

When explaining "sequence limits and the idea of the cyclotomic method" in class, to help students grasp the limit concept of "infinite approximation and approaching a fixed value", a computer can be used to approximate the limit through finite iterations.

First, the algorithmic implementation of the idea of limits in a computer is given as follows:

- (1) Set the circle radius $r=1$;
- (2) Adopt regular n -sided polygons ($n=3, 6, 12, 24, 48, 96, \dots$);
- (3) Calculate the perimeter using the side length formula;
- (4) Obtain the approximate value of π by dividing the perimeter by 2;
- (5) The larger n is, the closer the result is to π .

The process of calculating the circumference ratio π through finite iterations with the help of a computer is shown in Figure 1:

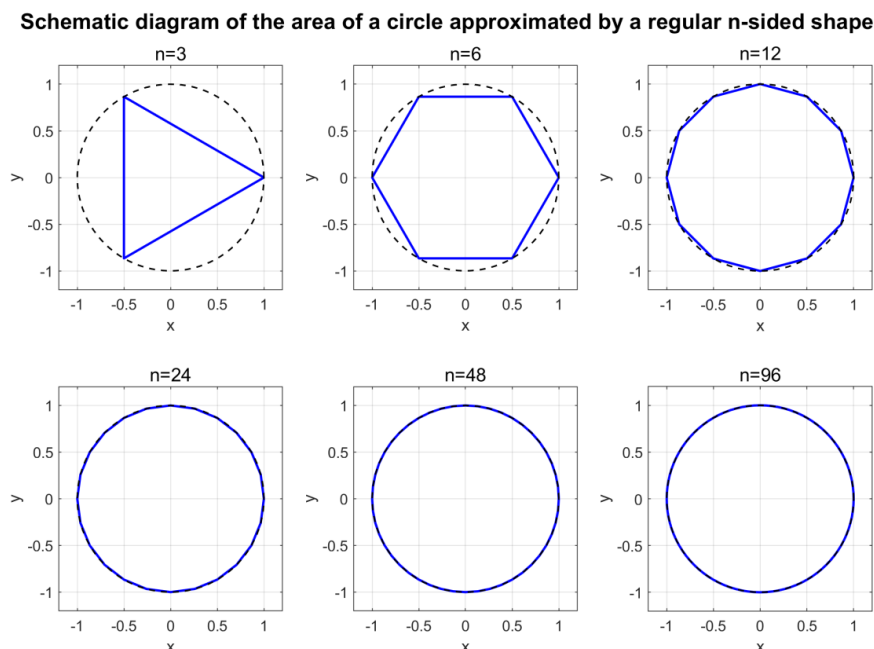


Figure 1: Schematic diagram of the area of a circle approximated by a regular n -sided shape

Finally, let the students observe the results:

$$n=6 \quad \pi \approx 3.0000$$

$$n=12 \quad \pi \approx 3.1058$$

$$n=96 \quad \pi \approx 3.1410$$

$$n=10000 \quad \pi \approx 3.1415926\dots$$

Such a mathematics class can not only improve students' mathematical application ability, that is, students can apply mathematical knowledge in the process of solving computer professional problems, thereby enhancing their mathematical application ability and innovative thinking. At the same time, it can also enhance students' learning motivation and interest. When students realize the importance of advanced mathematics in the study of computer majors and can connect mathematical knowledge with practical applications, their learning enthusiasm and initiative will be significantly improved, thus improving learning effects.

3.1.2 Derivative and Differential Module

Corresponding Content: Optimization algorithms (such as gradient descent), loss functions in machine learning, image edge detection, speed and acceleration calculation, etc.

Key Explanations: The definition and geometric meaning of derivatives, the calculation method of differentials, the application of higher-order derivatives, which are explained in combination with the principle of gradient descent, the derivation of loss functions, the mathematical principle of image edge detection, etc [9].

Additional Content: Derivative derivation of common optimization algorithms, implementation of simple optimization programs based on derivatives.

3.1.3 Integral Module

Corresponding Content: Numerical integration, area and volume calculation, data feature extraction, integral transformation in image processing, etc.

Key Explanations: The calculation methods of definite integrals and indefinite integrals, the applications of multiple integrals, line integrals and surface integrals, which are explained in combination with numerical integration algorithms, integral calculation of image pixels, integral feature extraction of data, etc.

Additional Content: Programming implementation of numerical integration, application cases of integrals in image processing.

3.1.4 Differential Equation Module

Corresponding Content: System modeling, dynamic process simulation, dynamic analysis of neural networks, epidemic models, etc.

Key Explanations: The solution methods and stability analysis of ordinary differential equations, which are explained in combination with simple system modeling, numerical simulation of dynamic processes, dynamic behavior analysis of neural networks, etc.

Additional Content: Numerical solution methods of differential equations, modeling and simulation cases based on differential equations.

3.1.5 Infinite Series Module

Corresponding Content: Data compression, signal processing, activation functions of neural networks, polynomial approximation, etc.

Key Explanations: The convergence of series, the applications of power series and Fourier series, which are explained in combination with the principle of data compression, spectral analysis of signals, approximation of activation functions of neural networks, etc.

Additional Content: Application cases of series in data processing and signal processing.

3.2 Integration of Computer-Related Elements and Practical Cases

In each teaching module, computer-related elements and practical cases are proactively integrated to closely link mathematical knowledge with professional computer applications.

3.2.1 Introduction of Typical Computer Cases

Typical problems in the computer field are selected as teaching cases, such as calculating the area of an image using integration, analyzing the time complexity of sorting algorithms with derivatives, and establishing infectious disease transmission models via differential equations. Through case-based teaching, students can intuitively perceive the application value of mathematical knowledge in the computer discipline. This is also consistent with relevant foreign scholars' research on the application of mathematical models in the computer field [10].

Case 2: Analyzing the Time Complexity of Sorting Algorithms Using Derivatives

In computer science, the time complexity of an algorithm describes how its running time evolves with the input size n . By analyzing the growth rates of functions using mathematical derivatives, the merits of different algorithms can be rigorously established in theory.

(1) Define the algorithm complexity function

The time complexity function of quadratic-order algorithms (bubble sort, insertion sort) is denoted as $T_1(n) = n^2$, and the time complexity function of logarithmic-order algorithms (quick sort, merge sort) is denoted as $T_2(n) = n \log n$.

(2) Analyze the growth rate based on derivatives

Differentiate the two complexity functions respectively to obtain the growth rate functions: the growth rate of quadratic-order algorithms is $T_1'(n) = 2n$, and the growth rate of logarithmic-order algorithms is $T_2'(n) = \log n + 1$.

(3) Strictly prove the superiority of algorithms

When the input size n is sufficiently large, it is obvious that $2n \gg \log n + 1$ holds, meaning $T_1(n)$ grows much faster than $T_2(n)$.

Thus the conclusion can be drawn: in scenarios with large data sizes, quadratic-order algorithms (bubble sort / insertion sort) are less efficient, while logarithmic-order algorithms (quick sort / merge sort) are more efficient.

3.2.2 Strengthen Computational Thinking and Algorithmic Ideas

In teaching, emphasis is placed on cultivating students' computational thinking, guiding them to transform mathematical problems into algorithmic problems, design reasonable algorithmic steps, and implement them through programming. For instance, when explaining the extreme values of functions, students are guided to design algorithms for solving function extrema and implement them with code.

3.3 Optimize Content Structure and Strengthen Practical Orientation

(1) Remove overly abstract, complex theoretical proofs that have little relevance to the computer discipline, such as proofs of some complicated integral theorems and profound theoretical proofs of infinite series. Shift the focus of teaching to the application and practice of knowledge.

(2) Supplement numerical computation methods, including numerical integration, numerical differentiation, numerical solutions to systems of linear equations, etc., as these contents form the foundation of numerical computation for computer majors. Add basics of mathematical modeling to guide students in using mathematical knowledge to establish mathematical models for computer-related problems, as well as solve and analyze them. Include training in the use of mathematical software and programming tools such as Python, MATLAB, GeoGebra, etc., to improve students' ability to apply mathematical software and their programming skills.

4 Innovation in Teaching Methods

Innovation in teaching methods is the key to integrating advanced mathematics with computer professional competencies. It is necessary to change the traditional single teaching mode of "teachers lecture and students listen", adopt diversified teaching methods, emphasize the combination of theory and practice, and stimulate students' enthusiasm and initiative in learning.

4.1 Problem-Based Learning (PBL): Guiding Mathematics Learning with Real-World Computer Problems

Problem-based learning is driven by real-world problems in the computer field, guiding students to learn and explore mathematical knowledge around these problems. The specific implementation steps are as follows:

(1) **Problem Introduction:** At the beginning of each class, a practical problem related to the computer major is raised to arouse students' interest and thinking. For example, when teaching definite integrals, the question "How to calculate the area of a digital image?" can be posed; when teaching derivatives, the question "How to optimize the loss function of a machine learning model?" can be proposed.

(2) **Problem Analysis:** Guide students to analyze the problem, clarify the mathematical knowledge and computer skills involved in the problem, and define learning objectives.

(3) **Knowledge Inquiry:** Organize students to learn relevant mathematical knowledge centered on the problem, and guide them to apply mathematical knowledge to solve the problem.

(4) **Solution Design:** Encourage students to discuss in groups and design problem-solving schemes, including mathematical modeling, algorithm design, programming implementation, etc.

(5) **Achievement Presentation and Evaluation:** Each group presents its solution; the teacher comments and evaluates the schemes, and summarizes experiences and lessons.

Through problem-driven teaching, students can learn mathematical knowledge in the process of solving practical problems, and improve their mathematical application ability and problem-solving ability.

4.2 Integration of Theory and Practice: Synchronous Mathematical Derivation and Programming Implementation

Integration of theory and practice refers to the organic combination of mathematical knowledge derivation and computer program realization in classroom teaching, so as to achieve an integrated teaching model of "learning mathematics, applying mathematics, and programming". The specific implementation methods are as follows:

(1) **Synchronous Classroom Teaching:** When explaining the derivation of mathematical formulas or theorems, the corresponding computer program implementation is introduced simultaneously. For example, when explaining the principle of gradient descent, derive the calculation method of the gradient while writing simple Python code examples to implement the gradient descent algorithm, allowing students to intuitively perceive the connection between mathematical derivation and program implementation.

(2) **Mathematical Visualization:** Use mathematical software (such as GeoGebra, Matplotlib, etc.) to visualize abstract mathematical concepts, formulas and theorems, helping students understand mathematical knowledge. For instance, when explaining function graphs, draw function images and dynamically demonstrate the change process of functions to enable students to intuitively understand function properties; when explaining the geometric meaning of integrals, dynamically demonstrate the process of dividing and summing integral regions to help students understand the concept of definite integrals.

(3) **After-Class Practical Expansion:** Assign programming practice tasks related to classroom content, allowing students to verify mathematical knowledge through programming after class, so as to deepen their understanding and application of knowledge. For example, after explaining numerical integration, assign tasks for students to implement different numerical integration methods using Python and compare the calculation results.

4.3 Project-Based Learning (PBL): Integrating Mini-Projects Throughout the Course

Project-based learning uses one or more mini computer projects as a carrier to integrate knowledge and skills from advanced mathematics into the project implementation process. Students learn mathematical concepts and improve professional competencies while completing the projects. The specific implementation steps are as follows:

(1) **Project Design:** Based on the teaching content of advanced mathematics, design mini-projects relevant to the computer science major. Examples include: Simple image processing project based on integration, Function optimization program based on derivatives, Dynamic system simulation project based on differential equations.

(2) **Grouping:** Divide students into several groups of 3–5 members, with clear roles and responsibilities assigned to each student.

(3) **Project Implementation:** Each group conducts requirements analysis, mathematical modeling, algorithm design, programming, testing, and optimization according to project requirements. The instructor provides guidance and answers questions throughout the process.

(4) **Project Acceptance and Evaluation:** Each group submits deliverables including project reports, source code, demonstration videos, etc. The instructor organizes project presentations and evaluates the outcomes.

Through project-based learning, students can systematically apply advanced mathematics knowledge to solve computer science problems, and enhance their teamwork, project management, and engineering practice abilities.

4.4 Information-Based Teaching: Enhancing Teaching Effect with Intelligent Tools

Full use shall be made of information technology to strongly support the integrated teaching of Advanced Mathematics and the computer specialty.

(1) Use of online teaching platforms

Online platforms such as Chaoxing Learning Platform and Rain Classroom are adopted to realize the sharing of teaching resources, interaction of teaching activities, and monitoring of the learning process. Teachers can upload courseware, operation videos of mathematical software, programming cases, assignments and experimental tasks on the platform. Students can watch teaching videos, finish homework, participate in discussions, and submit experimental reports via the platform [11].

(2) Use of intelligent teaching systems

Intelligent teaching systems are utilized to provide students with personalized learning guidance and feedback. According to students' learning progress, the system can automatically recommend customized learning materials and exercises, diagnose learning difficulties, and offer targeted solutions.

(3) Use of mathematical software and programming tools

Students are encouraged to use mathematical and programming tools including Python, MATLAB and GeoGebra for mathematical learning and practice. Teachers can demonstrate the operation of such software in class and guide students to perform mathematical calculations, graph plotting, and program implementation, so as to improve students' information literacy and practical abilities.

5 Reform of Assessment Methods: Establishing a Diversified Competency Evaluation System

Assessment methods act as the guide for teaching. Scientific and reasonable assessment plays a vital role in guiding student learning, evaluating teaching effectiveness, and achieving training objectives. In response to the teaching goal of integrating advanced mathematics with computer professional competencies, it is necessary to reform traditional assessment methods and establish a diversified competency evaluation system.

5.1 Increasing the Proportion of Process Assessment

The proportion of process assessment will be increased to 50% or above to comprehensively evaluate students' learning process and competency development. Process assessment mainly includes the following components:

(1) Daily Assignment Assessment

Diversified assignments will be assigned, including basic mathematical problems, programming implementation tasks, case analysis questions, and mathematical modeling problems. Through assignments, students' mastery of mathematical knowledge, programming skills, application ability, and innovative thinking will be evaluated.

(2) Class Performance Assessment

Attention will be paid to students' classroom participation, question responses, performance in group discussions, project presentations, etc., so as to assess their learning initiative, communication skills, and teamwork ability.

(3) Experiment Assessment

Special mathematical experiment sessions will be arranged, requiring students to implement mathematical algorithms through programming, verify mathematical conclusions, and solve practical computer problems. Experiment assessment includes experiment reports, operational performance, and result analysis, evaluating students' practical operation ability, data analysis ability, and problem-solving ability [12].

(4) Study Notes and Reflection Assessment

Students will be required to write study notes and learning reflections, summarizing key and difficult points, insights, and areas for improvement, so as to evaluate their autonomous learning ability and reflective thinking.

5.2 Reform of the Content and Form of Summative Assessment

Summative assessment adopts a combination of closed-book written examination and open-book assessment, focusing on evaluating students' comprehensive application ability and innovative ability.

(1) Optimization of closed-book written examination content

In the closed-book written examination, purely computational questions will be reduced, while application-oriented and comprehensive questions will be increased. For example, mathematical modeling problems, algorithm analysis problems, programming design problems under computer scenarios will be added to examine students' ability to use mathematical knowledge and computer professional knowledge to solve problems collaboratively.

(2) Design of open-book assessment content

An open-book assessment session will be set up, in forms such as mathematical modeling papers, project design reports, comprehensive case analysis reports, etc. Students may refer to materials and use mathematical software and programming tools to complete assessment tasks, which mainly assess their autonomous learning ability, information retrieval ability, innovation ability and engineering practice ability.

Advanced Mathematics is the foundation for computer science students to learn professional courses such as data structures, algorithm analysis, artificial intelligence, and machine learning. It plays an irreplaceable role in cultivating students' logical reasoning, abstract modeling, numerical calculation and systematic thinking. Through reconstructing teaching content, innovating teaching methods and reforming assessment modes, we will deeply integrate curriculum teaching with the specialty, guide students to focus on classroom learning, and improve the quality of classroom teaching.

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MODERN EDUCATIONAL TECHNOLOGIES IN CHEMISTRY LESSONS FOR WORKING WITH GIFTED SCHOOL STUDENTS**Nurekenova A.***candidate of biological Sciences, associate professor,
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of the Department of chemistry and biology,
Non-profit joint-stock company «Shakarim University»***СОВРЕМЕННЫЕ ОБРАЗОВАТЕЛЬНЫЕ ТЕХНОЛОГИИ НА УРОКАХ ХИМИИ ПРИ РАБОТЕ С ОДАРЁННЫМИ ШКОЛЬНИКАМИ****Нуременова А.Н.***кандидат биологических наук,
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<https://doi.org/10.5281/zenodo.19573247>***Abstract**

The article analyzes modern educational technologies used in working with chemically gifted school students. The aim of the study is to determine their potential for developing chemical giftedness. The methodological basis of the study was a theoretical and analytical review of domestic and foreign research. It was found that differentiated, project-based, research, interactive, and digital technologies demonstrate the greatest effectiveness when they are systematically integrated into the methodological system of chemistry teaching.

Аннотация

В статье анализируются современные образовательные технологии, применяемые на уроках химии при работе с одарёнными школьниками. Цель исследования — определить их потенциал для развития одарённости. Методологическую основу составил теоретико-аналитический обзор отечественных и зарубежных исследований. Установлено, что наибольшую эффективность демонстрируют дифференцированные, проектные, исследовательские, интерактивные и цифровые технологии при условии их системного включения в методическую систему обучения химии.

Keywords: gifted school students; methodological system; modern educational technologies; project-based and inquiry-based learning; interactive and game-based technologies; information and communication technologies and digital technologies.

Ключевые слова: одарённые школьники; методическая система; современные образовательные технологии; проектное и исследовательское обучение; интерактивные и игровые технологии; информационно-коммуникационные и цифровые технологии.

1. Введение

Сегодня к качеству естественно-научной подготовки школьников предъявляются всё более высокие требования. Это связано не только с быстрым развитием науки и технологий, но и с растущим спросом на специалистов в STEM-сфере. В этом отношении школьная химия занимает особое место: именно она помогает развивать исследовательское мышление, навыки эксперимента и умение объяснять явления с научной точки зрения. На уроках химии особенно заметны учащиеся, которые быстро осваивают материал, проявляют устойчивый интерес к предмету и охотно берутся за нестандартные задачи. Таких школьников можно рассматривать как химически одарённых.

В то же время обычная школьная практика по-прежнему в значительной степени ориентирована на «среднего» ученика. Из-за этого возможности

сильных и мотивированных школьников нередко раскрываются не полностью. Именно поэтому проблема организации целенаправленной работы с химически одарёнными учащимися остаётся актуальной.

В отечественной и зарубежной педагогике в последние годы всё чаще обсуждаются вопросы, связанные с построением системы работы с одарёнными школьниками по химии. Исследователи подчёркивают, что такая работа должна быть не эпизодической, а выстроенной как целостная методическая система, включающая цели, содержание, технологии и организационные формы урочной и внеурочной деятельности [1, с. 4–11]. Одновременно усиливается интерес к современным образовательным технологиям, которые применяются в преподавании химии: цифровым ресурсам, интерактивным форматам, виртуальным лабораториям и

инструментам на основе искусственного интеллекта [4, с. 30–32; 5, с. 17–18]. Их использование открывает новые возможности для поддержки одарённых школьников, но требует педагогически продуманного подхода.

Актуальность данной обзорной статьи определяется необходимостью обобщить существующие подходы к использованию современных образовательных технологий в работе с химически одарёнными школьниками и оценить их потенциал. Объект исследования — процесс обучения химии в общеобразовательной школе. Предмет исследования — современные образовательные технологии, применяемые для развития химической одарённости учащихся. Цель статьи состоит в том, чтобы проанализировать возможности этих технологий и определить педагогические условия, при которых их применение может быть наиболее эффективным в системе работы с одарёнными школьниками по химии. Для достижения этой цели в статье решаются следующие задачи: рассматриваются теоретические подходы к пониманию одарённости и химической одарённости; характеризуется методическая система работы с одарёнными учащимися по химии; анализируются основные группы современных образовательных технологий, используемых в химическом образовании; раскрываются их возможности и ограничения в школьной практике.

2. Теоретические основы химической одарённости

2.1. Понятие одарённости и её виды

В современной психолого-педагогической литературе одарённость понимается как целостное качество психики, которое позволяет ребёнку достигать более высоких результатов в одном или нескольких видах деятельности по сравнению со сверстниками. Исследователи подчёркивают, что одарённость нельзя свести к одному показателю: в её структуру обычно включают интеллектуальный, творческий, мотивационный и личностный компоненты, а также учитывают влияние образовательной среды, которая либо помогает, либо, наоборот, мешает раскрытию потенциала ребёнка.

Принято выделять несколько видов одарённости: общую интеллектуальную, академическую (учебную), творческую, художественно-эстетическую, социальную, психомоторную и другие. В контексте школьного изучения химии особый интерес представляет академическая одарённость в области естественно-научных дисциплин. Она проявляется в том, что ученик быстрее усваивает профильный материал, проявляет устойчивый интерес к научному знанию и охотно берётся за задачи повышенной сложности, требующие самостоятельных рассуждений.

2.2. Химическая одарённость как педагогическая категория

В работах, посвящённых методике преподавания химии и сопровождению одарённых школьников, подчёркивается необходимость выделять особый вид предметной одарённости — химическую [1, с. 12–40]. Под химической одарённостью, как правило, понимают сочетание интеллектуальных,

практических и личностных качеств, которые обеспечивают успешность именно в области химического образования. К их числу относят развитое абстрактно-логическое и образно-символическое мышление, умение оперировать химическими моделями и формулами, склонность к эксперименту, наблюдательность и аккуратность при работе с веществами и оборудованием.

Отмечается, что химически одарённые школьники обычно быстро продвигаются в освоении курса, хорошо видят причинно-следственные связи между химическими явлениями, проявляют интерес к нестандартным и олимпиадным задачам, стремятся проводить опыты и самостоятельно объяснять наблюдаемые эффекты. При этом химическая одарённость не сводится к высоким отметкам: большое значение имеют внутренняя мотивация к познанию, устойчивый интерес к химии как науке, готовность прилагать усилия при выполнении сложных заданий, участие в проектной и исследовательской деятельности [1, с. 58–79].

Ряд авторов подчёркивает, что химическая одарённость имеет динамический характер: она может развиваться при благоприятных условиях и «затухать» при отсутствии поддержки. На её формирование заметно влияют качество образовательной среды, степень дифференциации и индивидуализации обучения, а также наличие у школьника возможностей для творческой самореализации в изучении химии. Это делает особенно важной задачу продуманного педагогического сопровождения химически одарённых учащихся на разных этапах обучения [1, с. 41–57].

2.3. Диагностика и выявление химической одарённости

Чтобы работа по развитию химической одарённости была результативной, важно своевременно заметить и подтвердить наличие соответствующих способностей. Для этого применяется комплекс психолого-педагогических диагностических средств. В исследованиях по методике обучения химии предлагаются, в частности, двухступенчатые модели диагностики: сначала проводится широкое первичное выявление школьников, которые проявляют повышенный интерес и успешность в естественно-научных дисциплинах, а затем организуется более детальный анализ их специфических химических способностей и мотивации к углублённому изучению предмета [1, с. 12–40].

К педагогическим методам диагностики относят систематическое наблюдение за работой ученика на уроках и во внеурочной деятельности, анализ выполнения заданий повышенного уровня сложности, участие в олимпиадах и конкурсах, проявление инициативы в проведении опытов и постановке вопросов, выходящих за рамки учебной программы. Существенную информацию дают результаты предметных олимпиад по химии, позволяющие оценить не только объём знаний, но и способность анализировать экспериментальные данные, переносить знания в новые ситуации и находить нестандартные решения.

Параллельно используются психодиагностические методики, направленные на оценку общего и творческого интеллекта, шкалы поведенческих характеристик одарённых школьников (например, шкала Дж. Рензулли в отечественной адаптации), а также комплексные программы диагностики одарённости. При этом подчёркивается необходимость соблюдать принципы комплексности и длительности наблюдений, опираться на «живые» для ребёнка ситуации, а также обеспечивать взаимодействие учителя, психолога, родителей и самого ученика на этапах выявления и дальнейшего сопровождения одарённости [1, с. 12–40; 3].

3. Методическая система работы с одарёнными школьниками по химии

3.1. Структура методической системы

В работах по методике обучения подчёркивается, что с одарёнными по химии школьниками нельзя работать только через отдельные разовые мероприятия — кружок, олимпиаду или эпизодический проект. Такая деятельность должна быть встроена в целостную методическую систему, которая пронизывает и уроки, и внеурочную деятельность [1, с. 4–11]. Обычно выделяют несколько взаимосвязанных компонентов этой системы: целевой, содержательный, технологический, организационный и оценочный [1, с. 80–139; 2, с. 120–121].

Целевой компонент задаёт ориентиры: развитие химических способностей, формирование устойчивой мотивации к предмету, включение школьников в исследовательскую и проектную деятельность [1, с. 80–100]. Содержательный компонент связан с отбором материала: в программу вводятся углублённые темы, усиливается экспериментальная часть, используются межпредметные связи, появляются задания, выходящие за рамки базового стандарта. Технологический и организационный компоненты отвечают за то, как именно это содержание реализуется: через какие формы урока и внеурочной работы, какие образовательные технологии и режимы обучения выбираются. Наконец, оценочный компонент включает диагностику результатов и отслеживание динамики развития одарённых школьников, что позволяет корректировать их индивидуальные образовательные маршруты [1, с. 100–139; 2, с. 122].

3.2. Формы работы с одарёнными по химии

Реализация методической системы опирается на широкий спектр форм работы, которые обеспечивают дифференциацию и индивидуализацию обучения. На уроках это могут быть углублённые и профильные занятия, элективные курсы и модули, позволяющие расширять и усложнять содержание, а также варьировать уровень и характер заданий для разных групп учащихся [1, с. 80–100]. Включение задач олимпиадного уровня, проблемных и исследовательских заданий даёт возможность сильным школьникам работать на пределе своих возможностей и проявлять инициативу.

Особая роль отводится внеурочной деятельности. В школах создаются предметные кружки, научные общества учащихся, исследовательские элективы, лабораторные практикумы [1, с. 100–139]. В

этих форматах можно организовать длительные проекты, подготовку к конференциям и конкурсам, выполнение сложных экспериментов, которые трудно провести в рамках обычного урока. Важным направлением становится и целенаправленная олимпиадная подготовка: регулярное решение задач повышенной сложности, разбор типичных ошибок, моделирование олимпиадных туров, участие в школьных, районных и республиканских соревнованиях по химии.

3.3. Педагогические условия эффективности методической системы

То, насколько успешно работает описанная система, во многом зависит от соблюдения ряда педагогических условий [1, с. 4–11; 2, с. 123]. Одно из ключевых — реальная индивидуализация и дифференциация обучения. Учителю необходимо иметь возможность менять темп и глубину изучения тем, подбирать задания разного уровня сложности, предлагать индивидуальные маршруты, которые учитывают интересы и возможности конкретного ученика. Это, в свою очередь, требует предварительной диагностики особенностей одарённых школьников и регулярного анализа того, как они продвигаются, какие формы и методы работы оказываются для них более продуктивными.

Не менее важно сформировать развивающую образовательную среду. Речь идёт не только о материально-технической базе — оснащённой химической лаборатории, наличии реактивов, оборудования, доступа к современным цифровым ресурсам, — но и об организации пространства для самостоятельных и коллективных исследований. К такой среде относится и психологический климат в классе: атмосфера, в которой ценятся инициатива, умение выдвигать гипотезы, обсуждать результаты и не бояться ошибок.

Отдельным условием выступает готовность самого учителя к работе с одарёнными и к использованию современных образовательных технологий. Это подразумевает владение приёмами дифференциации, опытом организации проектной и исследовательской деятельности, умением выбирать и сочетать цифровые ресурсы в обучении химии [2, с. 121–124]. В исследованиях подчёркивается необходимость системной подготовки педагогов: курсов повышения квалификации, методических семинаров, стажировок, а также сотрудничества школ с вузами и научными организациями. Такая кооперация расширяет спектр возможностей для одарённых школьников и позволяет им включаться в более серьёзные исследовательские и образовательные проекты [1, с. 140–185; 2, с. 124–125].

4. Современные образовательные технологии в обучении химии

4.1. Классификация современных технологий в химическом образовании

Химическое образование сегодня развивается в русле общепедагогических тенденций: от простого усвоения знаний к формированию компетенций, личностному развитию ученика и организации активной деятельности на уроке. В методической литературе по химии обычно выделяют несколько

крупных групп технологий, которые особенно часто применяются в школьной практике: проблемное и исследовательское обучение, проектные технологии, интерактивные и игровые формы, личностно-ориентированные подходы, а также информационно-коммуникационные и цифровые технологии, включая инструменты на основе искусственного интеллекта [4, с. 30; 5, с. 18–19].

Проблемное и исследовательское обучение связано с постановкой перед учащимися познавательных задач, для решения которых недостаточно просто воспроизвести параграф из учебника: необходимо выдвинуть гипотезу, подобрать способ её проверки, провести эксперимент или логический анализ. Проектные технологии ориентированы на создание учащимися конкретного продукта — исследовательского отчёта, презентации, модели, практико-ориентированного решения — и тем самым сближают урок химии с реальной научной и инженерной практикой. Интерактивные и игровые формы помогают включить школьников в обсуждение, совместный поиск решения и работу в команде, а цифровые средства расширяют возможности визуализации, моделирования и индивидуализации обучения [4, с. 31; 5, с. 18–19].

4.2. Проблемное и исследовательское обучение в химии

При проблемном обучении по химии учитель сознательно создаёт ситуации, в которых ученику нужно разобраться в причине наблюдаемого явления или объяснить неожиданный результат опыта. Это могут быть вопросы, на которые нельзя ответить прямой цитатой из текста, демонстрации с «неожиданным» исходом, задания с неполными или избыточными данными, требующие анализа и выбора стратегии решения. Исследовательская составляющая проявляется, когда учащиеся проходят весь цикл мини-исследования: от формулировки гипотезы и планирования эксперимента до обработки результатов и формулировки выводов.

Для химически одарённых школьников такие форматы особенно значимы. Они стимулируют развитие критического и творческого мышления, учат грамотно задавать вопросы, делать осознанный выбор методов исследования и отвечать за принятые решения. Освоение базовой логики научного поиска и экспериментальной культуры в рамках проблемного и исследовательского обучения становится фундаментом для более серьёзного участия в олимпиадах, конкурсах и проектно-исследовательских программах [1, с. 58–79].

4.3. Проектные технологии в обучении химии

Проектная деятельность рассматривается как один из наиболее действенных способов индивидуализации обучения и придания химии практико-ориентированного характера. В ходе работы над проектом школьники индивидуально или в малых группах выбирают значимую для них проблему — экологическую, технологическую, бытовую, краеведческую, — формулируют цель и задачи, подбирают методы исследования, собирают и

анализируют информацию. Результаты могут представляться в форме доклада, презентации, модели, рекомендаций для школы или местного сообщества. Проекты по химии бывают исследовательскими, информационными, прикладными; возможны как моно-, так и межпредметные форматы.

Для одарённых учащихся метод проектов ценен тем, что даёт возможность работать в собственном темпе, выходить за рамки учебника, объединять знания из разных областей и при этом осваивать «надпредметные» навыки — планирование работы, самоорганизацию, публичное представление результатов. Участие в длительных химических проектах, особенно связанных с реальными проблемами (качество воды, бытовая химия, экологическое состояние района), усиливает внутреннюю мотивацию к изучению предмета и формирует готовность к более серьёзной научно-исследовательской деятельности [1, с. 100–139].

4.4. Интерактивные и игровые технологии

Интерактивные технологии в обучении химии включают разные формы работы, где ключевую роль играет живое взаимодействие: групповые задания, учебные дискуссии, «мозговые штурмы», кейс-метод, ролевые и деловые игры, учебные дебаты и т.п. Их объединяет ориентация на совместное конструирование знаний: ученики не только слушают объяснение учителя, но и обсуждают варианты решений, обосновывают свою позицию, реагируют на аргументы одноклассников [4, с. 31]. На уроках химии такие методы продуктивны, например, при обсуждении экологических последствий химических производств, сравнении альтернативных технологических процессов, решении ситуационных задач, где нужно учитывать несколько критериев (эффективность, безопасность, стоимость).

Игровые технологии — предметные викторины, химические брейн-ринги, турниры, сюжетно-ролевые игры вроде «совета учёных» или «экспертной комиссии» — позволяют превратить отработку сложного содержания в захватывающий процесс. Для одарённых школьников это шанс проявить и академическую сильную сторону, и лидерские качества, и быстроту мышления в условиях соревновательной, но психологически безопасной среды. Игровые форматы помогают им тренировать коммуникативные умения, отрабатывать навык аргументации и взаимодействия в команде.

4.5. Информационно-коммуникационные и цифровые технологии

Информационно-коммуникационные технологии занимают особое место среди современных средств обучения химии. Презентации, анимации, интерактивные модели и видеодемонстрации помогают «увидеть» то, что недоступно непосредственному наблюдению: строение вещества, микромир, механизмы реакций, динамику процессов. Это облегчает понимание абстрактных понятий и связей в химии [4, с. 31–32]. Виртуальные лаборатории и компьютерные симуляторы позволяют моделировать эксперименты, которые по тем или иным при-

чинам трудно провести в школе (опасность, дефицит оборудования, ограничение по времени) [5, с. 19–20].

Онлайн-платформы, электронные учебники, системы тестирования и автоматизированного контроля используются для организации самостоятельной работы и индивидуальных траекторий обучения, обеспечивают быструю обратную связь и помогают учителю отслеживать продвижение учащихся [5, с. 22–23]. В исследованиях подчёркивается, что цифровая трансформация химического образования предполагает не только использование готовых ресурсов, но и внедрение новых инструментов: систем на основе искусственного интеллекта, адаптивных платформ, виртуальной и дополненной реальности. Эти средства рассматриваются как перспективный путь повышения мотивации и качества усвоения учебного материала [5, с. 18–19].

Для одарённых школьников ИКТ и цифровые технологии особенно важны тем, что расширяют их познавательное пространство: дают доступ к задачам повышенной сложности, олимпиадным тренажёрам, специализированным базам данных и научным публикациям, позволяют выстраивать индивидуальный темп и стиль работы. При грамотном использовании цифровые инструменты становятся для таких учащихся не просто «дополнительной опцией», а реальным ресурсом для углублённого и опережающего обучения [4, с. 32; 5, с. 22–23].

5. Потенциал современных образовательных технологий для развития химической одарённости школьников

5.1. Личностно-ориентированные и дифференцированные технологии

Личностно-ориентированные и дифференцированные технологии дают учителю возможность действительно учитывать особенности конкретного ребёнка: его интересы, уровень подготовки, темп работы. В отношении химически одарённых школьников это особенно важно. В рамках таких подходов выстраиваются индивидуальные образовательные маршруты: часть учеников раньше осваивает отдельные темы, работает с более сложными задачами, получает доступ к расширенному экспериментальному материалу [1, с. 80–100]. Такая организация обучения помогает продвигаться вперёд в собственном темпе, не «застывать» на уже усвоенном материале и поддерживать устойчивый интерес к предмету.

Дифференциация заданий по уровню сложности, степени самостоятельности, типу познавательной деятельности способствует развитию познавательной активности, ответственности за результат и навыков саморегуляции. Для одарённых школьников важен сам опыт выбора: можно подобрать более сложный уровень задач, выбрать формат представления результата (доклад, стендовый доклад, видеопрезентация), решить, в каком проекте или исследовательском мероприятии участвовать. Это усиливает их субъектную позицию в обучении химии и позволяет почувствовать себя не только «хорошим учеником», но и активным участником

собственного образовательного пути [1, с. 100–139].

5.2. Проектные технологии как средство развития исследовательского и творческого потенциала

Проектные технологии создают благоприятные условия для одновременного развития интеллектуальных и творческих способностей химически одарённых учащихся. Работая над учебными или учебно-исследовательскими проектами, школьники учатся видеть проблему, формулировать цель и задачи, планировать этапы работы, выбирать методы, собирать и анализировать данные, представлять результаты в форме, понятной другим. По структуре такая деятельность близка к реальной научной практике и требует опоры на знания из разных разделов химии и смежных дисциплин.

Для одарённых школьников участие в проектах особенно значимо, поскольку даёт возможность выйти за рамки учебника и реализовать собственные интересы: выбрать тему, которая действительно «цепляет», попробовать себя в роли исследователя. Проектная деятельность помогает формировать важные компоненты химической одарённости: умение увидеть проблему в знакомой ситуации, предлагать нестандартные решения, конструировать эксперимент, критически относиться к полученным данным и делать аргументированные выводы [1, с. 58–79]. Дополнительным эффектом становится развитие коммуникативных навыков и опыта публичных выступлений, что важно для участия в конференциях, конкурсах, олимпиадах [2, с. 122–123].

5.3. Исследовательские технологии и учебное исследование

Исследовательские технологии ориентированы на включение школьников в полный цикл учебного исследования, максимально приближенный к профессиональной научной деятельности. Урок или внеурочное занятие строится вокруг исследовательской задачи, для решения которой требуется сформулировать гипотезу, спланировать эксперимент, подобрать приборы и реактивы, провести серию опытов, обработать и интерпретировать результаты. Для одарённых учащихся такая форма работы является естественной средой развития: она находит опору в их интересе к эксперименту, стремлении к самостоятельному поиску и готовности брать на себя ответственность за итог.

Регулярное участие в учебно-исследовательских проектах развивает у химически одарённых школьников целый спектр ключевых способностей: аналитическое и критическое мышление, гибкость и вариативность мышления, устойчивое внимание, точность и аккуратность в эксперименте, умение работать с различными источниками информации. На этой основе формируется готовность к более серьёзным исследованиям, в том числе совместно с вузами и научными организациями, а также к участию в конкурсах и олимпиадах исследовательского типа [1, с. 140–185].

5.4. Интерактивные и игровые технологии как средство развития мотивации и коммуникативных умений

Интерактивные и игровые технологии заметно влияют на мотивационную и коммуникативную составляющие химической одарённости [4, с. 31]. Участие в дискуссиях, ролевых и деловых играх, совместном решении кейсов требует от одарённого школьника не только хороших предметных знаний, но и умения ясно формулировать и отстаивать свою позицию, слушать и учитывать аргументы других, вести конструктивную научную полемику. Это особенно важно для тех учащихся, у которых высокая познавательная активность сочетается с трудностями в общении или неуверенностью в себе.

Игровые форматы — турниры, брейн-ринги, командные соревнования — создают ситуацию интеллектуального соревнования, в которой ученик сталкивается и с победами, и с неудачами. Это помогает выработать более зрелое, конструктивное отношение к результату, развивать стрессоустойчивость и навыки саморегуляции. Для химически одарённых школьников игровая среда нередко становится пространством, где они могут открыто проявить свои сильные стороны и получить позитивное признание от сверстников, а не только от учителя..

5.5. Информационно-коммуникационные и цифровые технологии как инструмент индивидуализации и расширения познавательного пространства

Информационно-коммуникационные и цифровые технологии обладают значительным потенциалом в работе с химически одарёнными школьниками, прежде всего как средство индивидуализации обучения и расширения их познавательного пространства [4, с. 30–32; 5, с. 17–18]. Доступ к электронным образовательным ресурсам, виртуальным лабораториям, специализированным сайтам и базам данных позволяет ученикам самостоятельно выходить за рамки школьной программы, знакомиться с современными научными результатами и сложными задачами, ориентированными на старший уровень и олимпиадную подготовку [4, с. 32].

Системы электронного тестирования и адаптивные обучающие платформы дают возможность подстраивать темп и сложность заданий под индивидуальные возможности учащегося, при этом обеспечивая оперативную обратную связь [5, с. 22–23]. Цифровые средства визуализации и моделирования помогают освоить сложные теоретические конструкции — строение вещества, механизмы реакций, энергетические диаграммы — и способствуют развитию пространственного и образно-символического мышления, важного для успешного изучения химии [5, с. 19–20]. Перспективным направлением считается использование технологий искусственного интеллекта для подбора индивидуальных образовательных траекторий, рекомендаций по дополнительным заданиям, анализа типичных ошибок. При грамотной педаго-

гической настройке такие инструменты могут заметно повысить эффективность работы с одарёнными школьниками [5, с. 27–29].

6. Условия и ограничения внедрения современных технологий в работу с одарёнными по химии

6.1. Организационно-педагогические условия

Чтобы современные образовательные технологии действительно работали на развитие химической одарённости, а не оставались набором разрозненных инициатив, необходима целенаправленная поддержка со стороны школы и администрации [1, с. 4–11; 2, с. 120]. Важную роль играет вариативный учебный план, который позволяет вводить углублённые и элективные курсы по химии, а также выделять время для внеурочной исследовательской и проектной деятельности [1, с. 100–139]. Без таких организационных решений даже самые продуманные методические идеи трудно реализовать.

Отдельного внимания требует подготовка и профессиональное развитие учителя. Эффективная работа с одарёнными по химии и одновременное использование современных технологий требуют от педагога не только предметных и методических знаний, но и готовности постоянно обновлять свои подходы [2, с. 121–124]. Для этого необходимы продуманные программы повышения квалификации, методические семинары, стажировки, в рамках которых учителя осваивают проектные, исследовательские, интерактивные и цифровые технологии именно в контексте работы с одарёнными школьниками [2, с. 124–125]. Важным условием остаётся и материально-техническая база: оборудованный кабинет химии, доступ к современным реактивам и приборам, использование цифровых ресурсов и стабильный Интернет [5, с. 27–28].

6.2. Методические риски и ограничения

Внедрение современных технологий в работу с одарёнными по химии, помимо очевидных плюсов, связано и с рядом методических рисков. Один из них — опасность подмены глубокого содержательного развития внешне эффектной формой. Яркие презентации, анимации и цифровые сервисы сами по себе не гарантируют роста химической одарённости и при неудачном использовании могут приводить к поверхностному усвоению материала. Существует и риск перегрузки учителя, который одновременно должен осваивать новые инструменты, разрабатывать дифференцированные задания и поддерживать высокий уровень организации экспериментальной работы [2, с. 121–124].

Ещё одно ограничение связано с различиями в ресурсах между школами. Недостаток лабораторного оборудования, слабая цифровая инфраструктура, отсутствие административной поддержки серьёзно осложняют реализацию даже хорошо продуманных методик [5, с. 27–28]. Кроме того, не все одарённые учащиеся одинаково комфортно чувствуют себя в условиях интенсивной групповой работы и публичных выступлений. Это требует гибкого сочетания разных технологий, возможности чередовать командные и индивидуальные форматы

и строить действительно индивидуально-ориентированный подход.

6.3. Перспективные направления совершенствования практики

В качестве перспективного направления развития практики работы с химически одарёнными школьниками можно выделить создание адаптивных программ и модулей, специально на них ориентированных. В таких программах современные технологии выступают не как самоцель, а как средство углубления содержания и расширения исследовательских возможностей: от виртуальных лабораторий и онлайн-курсов до индивидуальных исследовательских треков [1, с. 80–100]. Важным шагом становится дальнейшая цифровизация сопровождения одарённых: использование электронных портфолио, онлайн-платформ для проектной и исследовательской деятельности, интеллектуальных систем рекомендаций, основанных на анализе учебных результатов [5, с. 27–29].

Большой потенциал имеет развитие сетевых форм сотрудничества школ, вузов и научных организаций. Такие партнёрства позволяют организовывать совместные проекты, виртуальные лаборатории, олимпиады и конференции, в которых школьники выходят за рамки одной образовательной организации [1, с. 140–185; 2, с. 124]. При этом выигрывают все участники: школы получают доступ к современным ресурсам и экспертам, вузы — мотивированных абитуриентов с опытом реальной исследовательской деятельности, а одарённые учащиеся — более широкие возможности для развития своих способностей.

7. Заключение

Обзор показал, что современные образовательные технологии могут серьёзно помочь в развитии химической одарённости школьников, но сами по себе они не решают задачу. Их потенциал раскрывается только тогда, когда работа с одарёнными встроена в продуманную методическую систему, где ясно обозначены цели, содержание, формы и способы оценивания результатов [1, с. 4–11]. Личностно-ориентированные и дифференцированные подходы дают возможность учитывать реальные различия между учениками и их образовательные запросы [1, с. 80–100]; проектные и исследовательские технологии создают пространство для самостоятельного поиска и проб в роли исследователя [1, с. 58–79]; интерактивные и игровые форматы поддерживают интерес к предмету и развивают коммуникативные навыки [4, с. 31]; цифровые ресурсы, включая решения на основе искусственного интеллекта, расширяют возможности индивидуализации обучения и доступа к более сложному содержанию [5, с. 22–24].

При этом внедрение таких технологий в реальную школьную практику связано с рядом требований и ограничений. Нужны подготовленные учителя, готовые работать с одарёнными и осмысленно использовать новые инструменты, необходима соответствующая материально-техническая база и доступ к цифровым ресурсам. Важно выстраивать систему диагностики и сопровождения одарённых школьников и при этом не допускать формализации работы и перегрузки как детей, так и педагогов [2, с. 123–125]. Полученные в обзоре выводы могут быть использованы при разработке программ работы с химически одарёнными учащимися, создании элективных курсов, исследовательских и проектных модулей, а также в системе повышения квалификации учителей химии [1, с. 4–11; 2, с. 120–125].

Дальнейшие исследования представляются важными в двух направлениях. Во-первых, требуется эмпирически оценить, какие именно технологии и в каких сочетаниях наиболее эффективно развивают отдельные компоненты химической одарённости. Во-вторых, необходимо глубже изучить возможности использования технологий искусственного интеллекта и новых форм цифровой среды для индивидуального сопровождения одарённых школьников, чтобы понять не только их потенциал, но и реальные границы и риски такого применения [5, с. 27–29].

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USING ARTIFICIAL INTELLIGENCE IN DEVELOPING STUDENTS' ACADEMIC WRITING COMPETENCE

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ИСПОЛЬЗОВАНИЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ФОРМИРОВАНИИ
АКАДЕМИЧЕСКОЙ ПИСЬМЕННОЙ КОМПЕТЕНЦИИ СТУДЕНТОВ

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Abstract

This article examines the integration of generative artificial intelligence technologies into the development of academic writing competence in students at higher education institutions. Based on an analysis of current empirical research (2023–2025), the article identifies the main areas of AI tool use in academic writing, their effectiveness in developing various components of writing competence, and the factors mediating the success of such interactions. Particular attention is paid to the concept of AI literacy as a key determinant of productive collaboration between humans and artificial intelligence in the educational process. The article also examines the ethical aspects of using generative models and proposes pedagogical conditions that ensure a balance between technological support and the development of student autonomy as a writing subject.

Аннотация

В статье рассматривается проблематика интеграции технологий генеративного искусственного интеллекта в процесс формирования академической письменной компетенции студентов высших учебных заведений. На основе анализа современных эмпирических исследований (2023–2025 гг.) выявляются основные направления использования ИИ-инструментов в академическом письме, их эффективность в развитии различных компонентов письменной компетенции, а также факторы, опосредующие успешность такого взаимодействия. Особое внимание уделяется концепции ИИ-грамотности как ключевой детерминанты продуктивного сотрудничества человека и искусственного интеллекта в образовательном процессе. В статье также рассматриваются этические аспекты использования генеративных моделей и предлагаются педагогические условия, обеспечивающие баланс между технологической поддержкой и развитием автономии студента как пишущего субъекта.

Keywords: academic writing, writing competence, generative artificial intelligence, AI literacy, higher education, feedback, instructional design.

Ключевые слова: академическое письмо, письменная компетенция, генеративный искусственный интеллект, ИИ-грамотность, высшее образование, обратная связь, педагогический дизайн.

1. Введение

Академическое письмо представляет собой сложный вид интеллектуальной деятельности, требующий координации множества когнитивных навыков: управления ресурсами памяти, решения проблем, целеполагания, а также демонстрации критического мышления и предметного знания. В современном высшем образовании письменная компетенция рассматривается не просто как техническое умение продуцировать текст, но как способ участия в академическом сообществе, инструмент конструирования знания и развития сложных форм мышления.

Стремительное развитие технологий генеративного искусственного интеллекта (ИИ) в 2022–2025 годах коренным образом трансформировало ландшафт академического письма. Языковые модели, такие как ChatGPT, способные генерировать человекоподобный текст и предоставлять обратную связь в реальном времени, стали неотъемлемой

частью образовательной практики. Согласно исследованию Intelligent (2024), 37% студентов в США и 53% в Великобритании используют ИИ для выполнения учебных заданий, причем две основные области применения — помощь в написании текстов (69%) и проведение исследований (67%).

Однако массовое внедрение ИИ-инструментов опережает их осмысление с педагогической точки зрения. Перед исследователями и практиками встают принципиальные вопросы: как использование ИИ влияет на формирование письменной компетенции в долгосрочной перспективе? Какие модели взаимодействия студента с ИИ оказываются наиболее продуктивными? Как обеспечить баланс между технологической поддержкой и развитием автономного письма? Данная статья предлагает анализ современного состояния проблемы на основе рецензируемых эмпирических исследований последних двух лет.

2. Теоретические основания исследования

2.1 Академическое письмо как компетенция

Академическое письмо в современном понимании выходит за рамки владения грамматикой и орфографией. Оно включает способность выстраивать аргументацию, интегрировать источники, следовать конвенциям дисциплинарного дискурса, учитывать ожидания академической аудитории и демонстрировать критическую позицию по отношению к собственному тексту и текстам других авторов.

Паради (2010) подчеркивает неразрывную связь академического чтения и письма: понимание сложных дисциплинарных текстов и продуцирование собственных научных текстов представляют собой взаимообусловленные процессы, формирующие академическую грамотность в целом. В условиях цифровой трансформации образования эти процессы все чаще опосредуются технологиями, включая инструменты на основе ИИ.

2.2 Эволюция инструментов автоматической оценки письма

История использования технологий для поддержки письма насчитывает несколько десятилетий. Традиционные инструменты автоматической оценки письма (Automated Writing Evaluation — AWE), такие как Criterion, e-rater и Grammarly, фокусировались преимущественно на поверхностных аспектах текста: грамматике, орфографии, пунктуации. Многочисленные исследования подтверждают их эффективность в снижении количества ошибок, однако указывают на неспособность таких систем работать с высшими порядками письма: аргументацией, организацией текста, содержательной глубиной. Ситуация качественно изменилась с появлением генеративных моделей, обладающих способностью к пониманию контекста и порождению связных текстов. В отличие от предшественников, ChatGPT и аналогичные системы могут предоставлять обратную связь не только на уровне лексики и грамматики, но и в отношении структуры, логики изложения и соответствия академическим конвенциям.

3. Основные направления использования ИИ в академическом письме Анализ современных исследований позволяет выделить несколько ключевых направлений применения ИИ-инструментов в процессе формирования письменной компетенции.

3.1 Поддержка процессов порождения текста

Генеративные модели активно используются студентами на этапе инкубации замысла и первичного продуцирования текста. Малик с соавторами (2023) показывают, что ИИ может выступать в роли «когнитивного партнера», помогая генерировать идеи, преодолевать «боязнь чистой страницы» и создавать первоначальные наброски, которые студент впоследствии дорабатывает. Важно подчеркнуть, что продуктивность такого взаимодействия зависит от характера использования ИИ. Нгуен с коллегами (2024) выявили два принципиально различных паттерна: при итеративном взаимодействии студенты последовательно уточняют запросы, критически

анализируют сгенерированное содержание и интегрируют его в собственную работу, что ведет к повышению качества итогового текста. При линейном использовании студенты копируют сгенерированные фрагменты без существенной переработки, что коррелирует с более низкими результатами.

3.2 Обратная связь и оценивание

Одно из наиболее перспективных направлений использования ИИ — автоматизированная обратная связь на различных этапах письменной работы. Мейер с соавторами (2024) обнаружили, что студенты, получавшие обратную связь от ChatGPT, продемонстрировали большее улучшение письменных навыков по сравнению с контрольной группой, не получавшей обратной связи. Особый интерес представляют результаты исследования Ши с коллегами (2025), показавшие, что студенты, использовавшие ChatGPT, превосходили по итоговым оценкам за письменные работы студентов, применявших традиционную AWE-систему Pigai. Это свидетельствует о качестве новых возможностях генеративных моделей в сравнении с предшествующим поколением инструментов.

В исследовании Бархударян и др. (2025) изучалось влияние различных форматов обратной связи на академическое письмо магистрантов. Группа, получавшая только обратную связь от ChatGPT, показала значимые улучшения в механике текста, тоне, грамматике и соблюдении формата APA, однако менее выраженную динамику в организации текста и незначимые изменения в содержательном компоненте. Группа, получавшая комбинированную обратную связь (ChatGPT + преподаватель), продемонстрировала улучшения по всем оцениваемым параметрам.

3.3 Метакогнитивная поддержка

Инновационные ИИ-инструменты начинают использоваться не только для продуцирования текста или обратной связи, но и для развития метакогнитивных навыков пишущего. Проект REVISAGE Analytics, разработанный в Сиань-Цзяотун-Ливерпульском университете, представляет собой систему, помогающую студентам выстраивать рефлексию собственного письменного процесса. Инструмент визуализирует структуру аргументации, логику развертывания тезисов и функциональную нагрузку отдельных абзацев, делая «невидимые» аспекты письма доступными для анализа самим студентом. Разработчики подчеркивают принципиальное отличие своего подхода от традиционных корректоров: REVISAGE не исправляет текст за студента, но создает условия для понимания логики собственного письма.

3.4 Поддержка студентов с различным языковым бэкграундом

Отдельного внимания заслуживает потенциал ИИ в выравнивании возможностей студентов, для которых английский язык не является родным. Исследование Шаффер и др. (2025) показало, что при использовании генеративного ИИ в сочетании с целенаправленным обучением время выполнения письменных заданий сократилось на 56,7%, а сред-

ная оценка повысилась с А- до А+. При этом улучшение качества письма было более выраженным у студентов, не являющихся носителями английского языка, что указывает на потенциальный «выравнивающий эффект» технологии.

4. Роль ИИ-грамотности в формировании письменной компетенции

4.1 Концептуализация понятия

Стремительное внедрение генеративных моделей в образовательную практику актуализировало вопрос о формировании особого типа грамотности — ИИграмотности (AI literacy). Ли с соавторами (2023) определяют ИИ-грамотность как критическое понимание принципов работы ИИ (включая осознание ограничений, связанных с «черным ящиком» алгоритмов), способность к эффективному взаимодействию и сотрудничеству с ИИ, а также умение использовать ИИ как инструмент для решения разнообразных задач.

Систематический обзор Ромеро-Родригес и др. (2025) выявил несколько валидированных инструментов измерения ИИ-грамотности, включая шкалу AILSCCS, оценивающую четыре ключевых измерения: осведомленность о работе ИИ, критическое отношение к результатам, способность к взаимодействию и этическое понимание технологии.

4.2 Эмпирические данные о связи ИИ-грамотности и письменной компетенции Принципиально важные результаты получены в исследовании Джин с соавторами (2025), введшими понятие «разрыва агентности» (agency gap). Ученые обнаружили, что уровень ИИ-грамотности предсказывает успешность независимого письма (без поддержки ИИ) только в условиях, требующих активной мобилизации студентом собственных стратегий. При этом медиационный анализ показал отсутствие косвенного эффекта через успешность выполнения задания с ИИ, что позволяет рассматривать ИИграмотность как прямую, задачно-общую компетенцию, а не как прокси предметного знания.

В исследовании Ким и др. (2026) с помощью эпистемического сетевого анализа были выявлены различные паттерны взаимодействия студентов с ИИ в зависимости от уровня их ИИ-грамотности. Студенты с высоким уровнем грамотности демонстрировали коллаборативный подход: они активно принимали предложения ИИ, вовлекали его в метакогнитивные активности (планирование, оценка собственной работы) и использовали как партнера по письменной деятельности. Студенты с низким уровнем грамотности взаимодействовали с ИИ минимально, предпочитая генерировать идеи и оценивать текст самостоятельно, что парадоксальным образом приводило к более низким результатам по всем критериям оценки (содержание, структура, выражение).

4.3 ИИ-грамотность как фактор преодоления ограничений технологии Осознание ограничений генеративных моделей представляет собой важнейший компонент ИИ-грамотности. Исследователи указывают на такие проблемы, как склонность ИИ к «галлюцинациям» — порождению уверенных, но

фактически неверных утверждений, включая создание несуществующих научных источников.

Другое ограничение — неспособность ИИ сгениерировать о выходе задачи за пределы его компетенции: модель сохраняет уверенность даже при генерации ошибочных ответов.

В исследовании Делль'Акка с соавторами (2023) консультанты, использовавшие ChatGPT для задач, выходящих за границы его возможностей, предлагали корректные решения на 19% реже, чем консультанты без доступа к ИИ. Это подчеркивает критическую важность формирования у студентов способности различать задачи, которые ИИ может решить продуктивно, и те, где его использование контрпродуктивно.

5. Педагогические условия эффективной интеграции ИИ

5.1 От запретов к формированию компетенций

Реакция академического сообщества на распространение генеративных моделей варьировалась от полного запрета до неограниченного принятия. Исследователи все более сходятся во мнении, что запретительные стратегии неэффективны и контрпродуктивны. Как отмечает Селун (2023), важно сместить фокус с предотвращения «нечестного использования» на формирование у студентов способности к критическому, рефлексивному и этичному взаимодействию с ИИ.

5.2 Интеграция ИИ-грамотности в учебные программы

Шаффер с соавторами (2025) подчеркивают, что простое предоставление доступа к ИИ-инструментам без целенаправленного обучения их эффективному использованию не гарантирует улучшения образовательных результатов. В их исследовании все студенты проходили специальное обучение работе с генеративным ИИ до начала выполнения заданий, что рассматривалось как необходимое условие продуктивного использования технологии.

Ключевыми элементами такого обучения должны стать: понимание принципов работы языковых моделей и их ограничений; освоение техник эффективного промптинга; формирование навыков критической оценки сгенерированного контента; развитие способности к интеграции результатов работы ИИ в собственный текст с сохранением авторского голоса.

5.3 Баланс поддержки и автономии

Важнейшая педагогическая задача — обеспечение баланса между использованием ИИ как инструмента поддержки и развитием автономной письменной компетенции студента. Исследование Джин с соавторами (2025) демонстрирует, что характер взаимодействия студента с ИИ может по-разному влиять на способность к независимому письму. В условиях реактивной поддержки (когда студент сам инициирует обращение к ИИ) значимым фактором успеха становится ИИ-грамотность. В условиях проактивной поддержки (когда система сама предлагает помощь) различия в успешности, связанные с уровнем грамотности, нивелируются.

Это указывает на возможность педагогического дизайна, учитывающего индивидуальные особенности студентов: для обучающихся с недостаточно сформированной ИИ-грамотностью целесообразна более структурированная поддержка и постепенное ослабление «скаффолдинга» по мере развития компетенций.

6. Дискуссия и перспективы исследований

6.1 Противоречия и нерешенные вопросы

Представленный анализ выявляет ряд противоречий, требующих дальнейшего исследования. Первое противоречие связано с различной эффективностью ИИ для разных компонентов письменной компетенции. Данные Бархударян и др. (2025) показывают, что ИИ-обратная связь наиболее эффективна для поверхностных аспектов письма (грамматика, механика, форматирование) и менее эффективна для содержания и организации текста. Это ставит вопрос о том, в какой степени ИИ может способствовать развитию высших порядков письменной компетенции и не создает ли его использование риска «застывания» на технических аспектах в ущерб содержательным.

Второе противоречие связано с долгосрочными эффектами использования ИИ. Подавляющее большинство существующих исследований фиксируют краткосрочные улучшения, однако практически отсутствуют лонгитюдные исследования, отслеживающие траектории развития письменной компетенции студентов, регулярно использующих ИИ-инструменты.

Третье противоречие касается дисциплинарной специфики. Существующие исследования проводятся преимущественно в контексте изучения английского как иностранного или общего академического письма. Вопрос о том, как различается эффективность ИИ-поддержки при освоении письменных практик в разных дисциплинарных сообществах (естественные науки vs. гуманитарные дисциплины), остается открытым.

6.2 Этические аспекты

Этическая проблематика использования ИИ в академическом письме затрагивает несколько измерений. Первое — проблема авторства и оригинальности. Когда текст создается в коллаборации человека и ИИ, как определить меру авторского вклада и границы допустимого использования? Второе — проблема справедливости. Создает ли доступ к платным версиям языковых моделей новые формы неравенства? Третье — проблема прозрачности. Должны ли студенты декларировать использование ИИ, и если да, то в каком формате?

В систематическом обзоре Ромеро-Родригес и др. (2025) этические вопросы выделены в отдельную тематическую область, требующую как исследовательского внимания, так и нормативного регулирования на уровне образовательных институций.

6.3 Направления будущих исследований

Перспективные направления исследований включают: изучение долгосрочных эффектов использования ИИ на развитие письменной компетен-

ции; разработку и валидацию педагогических моделей интеграции ИИ, дифференцированных по дисциплинам и уровням подготовки; исследование возможностей ИИ для поддержки академического чтения как неразрывно связанного с письмом процесса; изучение влияния различных интерфейсов и режимов взаимодействия на качество письменного продукта и опыт пишущего.

7. Заключение

Интеграция технологий генеративного искусственного интеллекта в процесс формирования академической письменной компетенции студентов представляет собой не временный тренд, а долгосрочную трансформацию образовательной реальности. Современные исследования свидетельствуют о значительном потенциале ИИ-инструментов для поддержки различных аспектов письма — от генерации идей и преодоления писательских блоков до получения персонализированной обратной связи и развития метакогнитивных навыков. Ключевым фактором, опосредующим успешность использования ИИ, выступает ИИ-грамотность студентов — интегративная способность к критическому, рефлексивному и продуктивному взаимодействию с технологией. Формирование этой грамотности должно стать не дополнением к существующим образовательным программам, но их неотъемлемым компонентом. Эффективная педагогическая интеграция ИИ предполагает отказ от запретительной логики в пользу логики развития компетенций. Задача педагогов заключается не в том, чтобы оградить студентов от использования ИИ, но в том, чтобы создать условия, в которых технология выступает инструментом развития автономной письменной компетенции, а не ее суррогатом.

Дальнейшие исследования должны быть направлены на изучение долгосрочных эффектов ИИ-опосредованного письма, дисциплинарной специфики использования технологии и разработку валидных методов оценки письменной компетенции в условиях, когда граница между человеческим и машинным авторством становится все более подвижной.

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PROBLEMS IN THE ORGANIZATION AND MODERN OPPORTUNITIES FOR THE DEVELOPMENT OF PROJECT-BASED LEARNING (ON THE EXAMPLE OF CHEMISTRY)**Sapakova A.***Candidate of Biological Sciences, Associate Professor,
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Department of chemistry and biology,
«Shakarim University of Semey»*<https://doi.org/10.5281/zenodo.19573253>**Abstract**

This article examines the pedagogical features of organizing chemistry teaching based on project-based learning. Project-based learning is considered an effective educational approach that promotes students' research, analytical, and practical skills. Since chemistry involves experimental activities, laboratory work, and scientific modeling, project-based learning helps increase students' motivation and fosters scientific thinking. The paper analyzes the main pedagogical challenges, organizational issues, and development prospects related to the implementation of project-based learning in chemistry education.

Keywords: project-based learning, chemistry teaching methodology, research skills, educational project, practical learning, STEM education.

Introduction

In the modern education system, one of the most important pedagogical directions is the justification of the learning process of active cognitive activity of the student. In this sense, Project-Based Learning is considered as an effective pedagogical technology that allows students to develop their research, creative and analytical abilities [1, p. 15]. This approach is not limited to the theoretical assimilation of educational material by students, but is aimed at applying knowledge by solving specific practical tasks.

The subject of chemistry is a science that is experimental and exploratory in content. Laboratory experiments, chemical models and scientific observations occupy an important place in the teaching of chemistry. Therefore, the method of project-based learning is naturally combined with the content of the chemistry subject and creates conditions for the development of scientific thinking of students [2, p. 45].

During project-based learning, students study a specific scientific problem, collect information, conduct experiments, analyze the results and draw conclusions. This process allows students to develop critical thinking, independent decision-making, and teamwork skills [3, p. 45]. At the same time, the project method increases students' interest in the subject and strengthens their learning motivation.

At the same time, the application of project-based learning in chemistry creates certain pedagogical and organizational difficulties. Among them, issues such as lack of time, lack of laboratory equipment, and different levels of teacher training can be noted [4, p. 40]. These conditions require the search for new methodological approaches to the effective organization of project-based learning.

In this regard, identifying the problems of using the project method in teaching chemistry and substantiating the directions of its development is one of the urgent problems of modern pedagogical research.

Main part

Project - Based Learning is considered in modern pedagogy as one of the most effective methods aimed at developing active cognitive activity of students. This approach allows you to master the content of learning through practical tasks and contributes to the development of research, analytical and creative abilities of students [1, p. 18]. Especially in natural sciences, including chemistry, project learning is naturally combined with elements of scientific research. This is because Chemical Science is based on experimental activity, observation, modeling, and experimental proof.

Project-based learning in chemistry allows students not only to master ready-made information, but also to independently build knowledge through the study of a scientific problem. For example, project topics such as "determining the level of water pollution", "composition of household chemicals", "environmentally safe reactions" direct students to the experimental study of chemical phenomena. In the course of such work, students develop the skills of observing chemical reactions, analyzing the results and drawing scientific conclusions [2, p. 52].

In foreign educational practice, project-based learning is widely used as an important element of the STEM education system. In the education system of countries such as the USA, Finland, Germany, the project method is considered in close connection with research teaching in the teaching of Natural Sciences [3, p. 45]. In these countries, chemistry classes are often organized through experimental research, laboratory

work, and research projects. Students study specific scientific problems, conduct an experiment and present the results obtained in the form of a scientific presentation or research report.

The introduction of project-based learning technology in Kazakhstan's education system has been actively considered in recent years. The updated content of education is aimed at developing students' research skills. In this context, project work, laboratory experiments and practical tasks play an important role in Chemistry [4, p. 42]. However, as practice shows, in the process of Organizing Project-Based Training, certain difficulties are encountered. Among them, factors such as time limits, the size of the curriculum, insufficient laboratory equipment and a different level of methodological training of teachers can be noted.

One of the most important conditions for the effective organization of Project training in chemistry is the availability of a sufficient subject environment and material base. Chemistry classrooms, as a specially equipped laboratory space, allow you to organize the practical activities of students. Laboratory instruments, reagents, safety devices and demonstration equipment directly affect the quality performance of project work [5, p. 12]. If the chemistry room is equipped in accordance with laboratory requirements, students can implement their projects through experimental research. This contributes to the development of their scientific thinking and increased interest in the subject.

At the same time, the pedagogical role of the teacher in the organization of project-based learning is special. The teacher acts as an organizer and guide of the research process, and not just an informant. It helps

students determine the subject of research, guides the use of scientific methods, and supports the analysis of the results obtained [6, p. 25]. Training in this format allows you to develop independent cognitive activity of students.

The use of the project method in teaching chemistry creates conditions for the formation of a research culture of students, the practical application of subject knowledge and the development of a scientific worldview. However, for the full implementation of project-based learning, it is necessary to comprehensively develop such factors as the material base, methodological support and professional training of teachers [7, p. 35].

International and Kazakhstan experience in Organizing Project-based learning

Project-based learning technology has been widely used in many educational systems around the world. Especially in the teaching of Natural Sciences, this approach is considered one of the most effective methods aimed at the formation of students' research skills. In foreign practice, the teaching of chemistry is largely based on experimental activity, elements of scientific research and laboratory work. And in Kazakhstan, project-based learning technology has been actively implemented in recent years within the framework of the updated content of Education [1, p. 20; 2, p. 48].

The table below shows the main features of the application of the project method in the study of chemistry in the practice of Kazakhstan and abroad in comparison.

Table 1.

Organization of chemistry on the basis of Project Training: Experience of Kazakhstan and abroad

Indicators	Kazakhstan experience	Foreign experience
Training format	Project work is used in certain sections of the curriculum	Project learning is one of the main teaching approaches in many schools
Laboratory work	There is a limited supply of equipment in some schools	Laboratory experiments are organized on a regular basis
STEM integration	It has been introduced in recent years	STEM is the main element of the education system
The role of the teacher	Teacher guide and organizer	Teacher scientific supervisor and research coordinator
Research activities of students	Project work is often carried out at the subject level	In most cases, interdisciplinary research projects are implemented
Assessment system	Project work is often evaluated through a formative assessment	The result of the study, the presentation and the result of the experiment are evaluated comprehensively

As shown in the table, in the system of Foreign Education, Project-Based Learning has become a constant element of teaching chemistry. This approach is aimed at creating a culture of scientific research in students. Although the project method is actively being

implemented in Kazakhstan's practice, the material base and laboratory capabilities may still be limited in some schools. Therefore, it is important to improve the practical infrastructure for the development of project-based learning in chemistry.



Picture 1. Chemistry classrooms at school (school of the Republic of Kazakhstan on the right, school of Finland on the left)

One of the most important factors in the effective organization of project training in chemistry is the availability of specially equipped chemistry classrooms. Since chemistry is an experimental science, the research activity of students is largely carried out through laboratory work. The chemistry room must

have laboratory tools, reagents, safety equipment and demonstration equipment [3, p. 39].

In this regard, it is important to consider in comparison the possibilities of chemistry classrooms in the implementation of Project training.

Table 2.

Equipment level of the chemistry room and project-based learning opportunities		
Room position	Ability to organize project work	Example of projects
Fully equipped laboratory	The possibility of conducting an experimental study is high	Analysis of water composition, study of reaction rate
Medium equipped room	Organization of simple experiments and control work	Household chemicals research
Minimally equipped room	Theoretical or model projects	Environmental chemistry, models of chemical processes
Cabinet equipped with digital resources	Using virtual laboratories and simulations	Modeling of chemical reactions

As can be seen from the table, the material and technical condition of the chemistry room directly affects the content and format of Project training. In the case of a fully equipped laboratory, students can conduct real experiments, and in the case of limited resources, projects can be organized theoretical or model in nature. In recent years, virtual laboratories and digital simulations have also become important tools in project learning.

Implementation stages of Project-Based Learning in chemistry

The effective organization of project-based learning in chemistry requires a certain pedagogical consistency and periodization structure. Project activity is not a set of randomly organized tasks, it is a complex pedagogical process aimed at the gradual development of students' research skills. Therefore, the implementation of project-based learning is carried out through several interrelated stages. At each stage, the specific actions of the teacher and students are determined, and the purpose and results of the research work are gradually formed. Such a phased organization allows students to develop scientific thinking and apply chemical knowledge in practical terms.

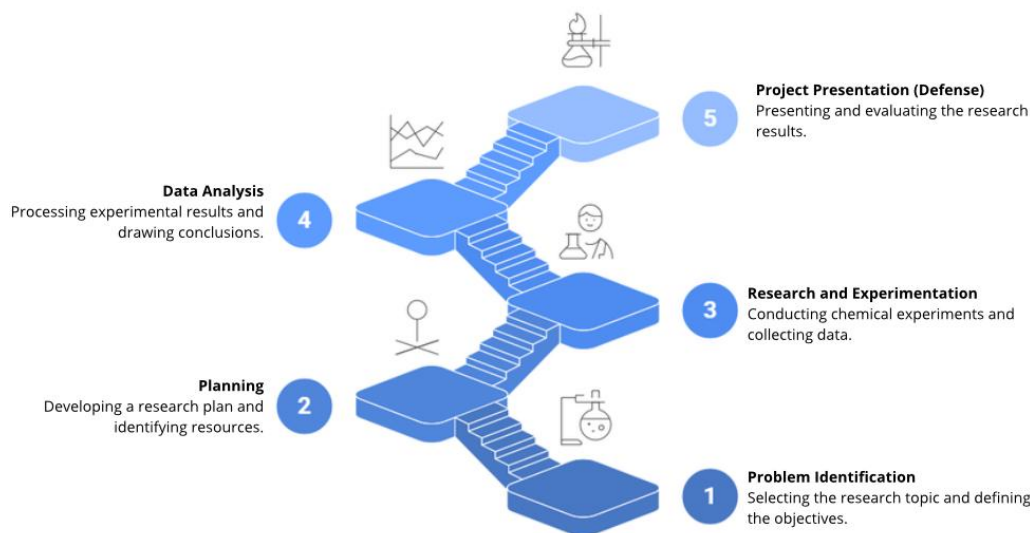


Diagram 1. Stages of implementation of Project-based learning in chemistry

The proposed phased model allows you to systematically organize project-based training in chemistry. Especially the period of experimental research plays an important role in the formation of a culture of scientific research of students. During the implementation of the project, students acquire such important skills as analyzing information, conducting experiments and drawing scientific conclusions. At the same time, the stage of project protection contributes to the development of students' communication skills and skills of evidence-based presentation of scientific results. Thus, Project training not only deepens the content of teaching chemistry, but also creates conditions for the development of the research and creative potential of students.

The main problems in the organization of teaching chemistry on the basis of Project training

The organization of chemistry on the basis of project-based learning is one of the pedagogical approaches that provides a great opportunity for the development of research and practical skills of students. However, in the process of full-fledged introduction of this method into educational practice, a number of organizational, material and methodological difficulties are encountered. These problems often arise due to the material and technical condition of schools, professional training of teachers and the peculiarities of the organization of the educational process.

First of all, one of the main problems in the organization of chemistry on the basis of Project training is insufficient laboratory equipment. In many schools, chemistry classrooms are not fully equipped according to laboratory requirements. The lack of laboratory utensils, measuring instruments, reagents and safety equipment limits the ability of students to conduct experimental work. As a result, project work often remains theoretical in nature, and the elements of experimental research are not fully realized.

At the same time, the issue of the material and technical base in rural schools requires special attention. Compared to urban schools, the quantity and quality of laboratory equipment is often limited in rural educational institutions. This situation creates inequality

in the organization of project-based learning and reduces students' ability to conduct experimental research.

Another important problem when carrying out design work in chemistry is the complete absence of reagents and precursors. Some chemicals are not used in school laboratories due to safety requirements or regulatory restrictions. This makes it difficult to carry out certain chemical reactions or research. As a result, some projects are implemented only at the level of theoretical modeling or demonstration experiments.

The lack of time in the organization of project training is also an important factor. Since the curriculum of chemistry is voluminous, teachers often have to give priority to mastering theoretical material. And for the organization of project work, additional time is required. The stages of conducting experiments, data analysis and project protection require certain time resources.

At the same time, the presence of methodological training of teachers on project-based learning technology at different levels also creates certain difficulties. The project method differs from traditional teaching approaches in that the teacher in this case acts not as an informant, but as an organizer and scientific supervisor of the research process. Therefore, an important role is played by the professional training of teachers in the organization of research work, the use of experimental methods and the assessment of project work.

Another important point is compliance with safety requirements. In the process of conducting chemical experiments, safety techniques are of particular importance. In some schools, insufficient safety equipment or lack of special equipment for laboratory work force the restriction of experimental work.

The problems encountered in the process of organizing chemistry on the basis of project training are largely related to the material base, methodological support and organizational factors. The solution of these problems indicates the need to provide chemistry classrooms with modern equipment, increase the professional training of teachers and develop methodological resources for project training.

Conclusion

Project-based learning is an effective pedagogical approach that promotes the development of students' research, analytical, and creative abilities in chemistry education. The experimental nature of chemistry naturally aligns with project-based learning, fostering scientific thinking and practical application of knowledge.

In the process of performing project work, students acquire such important skills as studying a scientific problem, analyzing information, conducting an experiment and drawing conclusions based on the results obtained. At the same time, this approach increases students' interest in the subject and contributes to the development of their ability to work independently, cooperate in groups and present research results.

At the same time, in the process of organizing project training in chemistry, there are a number of difficulties. These include insufficient laboratory equipment, limited reagents and necessary materials, time constraints of the curriculum, and varying levels of methodological training of teachers. Especially in rural schools, the problem of the material and technical base can create certain obstacles to the full implementation of project work.

In this regard, for the effective development of project-based learning in chemistry, it is important to improve the material and technical base of schools, provide chemistry classrooms with the necessary laboratory equipment, improve the professional skills of

teachers and introduce digital laboratories and virtual simulations into the educational process.

Overall, project-based learning significantly enriches chemistry education and contributes to the development of students' scientific worldview and research culture.

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PHYSICAL SCIENCES

PRE-BREAKDOWN CURRENTS IN DIELECTRIC MATERIALS DURING ANODE ELECTRIC BREAKDOWN

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Abstract

The structure of pre-breakdown current in samples of crystalline NaCl, glass, polyethylene, water and transformer oil is considered. The primary breakdown current is caused by the mechanism of free electron generation through interatomic cascade Auger transitions in the valence band of the dielectric. The secondary current is associated with the movement of ions in the gas phase of the channel. The mechanisms of formation of primary and secondary breakdown currents are common in solid and liquid dielectric materials.

Keywords: pre-breakdown current, electrical breakdown, breakdown mechanism

Introduction

Electrical breakdown is characterized by a loss of electrical strength and the destruction of the dielectric. Research into the electrical breakdown process in insulating materials helps improve the power and reliability of high-voltage pulse power plants.

High breakdown channel velocities (10^5 - 10^8 cm/s) and low channel diameters (1-10 μ m) create significant difficulties in the experimental study of the breakdown process. Direct studies of breakdown parameters include measurements of the conduction current [1-5], the velocity of movement of the breakdown channel front [1-9] and the mass composition of the gas phase [10, 11]. In experiments, recording pre-breakdown currents at the voltage pulse front is associated with the need to use bridge measurement circuits to compensate for capacitive recharge currents [1, 2, 4]. Alternatively, the pre-breakdown current structure can be distinguished against the background of the discharge curve of the electrical circuit.

Electrical breakdown from the anode (anodic breakdown) in solid [12-22] and liquid dielectrics [23-26] is satisfactorily described by the mechanism of cascade Auger transitions in the valence band of the dielectric. The appearance, movement, and orientation of the electrical breakdown channel are determined taking into account data on the crystal-chemical and energy structure of the substance.

The application of the concept of the band structure of a substance implies the presence of short-range and long-range order in the crystal lattice of a sample. Long-range order ensures the band nature of carrier motion in a crystal, in contrast to the hopping nature in amorphous substances. Short-range order plays a major role in determining the energy spectrum of a material [27]. The quasi-crystalline structure of solid and liquid organic dielectrics arises from the ordering of long molecules, when the molecules are located more or less

parallel to each other [28]. In this case, the energy levels of the highest occupied molecular orbital (HOMO) correspond to the upper edge of the valence band W_v , and the lowest unoccupied molecular orbital (LUMO) correspond to the lower edge of the conduction band W_c . The highest occupied molecular orbital HOMO and the lowest unoccupied LUMO are separated by a band gap [28].

According to [12-16], the conduction current is caused by the mechanism of free electron generation via interatomic Auger transitions in the valence band of the dielectric. Carrier recombination results in heating and the formation of a gas phase in the breakdown channel. Secondary processes are associated with the destruction of the channel surface by bombardment with accelerated ions in a strong non-uniform field and the impact multiplication of ions during collisions with conglomerates of atoms of the substance in the region of its gas phase. The movement of ions creates a secondary breakdown current. The electrical parameters of the currents in samples of single-crystal NaCl and liquid water are presented in [22, 25, 26].

In this paper, the processes of formation of primary and secondary currents of anodic electrical breakdown are considered in a wider range of dielectric materials.

Model of electrical breakdown in crystalline NaCl

Generation of free charge carriers

The diagram of energy bands in the contact region of a metal electrode and a NaCl sample in a strong electric field is shown in Fig. 1. The crystal is oriented in the $\langle 110 \rangle$ direction. The energy levels of the states of Na and Cl atoms are given in accordance with the data of [29].

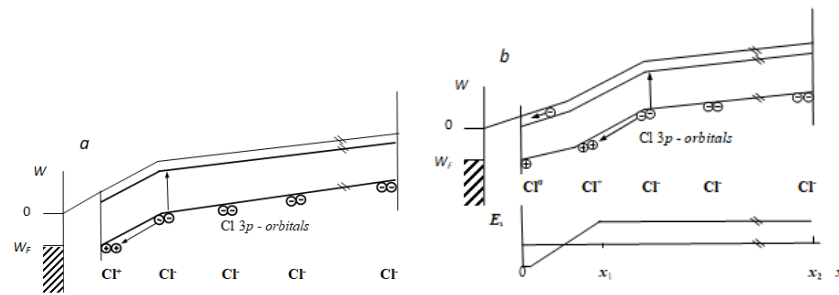


Fig. 1. Schematic of Auger transitions in NaCl in a strong electric field. W_F - energy levels of the Fermi metal; E_1 - space charge electric field

According to [15-16], the onset of breakdown channel formation is determined by processes at the metal-dielectric interface. With an average field strength in the sample of $\sim 10^6$ V/cm, the actual field strength near the electrode microtips can be greater than $\sim 10^8$ V/cm. In the near-electrode region of the dielectric, Cl^+ ions with two holes in the 3p orbitals are formed due to the tunneling transition of electrons into the metal. This requires a voltage U such that the edge of the valence band of the dielectric rises to the Fermi level of the metal. In a NaCl crystal, an electron at the 2p level of Na^+ is located ~ 22.4 eV below the bottom of the band gap and does not participate in the recombination of a hole into Cl^+ . The decay of a hole into Cl^+ occurs as a result of the interatomic Auger transition of an electron from the 3p orbital of an adjacent Cl^- atom and the subsequent generation of an Auger electron into the conduction band (Fig. 1,a). The Auger transition is possible under the condition that the minimum energy gap between the 3p levels of chlorine in an electric field is not less than the band gap of the dielectric $W_g=8.8$ eV. The necessary band bending for the Auger transition at a distance close to the interatomic distance is provided by the local electric field of the space charge (SC) and, first of all, the layer of doubly positively charged ions of the halide Cl^+ [16, 20].

A single cycle of the discharge front movement in a NaCl crystal can be divided into two successive

stages. In the first stage, when the critical local electric field strength of $\sim 10^8$ V/cm is reached, hole recombination on Cl^+ occurs due to the interatomic Auger transition of an electron from an adjacent chlorine atom over a time of $\tau_A \sim 10^{-16}$ s and the generation of an Auger electron into the conduction band of the dielectric. The channel advances by one interatomic distance (Fig. 1,a). The negative charge of the electrons reduces the hole charge field and, accordingly, the band bending near the conduction band boundary. The second stage is associated with the extraction of electrons from the discharge region by the external electric field and the achievement of the critical field strength for the next cycle. Cycle time Δt can be represented

$$\Delta t = \tau_A + \tau_1, \quad (1)$$

where τ_1 is the time to reach the critical electric field strength.

In NaCl crystals, Auger transitions propagate along the $Cl^- - Cl^-$ ion chain (Fig. 1,b). The spatial structure of the breakdown channel is formed by a set of individual Auger transition channels (Fig. 1) extending in the same direction. This mechanism ensures high stability of the breakdown channel's transverse dimensions in alkali halide crystals over a fairly long length (Fig. 2).

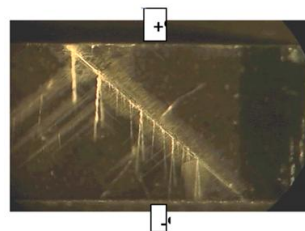


Fig. 2. Channel of pulsed anodic breakdown in crystalline NaCl. Electrode configuration: positive needle – plane [14]

It should be noted that long chains of $Cl^- - Cl^-$ ions (passing through the entire crystal) ensure stable movement of the breakdown channel without breaks (Fig. 2).

The channel comprises a positive space charge, a heated layer of material, and a conductive region of complex phase composition with electron-hole plasma. The channel front moves from the positive electrode into the sample.

The channel diameter is probably determined by the size of the layer of Cl^+ ions in the near-surface area

of the dielectric, and is proportional to the external voltage. According to [7], the breakdown channel diameter in KCl and KBr samples increases linearly with the voltage in the range of 100-300 kV. The breakdown channel movement may be delayed by the formation of the surface layer of Cl^+ ions.

Formation of space charge

The formation of a space charge at the boundary of the conducting layer $0 - x_1$ (Fig. 1,b) and an electric

current in a metal-insulator-metal structure are considered. The continuity equation (2) and Poisson's equation (3) were used in the calculation.

$$\frac{\partial \rho}{\partial t} = G - \frac{\partial}{\partial x}(en\mu E), \quad (2)$$

$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon \varepsilon_0}, \quad (3)$$

where n and p are concentrations of free electrons and immobile holes; e and μ are the electric charge and electron mobility, $\rho = e(p - n)$ is the space charge density; $E = E_0 + E_1$ is the total electric field strength ($E_0 = U/x_2$ and E_1 are the values of the strength of the external electric field and space charge, respectively); ε and ε_0 are the values of the dielectric permittivity of the sample and electric constant, respectively; $G = en_1/\tau_A$ is the volume rate of the Auger electron charge generation in the space from x_1 to $x_1 + \Delta x$ (n_1 - initial concentration of Auger electrons, Δx is the atomic layer thickness in the crystal $\sim 4 \text{ \AA}$). t_0 is the time of switching on the generation of Auger electrons at the moment of reaching the critical field strength.

$$\varepsilon \varepsilon_0 \int_0^{x_2} \frac{\partial E_1}{\partial t} dx = \int_{x_1}^{x_1 + \Delta x} G \Delta x dx - \sigma \int_0^{x_1} E_0 dx - \sigma \int_0^{x_1} E_1 dx - \varepsilon \varepsilon_0 \frac{x_1}{(x_2 - x_1)} \int_0^{x_1} \frac{\partial E_1}{\partial t} dx. \quad (10)$$

Given the short-circuiting condition (8), we obtain

$$\frac{\partial E_1}{\partial t} + \frac{E_1}{\tau} = -\frac{E_0}{\tau} + \frac{G \Delta x^2}{\sigma x_1 \tau}, \quad (11)$$

where $\tau = \tau_m x_1 / (x_2 - x_1)$ is the circuit time constant, $\tau_m = \varepsilon \varepsilon_0 / \sigma$ - Maxwell relaxation time. The solution to the equation (11) for E_1 is found to be

$$E_1 = -E_0 \left(1 - \exp\left(-\frac{t}{\tau}\right) \right) + \frac{G \Delta x^2}{x_1 \sigma} \left(1 - \exp\left(-\frac{\tau_A}{\tau}\right) \right). \quad (12)$$

A decrease in the field strength of the positive space charge E_1 occurs as a result of the actuation of the Auger electron field. Without the Auger generation, the field strength E in the sample region $0 - x_1$ is given by

$$E = E_0 \exp\left(-\frac{t}{\tau}\right). \quad (13)$$

In the space $x_1 - x_2$, the field strength of the space charge E_s with regard to (9) is written as

$$E_s = \frac{E_0 x_1}{(x_2 - x_1)} \left(1 - \exp\left(-\frac{t}{\tau}\right) \right). \quad (14)$$

The field strength E_s increases superlinearly with increasing coordinate x_1 .

The value of the positive space charge Q_s is determined as

$$\varepsilon \varepsilon_0 E_s = Q_s \left[\frac{k}{\text{cm}^2} \right]. \quad (15)$$

The spatial structure of the electric field E_1 of charge Q_s in the $0 - x_2$ region is shown in Fig. 1.

The initial and boundary conditions of the problem will be as follows:

at $t = 0$, the field strength $E = 0$, (4)

at $x \geq x_1$, $\sigma = 0$, denote $E_1 = E_s(t)$, (5)

where $E_s(t)$ is the electric field strength beyond the space charge boundary x_1 , $\sigma = en\mu$ is the conductivity. After the transformations (2) and (3), we get

$$\varepsilon \varepsilon_0 \frac{\partial^2 E}{\partial x \partial t} = G - \sigma \frac{\partial E}{\partial x}. \quad (6)$$

The integration (6) on the x coordinate using the boundary condition (5) gives

$$\varepsilon \varepsilon_0 \frac{\partial E}{\partial t} = G \Delta x - \sigma E_0 - \sigma E_1 + \varepsilon \varepsilon_0 \frac{\partial E_s}{\partial t}. \quad (7)$$

The short-circuiting condition takes the form (8)

$$\int_0^{x_2} E_1 dx = 0. \quad (8)$$

To a first approximation, the equation (8) can be written as

$$E_1 x_1 + E_s (x_2 - x_1) = 0. \quad (9)$$

To find E_1 in (7), we shall express E_s in terms of E_1 and integrate the equation (7) with respect to x from $x=0$ to x_2 .

Pre-breakdown conduction current

In a metal-insulator-metal structure, when voltage is applied, the conduction current density in the $0 - x_1$ space is

$$i_1 = \sigma E = \sigma E_0 \exp(-t/\tau). \quad (16)$$

The displacement current density in the space $x_1 - x_2$ has the form

$$i_s = \frac{\partial Q_s}{\partial t} = \sigma E_0 \exp\left(-\frac{t}{\tau}\right). \quad (17)$$

Conduction current (16) and bias current (17) are equal. Currents (16) and (17) arise when space charge Q_s forms at boundary x_1 ($\sigma = 0$). Equation (16) reflects the fact that, at the moment the voltage is applied, current i_1 is equal to σE_0 and decreases exponentially with time.

The generation of Auger electrons creates a conductive layer in the region $x_1 + \Delta x$. An electric current subsequently arises when space charge forms at the boundary $x_1 + \Delta x$ under the influence of an external field E_0 . In equation (16), the relaxation time t is limited by the onset of the next Auger transition after time τ_1 at time $t = t_0$. In the breakdown channel motion model, equation (16) can also be viewed as the dependence of the current density on the position of space charge $Q_s(x_1)$ in the sample at a time other than $t = 0$. The dependence of the conduction current density function (16) on the argument x_1 in coordinates $t_1 = x_1/v$ (where v is the breakdown channel velocity and $t_b = x_2/v$ is the breakdown time) for fixed times $t_{01} = 0.1 \tau_m$ (curve 1), $t_{02} = 0.05 \tau_m$ (curve 2), and $t_{03} = 0.01 \tau_m$ (curve 3) is shown in Figure 3.

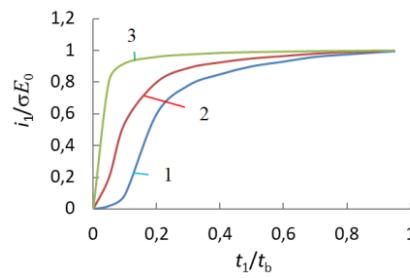


Fig.3. Dependence of the conduction current density function in the breakdown channel on the channel travel time

The current amplitude (curves 1-3) increases with decreasing argument t_0 , which occurs with increasing channel velocity. The current density (curve 3) increases slightly with increasing coordinate x_1 .

Breakdown channel movement speed

The time taken to reach the critical field strength τ_1 in the equation (1) can be found from the relationship $\tau_1 = Q_A/i_1$, (18)

where Q_A - is the charge density of Auger electrons according to the equation (12)

$$Q_A = \varepsilon\varepsilon_0 \frac{G\Delta x^2}{x_1\sigma} \left(1 - \exp\left(-\frac{\tau_A}{\tau}\right) \right). \quad (19)$$

Carrier injection occurs in a short time and does not depend on the field strength E_0 .

$$\Delta t = \tau_A + \frac{G\Delta x^2\tau_m}{E_0x_1\sigma} \exp\left(\frac{t_0}{\tau}\right) \left(1 - \exp\left(-\frac{\tau_A}{\tau}\right) \right). \quad (20)$$

The formula for Δt makes it possible to estimate the dependence of the channel velocity $v(x_1) \approx \Delta x/\Delta t$ on the field strength E_0 , conductivity σ , and coordinate x_1 .

Electrical breakdown parameters

The oscillograms of voltage U and pre-breakdown current I in a NaCl crystal with a thickness of $d = 2$ mm and a positive polarity of the needle electrode are shown in Fig. 4 [1]. A bridge circuit was used to compensate for capacitive currents. In the needle-plane structure of the electrodes, the distribution of E_x is non-uniform and decreases hyperbolically across the sample [1]. The average electric field strength $E_{mid} = U/d$ [30].

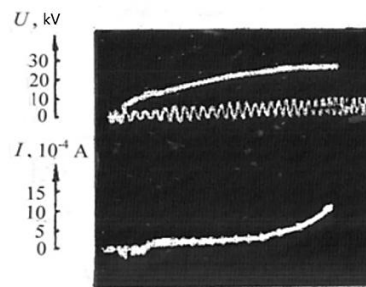


Fig. 4. Oscillograms of the voltage pulse U and current I in a NaCl crystal [1]

The onset of discharge propagation is indicated on the oscillograms by the appearance of a current of approximately $\sim 2 \cdot 10^{-4}$ A (Fig. 4) [1]. As the discharge advances deeper into the sample, the current amplitude remains constant and, after 1/2 the breakdown time, increases exponentially. The maximum current of $\sim 10^{-3}$ A corresponds to the time the breakdown channel reaches the cathode. This is followed by a sharp increase in current, which is not reflected in the photograph. According to [1], the breakdown channel diameter expands near the anode to $\sim 2-3$ μm and narrows towards the cathode to $\sim 0.5-1$ μm .

As shown above, the pre-breakdown current amplitude can increase by no more than a few percent as the channel passes through the sample. The primary current density is $i \approx 2 \cdot 10^4$ A/cm² for a channel diameter of 1 μm . At an average field strength $E_{mid} \sim 10^5$ V/cm, the breakdown front velocity $v \approx 10^6$ cm/s, conductivity $\sigma = i/E_{mid} \approx 0.2$ Ohm⁻¹ cm⁻¹.

According to [1], electrical breakdown in NaCl, KCl, KBr crystals of different thicknesses at the selected value of $E_{mid} \sim 10^5$ V/cm is characterized by a stable amplitude of the primary current $\sim 2.8 \cdot 10^{-4}$ A. With an increase in the length of the sample, the breakdown

time and the amplitude of the maximum current increase.

Secondary breakdown effects

An increase in the channel diameter near the anode surface of the NaCl sample was noted in [1].

The destruction of the channel surface is probably associated with its bombardment by ions accelerated in a strong non-uniform field in the gas phase region of the discharge. In general, ion sputtering begins when the ion energy W_i exceeds the threshold value W_b . The value of W_b weakly depends on the mass of the colliding particles and is in the range of $\sim 10-30$ eV [31]. The efficiency of the sputtering process increases with the increase in the mass of the bombarding ions, the angle of incidence of ions from 0 to 40-70° and the energy W_i to 70-80 eV [31]. A model of sputtering of two-component materials by light ions is presented in [32]. According to the model, the outgoing flow of atoms is associated with the movement of a certain conglomerate of atoms of both components.

Mass spectrometry studies of plasma clots ejected into a vacuum from the surface overlap region and from breakdown channels in solid dielectrics show that the bulk of the ionic charge is carried by singly ionized

molecules. In the case of KCl, these are KCl^+ , K_2Cl^+ , and $(K_2Cl_2)^+$ ions [10]. The degree of ionization in the breakdown channel in such cases does not exceed 10%. It can be assumed that the bulk of neutral particles have the same composition [10].

In NaCl samples, the impact particles are most likely Na^+ ions, and the sputtered particles are $NaCl^+$ conglomerates. Specifically, for positive ions, there is an angular component of the field strength relative to the channel wall surface. The gas phase includes neutral and positively charged ions and conglomerates of the original substance's atoms.

The increase in channel diameter and current buildup in the experiment (Fig. 4) can be attributed to secondary breakdown effects. The nature of the current increase corresponds to the exponential law $I(t) \sim 2^n$ (where n is an integer). The onset of the current is shifted by a time t_g and is likely associated with the onset of gas phase formation. The drift velocity v_d of a

charged particle in the gas phase in a nonuniform electric field E_x is determined as

$$v_d = \mu E_x. \quad (22)$$

The superlinear rise in the current $I(t)$ in Fig. 4 is satisfactorily described by the sum of stair step functions:

$$I(t) = \sum_i^M I_i(t_g + \Delta t_i), \quad (23)$$

where i – number of a cluster of charged particles; I_i – current with initial carrier concentration N_0 ; M – total amount of currents I_i ; t_g – time to the creation of gas phase, Δt_i – time lag between the start of the current flow and t_g . We have designated the number of steps as k and the duration of the step as t_k . The equation (23) is satisfied if the time lags Δt_i lie in the narrow time margin $\Delta t_i < t_k$.

The function of current I_1 created by the bunch of the charged particles in sample NaCl is presented in Fig. 5.

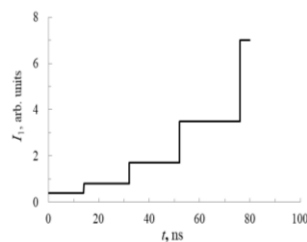
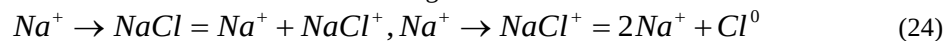


Fig. 5. View of the current function I_1 during impact multiplication of charged particles in a NaCl sample

A characteristic feature of the current structure is its periodic doubling at each time interval $t_{\square}$, which corresponds to the process of impact disintegration of conglomerates of atoms of the substance during bombardment with fast particles. The increase in the duration of the charged particle acceleration period $t_{\square}$ correlates satisfactorily with a decrease in the amplitude of the

electric field strength E_x in the tip-plane electrode system. This indicates the movement of an avalanche of positive ions from the anode electrode into the sample.

Sufficiently large values of $t_{\square}$ probably include the times of the process of spraying the channel walls with the formation of $NaCl^+$ conglomerates and the subsequent reaction of impact multiplication of Na^+ ions according to the scheme



The rate of reaction (24) is likely limited by the time it takes for conglomerates to form.

For a sodium chloride sample, the number of acceleration cycles at half the channel length is $k = 4$, and the gas phase formation time is $t_g \approx 80$ ns. The average path between two shock generation events, z_{mid} , is ~ 0.25 mm. The last acceleration cycles (Fig. 5) are close in time and correspond to motion in the mean field region E_{mid} . The drift velocity in this region for sodium ions is $v_d \approx z_{mid}/t_{\square} \sim 1.2 \cdot 10^6$ cm/s.

The kinetic energy of the ions Na^+ in the region of the average electrical field strength is ~ 10 eV. The amount of energy is probably enough to sustain impact multiplication of ions during the destruction of aggregates in the gas phase. Mobility of Na^+ ions in the gas phase of the breakdown channel in the region of average electrical field strength is equal to $\mu \approx 12$ cm²/Vs, according to formula (22).

The current density in the region of average field strength ($k=3$) is $i_3 \approx 1.7 \cdot 10^4$ A/cm² (Fig. 4), the carrier multiplication factor is $B=4$. The current density can be represented as $i_3 = eN_3v_d$, which gives the ion concentration $N_3 \approx 8 \cdot 10^{16}$ cm⁻³. Considering that $B=4$, the sodium ion concentration near the anode is $N_1 \approx 2 \cdot 10^{16}$ cm⁻³. In formula (23), the initial ion concentration N_0 can be taken to be equal to $0.1 \cdot N_1$, while the number of currents M is equal to 10.

Pre-breakdown currents in glass

A study of the pre-breakdown current in a glass sample is presented in [1]. Measurements were performed using voltage pulses with a rise time of 0.2-3 μ s, in a non-uniform field, and with a positive tip polarity. A bridge circuit was used to compensate for capacitive currents. Oscillograms of voltage U and pre-breakdown current I in a glass sample ~ 5 mm thick are shown in Fig. 6 [1].

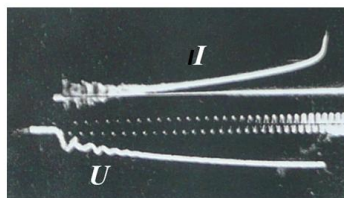


Fig.6. Oscillogram of the voltage pulse U and current I in a glass sample [1]

When the voltage reaches the breakdown value, a current of $\sim 1.6 \cdot 10^{-4}$ A is observed on the oscillogram [1]. As the discharge progresses deeper into the sample, the current amplitude remains constant and, after 0.3 of the breakdown duration, increases exponentially to $\sim 20 \cdot 10^{-4}$ A.

Glass is an amorphous substance with preserved short-range order of the crystal lattice of the sample. The primary processes of the breakdown channel are associated with Auger transitions of electrons along the chain of nearby oxygen ions and the generation of electrons in the conduction band, as occurs in a quartz crystal [17]. The superlinear increase in current is related to secondary phenomena in the gas phase of the discharge. The accelerated particles are likely silicon ions.

Pre-breakdown currents in polyethylene

The electronic properties of organic dielectrics are conditioned by the presence of covalent bonds with sp^3 - hybrid orbitals of the carbon atom [28]. In polyethylene, each atom of the carbon builds four σ - bonds with the neighboring atoms. The σ -bond is formed by overlapping sp^3 - hybridized orbitals, two with carbon atoms and the other two with hydrogen atoms. The energy spectrum of σ - electrons consists of levels that are filled with electrons and those that are not. The highest occupied molecular orbital HOMO and the lowest unoccupied molecular orbital LUMO are separated by a band gap. Opinion of the authors of [33], Wg one can consider ~ 8 eV for polymer insulators

According to the works [15-16], during anode-initiated breakdown, the generation of free electrons and holes is caused by the Auger transition of electrons in the valence band of the dielectric. In polyethylene, the electron transfer occurs along the chain of C- C atoms

oriented in the direction of the maximum electric field strength [20]. Some of the electrons recombine with holes with the release of heat. The released energy is spent on breaking chemical bonds and forming free macromolecules. Thermal pressure forms a hollow channel with the gas phase. Macromolecules disintegrate into ions under the action of thermal collisions [20]. Mass spectrometry of plasma clots ejected into a vacuum from the region of the surface breakdown channels in polyethylene shows that the main part of the ionic charge is carried by singly ionized clusters $C_2H_5^+$, $C_4H_9^+$, $C_8H_{17}^+$. The degree of ionization in the breakdown channel in such cases does not exceed 10% [11].

An experimental study of the pre-breakdown current in polyethylene samples with a needle-plane electrode configuration was conducted in [5]. A light-emitting diode connected to the sample's discharge circuit was used to record the current. The LED's glow intensity was proportional to the current. A bridge circuit for compensating capacitive recharge currents was not used.

According to [5], for samples with a thickness of ~ 1.49 mm, the pre-breakdown current appeared at the leading edge of a positive voltage pulse with an amplitude of ~ 60 kV. The voltage pulse duration was 760 ns. The average field strength in the sample, E_{mid} , was $\approx 4 \cdot 10^5$ V/cm.

The breakdown tree is shown in Fig. 7. In this case, partial breakdown is observed. The maximum breakdown channel length is ~ 0.4 mm. The channel diameter is ~ 10 μ m at the positive electrode and ~ 1 μ m deep within the sample.

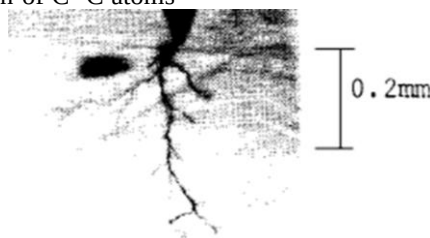


Fig. 7. The breakdown tree in polyethylene [5]

The current curve is highlighted against the background of the transient discharge current curve of the

circuit. The pre-breakdown current trace is shown in Fig. 8.

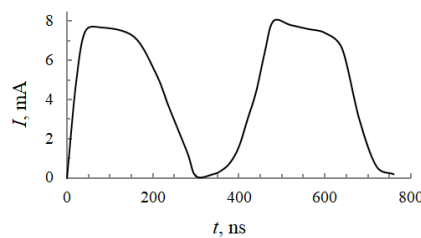


Fig. 8. The pre-breakdown current in polyethylene

The conduction current increased linearly from zero to ~ 7.6 mA over a period of ~ 50 ns. It then decreases to 7 mA at 170 ns and drops sharply to virtually zero at 300 ns. The first current pulse, 300 ns in duration (Fig. 8), corresponds to the primary breakdown current. With a channel diameter of ~ 10 μm (near the positive electrode), the current density is $\sim 7 \cdot 10^3$ A/cm², and the channel front velocity is $1.3 \cdot 10^5$ cm/s.

The increase in channel diameter and the increase in current $I(t)$ in the 300-480 ns range (Fig. 8) can be attributed to secondary breakdown effects. The super-linear increase in secondary current $I(t)$ in Fig. 8 is satisfactorily described by the sum of step functions in the form of equation (23). The form of the function I_1 is shown in Fig. 9.

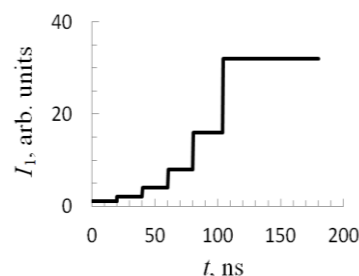
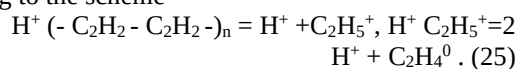


Fig. 9. View of the current function I_1 during impact multiplication of charged particles in polyethylene sample

A characteristic feature of the current structure is its periodic doubling at each time interval t_k , which corresponds to the process of impact disintegration of conglomerates of atoms of the substance when bombarded by fast particles.

Probably, in polyethylene, H^+ ions act as impactors, while C_2H_5^+ aggregates are sputtered. The process of sputtering the channel walls with the formation of C_2H_5^+ conglomerates and the subsequent reaction of impact multiplication of H^+ ions occurs according to the scheme



The relatively large values of t_k are likely due to the formation of C_2H_5^+ conglomerates.

The number of acceleration cycles per channel length of 0.4 mm is $k = 5$ and the gas phase formation time is $t_g \approx 300$ ns. The average path between two shock generation events, z_{mid} , is ~ 0.08 mm. The last acceleration cycles (Fig. 9) are close in time and correspond to motion in the mean field region E_{mid} . The hydrogen ion drift velocity in this region is $v_d \approx z_{\text{mid}}/t_3 \approx 4 \cdot 10^6$ cm/s. Mobility of H^+ ions in the gas phase of the breakdown

channel in the region of average electrical field strength is equal to $\mu \approx 10$ cm²/V·s, according to formula (22).

Pre-breakdown currents in water

A model of the breakdown channel motion in a liquid water sample is presented in [24,26]. The basic idea of this approach is that, at close range, the structure of water is the same as that of hexagonal ice I_h . According to [24], during anodic-initiated breakdown, the generation of free electrons and holes is caused by the Auger transition of electrons in the valence band of the dielectric. In a water sample, electron transfer occurs along the O-H-O atomic chain, oriented in the direction of maximum electric field strength [24,26].

Figure 10 gives us some information on channel diameter and the velocity of its propagation in a water gap at $d = 0.8$ mm in a homogeneous field ~ 2 MV/cm, according to [34]. The time between the frames is ~ 1 ns, the average velocity of expansion of the glowing region is $\sim 10^7$ cm/s. The length and the diameter of the glow near the anode increase superlinearly in the channel's propagation process towards the cathode. The diameter of the channel near the anode at the initial stage of the breakdown is $d_k \approx 80$ μm (see Fig. 10).

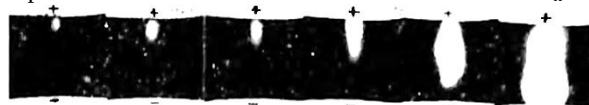


Fig.10. Change in the length and diameter of the anode glow over time during breakdown in water [34].

The dependence of the current on time during breakdown in a 1 cm thick water layer is shown in Fig.

11 [4]. A bridge circuit was used to compensate for capacitive currents.

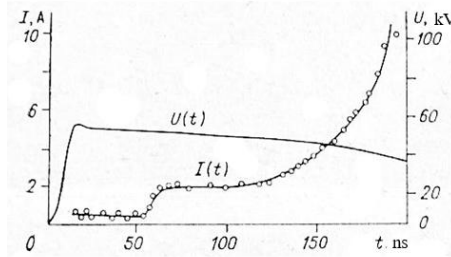


Fig. 11. Pre-breakdown current in water and voltage on the measuring capacitor [4]

The rise in current at ~50 ns corresponds to the beginning of the channel growth from the needle. At the initial stages of the expanding of the conduction area in the bulk of the sample the current remains stable (~2 A) until the length expands to ~5 mm, i. e. approximately a half of the distance from the tip of the needle electrode to the plane electrode. After that, the current increases by several times before the conducting channel spans the interelectrode gap. At the average electrical field strength of $\sim 5 \cdot 10^4$ V/cm, the breakdown channel front

propagation velocity is $\sim 6.7 \cdot 10^6$ cm/s. The conductivity current density in water is $\sim 3 \cdot 10^4$ A/cm², conductivity $\sigma \approx 0.6$ Ohm⁻¹ cm⁻¹ at $d_k \approx 80$ μ m.

The widening of the breakdown channel and the increase in current in the experiment (Fig. 11) can be attributed to secondary breakdown processes. The superlinear increase in current $I(t)$ in Fig. 11 is satisfactorily described by the sum of step functions in the form (23). The current function of a cluster of charged particles I_1 in a water sample is shown in Fig. 12.

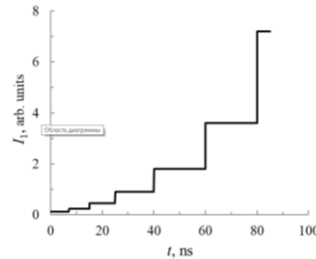
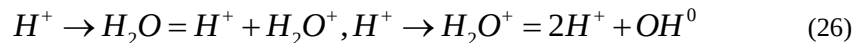


Fig. 12. Current function I_1 for impact multiplication of charged particles in a water sample

Most likely, in water samples, the impact particles are H^+ ions, and the H_2O^+ conglomerates are sprayed.

The rather large values of $t_{\square\square}$ likely include the times of the process of spraying the channel walls with



The reaction rate (26) is probably limited by the time of the formation of the aggregates.

The amount of the acceleration cycles at half of the channel length for water is $k=6$, and the time of gas phase formation is $t_g \approx 80$ ns. The average path between two acts of impact generation of ions z_{mid} in water is ~ 0.83 mm. The last cycles of acceleration (Fig. 12) are close in duration and correspond to the motion in the region of average field E_{mid} . The drift velocity in this region for water is $v_d \approx z_{mid}/t_4 \approx 5.5 \cdot 10^6$ cm/s. The kinetic energy of the ions H^+ in the region of the average electrical field strength is ~ 15.6 eV. The amount of energy is probably enough to sustain impact multiplication of ions during the destruction of aggregates in the gas phase. Mobility of H^+ ions in the gas phase of the breakdown channel in the region of average electrical field strength is equal to $\mu \approx 110$ cm²/V·s, according to formula (22).

The current $I(t)$ in the region of average field strength ($k=4$) is ~ 0.9 A (Fig. 11). Current density is $i_4 \approx 1.1 \cdot 10^4$ A/cm² at the channel diameter $d_k \sim 0.1$ mm and the carriers multiplication coefficient $B=8$. Current density may be presented in $i_4 = eN_4v_d$, where ion concentration $N_4 \approx 1.3 \cdot 10^{15}$ cm⁻³. Considering that $B=8$, the concentration of hydrogen ions near the anode is equal

the formation of H_2O^+ conglomerates and the subsequent reaction of impact multiplication of H^+ ions according to the scheme

to $N_1 \approx 1.6 \cdot 10^{14}$ cm⁻³. In formula (23) the initial ion concentration N_0 may be assumed to be equal to $0.1 \cdot N_1$, whereas the number of currents M equals 10.

Pre-breakdown currents in transformer oil

Typical liquid dielectrics include alkanes, perfluorooicosane, and others. The molecular model of naphthenic mineral oil [35] includes different types of alkanes: monocyclic $C_{14}H_{28}$ (32%), tricyclic $C_{16}H_{28}$ (26%), bicyclic $C_{13}H_{24}$ (18%), acyclic $C_{12}H_{26}$ (13%) and tetracyclic $C_{16}H_{26}$ (11%), which gives the density of 0.95 g/cm³. Calculations of the electronic structure of mineral oil ab initio are presented in paper [28]. The valence and conduction bands of mineral oil are formed by the energy levels of the HOMO and LUMO states of alkane molecules, respectively. Forbidden band width is 6 eV [35].

The patterns of anodic breakdown in perfluorooicosane are satisfactorily described by a mechanism based on cascade Auger transitions in the valence band of the dielectric [23].

A study of the pre-breakdown current in a transformer oil sample is presented in [2]. Measurements were performed by applying a pulsed voltage of 41.4 kV to a sample ~ 4 mm thick in a non-uniform field with a positive polarity of the needle tip. A bridge circuit was used to compensate for capacitive currents. The current

was recorded by a light-emitting diode included in the sample discharge circuit. The LED glow intensity is

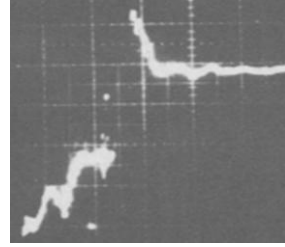


Fig. 13. Oscillograms of current pulse I in transformer oil. Current ~ 7 mA/div, time ~ 1 μ s/div [2]

The primary conduction current increases with time to a maximum amplitude of 5.3 mA at 250 ns and decreases slightly as the breakdown channel moves. The secondary current appears 500 ns from the onset of the breakdown process and increases to 8.8 mA within 250 ns. A sharp increase in current at 1.4 μ s then corresponds to the discharge current through the sample. In the experiment, the field strength E_{mid} was $\sim 10^5$ V/cm, and the breakdown channel velocity was $2.9 \cdot 10^5$ cm/s. The current density was $2 \cdot 10^4$ A/cm², the electron conductivity was $0.2 \text{ Ohm}^{-1} \text{ cm}^{-1}$ with a channel diameter of 5 μ m. The secondary current is likely due to the movement of light hydrogen ions.

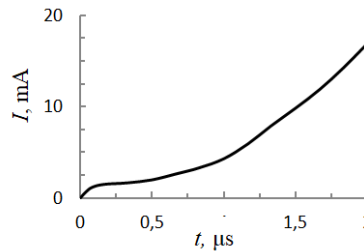


Fig. 14. The pre-breakdown current in a transformer oil sample

In the experiment, the average field strength in the sample was $\sim 0.9 \cdot 10^5$ V/cm, the breakdown channel velocity was $2.5 \cdot 10^5$ cm/s. The primary current amplitude was $\sim 1.5 \cdot 10^{-3}$ A. The current density was $0.6 \cdot 10^4$ A/cm², the electron conductivity was $0.07 \text{ Ohm}^{-1} \text{ cm}^{-1}$, and the channel diameter was 5 μ m.

A secondary current arises after 150 ns of breakdown. The current amplitude increases exponentially to $\sim 17 \cdot 10^{-3}$ A. The superlinear increase in current $I(t)$ in Fig. 14 is satisfactorily described by the sum of step functions in the form of equation (23). The current function of a cluster of charged particles I_1 in a transformer oil sample is shown in Fig. 15.

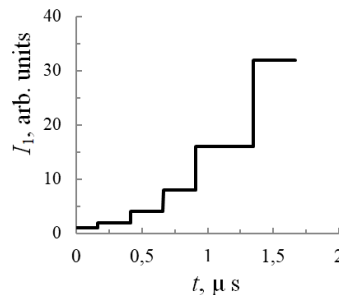


Fig. 15. Current function I_1 for impact multiplication of charged particles in a transformer oil sample

The impacting particles are likely hydrogen ions.

The amount of the acceleration cycles at half of the channel length for transformer oil is $k=6$, and the time of gas phase formation is $t_g \approx 150$ ns. The average path between two acts of impact generation of ions z_{mid} in transformer oil is ~ 0.83 mm. The last cycles of acceleration (Fig.15) are close in duration and correspond to the motion in the region of average field E_{mid} . The drift velocity in this region is $v_d \approx z_{\text{mid}}/t_3 \approx 3.3 \cdot 10^6$ cm/s.

Mobility of H^+ ions in the gas phase of the breakdown channel in the region of average electrical field strength is equal to $\mu \approx 40 \text{ cm}^2/\text{V} \cdot \text{s}$, according to formula (22).

Conclusion

It can be assumed that the mechanisms of primary and secondary current formation are similar during anodic breakdown in solid and liquid dielectric materials.

The primary processes (including conduction current and breakdown channel movement) are satisfactorily described by the mechanism of free electron generation through interatomic cascade Auger transitions of electrons in the valence band of the dielectric. The primary current density is $\sim 10^4$ A, and the channel velocity is $\sim 10^6$ cm/s at an average electric field strength of 10^5 V/cm in solid and liquid dielectric samples.

At high values of electrical field strength ($>10^6$ V/cm) and relatively long breakdown times (for long samples), the channel walls structurally degrade. The widening of the breakdown channel and the increase in current in the experiment can be attributed to secondary breakdown effects. The secondary current is associated with the movement of ions in the gas phase of the channel. The secondary current density in the final phase of breakdown is several times greater than the primary current density. The maximum value of hydrogen ion mobility in the gas phase of the channel is observed in the water sample ($110 \text{ cm}^2/\text{V}\cdot\text{s}$) compared to the transformer oil ($40 \text{ cm}^2/\text{V}\cdot\text{s}$) and polyethylene ($10 \text{ cm}^2/\text{V}\cdot\text{s}$) samples.

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PSYCHOLOGICAL PREPARATION OF BOXERS

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Abstract

This article systematically analyzes the aspects of mental, emotional and motivational preparation of boxers before and during a fight. The study covers such key areas as focus and concentration, coping with stress and fear, self-confidence and motivation, as well as psychological adaptation to a fighting strategy. Special attention is paid to the role of the coach — functions such as emotional support, motivation, tactical advice, stress management and maintaining focus are explained with theoretical and practical examples. Literature analysis, questionnaires, observation and standard psychological tests (e.g., SAS, ACSI) are proposed as methodologies; The results show that targeted psychological preparation enhances performance and that coaching intervention plays a critical role.

Xülasə

Bu məqalə boksçuların döyüşdən əvvəl və döyüş zamanı zehni, emosional və motivasion hazırlıq aspektlərini sisteməlik şəkildə təhlil edir. Tədqiqat fokus və konsentrasiya, stress və qorxu ilə mübarizə, özünəinam və motivasiya, həmçinin döyüş strategiyasına psixoloji adaptasiya kimi əsas sahələri əhatə edir. Məşqçinin roluna xüsusi diqqət ayrılır — emosional dəstək, motivasiya, taktiki məsləhətlər, stress idarəsi və fokusun qorunması kimi funksiyalar nəzəri və praktik misallarla izah olunur. Metodologiya kimi ədəbiyyat təhlili, sorğu-anketlər, müşahidə və standart psixoloji testlər (məs., SAS, ACSI) təklif olunur; nəticələr məqsədli psixoloji hazırlığın performansını artırdığını və məşqçi müdaxiləsinin kritik rolunu göstərir.

Keywords: Boxers' success depends not only on physical preparation, but also on psychological preparation. Focus and concentration during a fight directly affect an athlete's performance.

Açar sözlər: Boksçuların uğuru yalnız fiziki hazırlıqdan deyil, həm də psixoloji hazırlıqdan aslıdır. Döyüş zamanı fokus və konsentrasiya idmançının performansını birbaşa təsir edir.

Giriş. Boksçular döyüşdən əvvəl və döyüş zamanı həm zehni, həm emosional, həm də motivasion hazırlıq görməlidirlər. Əsas sahələr:

1.Fokus və konsentrasiya. Döyüş zamanı diqqət yayındırıcı amillərdən qorunmalı, rəqibin hərəkətlərinə və öz strategiyasına yönəlməlidir. Vizualizasiya (göz qabağında döyüşü canlandırmaq) və meditasiya məşqləri kömək edir.

2.Stress və qorxu ilə mübarizə. Döyüş stressi bəzən performansını mənfi təsir edir. Dərin nəfəs texnikaları, psixoloji məşqlər və qısa meditasiya döyüş zamanı sakit qalmağa kömək edir.

3.Motivasiya və özünəinam. İdmançı, məşq zamanı əldə etdiyi uğurlar və zəif tərəflərini tanımaqla özünəinamını artırır. Özünə təsdiqedicilərlə ("mən hazıram", "mən bacaracağam") motivasiyanı yüksəldir.

4.Döyüş strategiyasına psixoloji adaptasiya. Hər döyüş fərqli rəqib tələb edir; idmançı strategiyasını dəyişməyə hazır olmalıdır. Sürprizlərə qarşı psixoloji çeviklik vacibdir.

Məşqçinin rolu psixoloji hazırlıqda. Məşqçi yalnız fiziki bacarıqları inkişaf etdirmir, həm də idmançının psixologiyasını yönləndirir:

1.Emosional dəstək. İdmançının qorxusunu və gərginliyini azaltmaq, döyüşə inam yaratmaq.

2.Motivasiya. İdmançının ruhlandırmaq, həvəsləndirmək və ona məqsəd qoymaq.

3.Strategiya və taktik məsləhətlər. Döyüş zamanı hansı taktikanın işləyəcəyini izah etmək. Rəqibin psixoloji zəif tərəflərini analiz etmək.

4.Stress idarəsi. Döyüş öncəsi və döyüş zamanı idmançının sakit qalmasına kömək etmək. Məsələn, nəfəs məşqləri və vizualizasiya texnikalarını göstərməklə.

5.Fokus və disiplinin qorunması. Məşqçi idmançının diqqətini yayındıran amillərdən uzaq durmasını təmin edir. Psixoloji hazırlıq planlarını izləyir və lazımı düzəlişlər edir.

1. Mövzunu araşdırmaq üçün metodlar.

a) Ədəbiyyat və elmi mənbələr. Kitablار və dərslilər: İdman psixologiyası, boks və döyüş idmanları üzrə dərslilərdə əsas anlayışlar və texnikalar

izah olunur; Elmi məqalələr: PubMed, ResearchGate və Google Scholar kimi platformalarda “boxing psychology”, “coach role in athlete performance” və ya “sports mental training” kimi açar sözlərlə axtarış edə bilərsiniz; Təcrübələr və təhlillər: Akademik jurnallarda boksçuların stress səviyyəsi, motivasiya və performans arasındakı əlaqələr öyrənilir.

b) Empirik araşdırmalar (praktik tədqiqatlar). Sorğu və anketlər: Boksçulara psixoloji vəziyyət, motivasiya və məşqçi ilə münasibətləri soruşmaq. Məsələn: “Döyüş öncəsi ən çox hansı psixoloji çətinliklə üzləşirsiniz?” Müşahidə: Məşqlərdə və döyüşlərdə idmançının davranışını, məşqçinin yönləndirməsini müşahidə etmək. Fərqli məşqçilərin strategiyalarını müqayisə edə bilərsiniz. [1, s.293]

Psixoloji testlər və qiymətləndirmələr: Stress, motivasiya, fokus və özünəinam səviyyəsini ölçən standart testlərdən istifadə; Məsələn: Sport Anxiety Scale (SAS) və ya Athlete Coping Skills Inventory (ACSI).

c) Analiz və nəticələr. Topladığınız məlumatları statistik və ya keyfiyyət yönümlü analiz edə bilərsiniz; Məsələn, məşqçinin rolunun idmançının stress səviyyəsinə təsirini müqayisə etmək; Nəticələr göstərir ki, məqsədli psixoloji hazırlıq performansı artırır və məşqçinin dəstəyi kritik əhəmiyyət kəsb edir.

2. Məhsur idmançıların psixoloji hazırlıq barədə fikirləri.

a) Muhammad Ali – boks: Ali döyüşdən əvvəl vizualizasiya və özünə inam texnikalarından istifadə edirdi; Dedi ki, “Mən artıq qalib gəldiyimi görmüşəm, qalanı sadəcə döyüşməkdir.” Buradan aydın olur ki, psixoloji hazırlıq yalnız fiziki məşq deyil, həm də zehni şəkilləndirmə və özünəinamdır. [5, s.273-280]

b) Mike Tyson – boks: Tyson deyirdi ki, döyüşdən əvvəl özünü sakitləşdirmək üçün nəfəs məşqləri və fokuslanma vacibdir; O, həm də rəqibi qorxutmaqla psixoloji üstünlük qazanmağa çalışırdı, yəni psixoloji strategiyaları döyüşün bir hissəsi kimi görürdü.

3. Araşdırmaya inteqrasiya yolları. Sitata əsaslanan analiz: Məhsur idmançıların dediklərini birbaşa sitatlarla araşdırmaya əlavə etmək; Məsələn: “Muhammad Ali döyüşdən əvvəl vizualizasiya ilə hazırlanırdı (Ali, 1975).”

Fiziki və psixoloji hazırlığın müqayisəsi: Onların təcrübələrinə baxaraq idmançıların fiziki və zehni məşqlərinin qarşılıqlı təsirini göstərmək. [4, s.380-382]

Elmi yenilik:

Bu tədqiqatın elmi yeniliyi boks idmanında psixoloji hazırlığın yalnız ümumi nəzəri aspekt kimi deyil, konkret komponentlər (fokus və konsentrasiya, stress və qorxu ilə mübarizə, motivasiya və özünəinam, strategiyaya psixoloji adaptasiya) üzrə sistemli şəkildə təhlil edilməsindən ibarətdir. Araşdırmada məşqçinin rolu ayrıca və kompleks faktor kimi qiymətləndirilir və onun idmançının psixoloji vəziyyətinə təsiri empirik metodlarla (sorğu, müşahidə və psixoloji testlər) əsaslandırılır. Bundan əlavə, məşhur boksçuların

təcrübələrinin (vizualizasiya, nəfəs texnikaları, psixoloji üstünlük strategiyaları) elmi çərçivədə inteqrasiyası psixoloji hazırlığın praktik və tətbiqi modelinin formalaşdırılmasına imkan yaradır. Bu yanaşma fiziki və psixoloji hazırlığın qarşılıqlı təsirini müqayisəli şəkildə təqdim etməklə mövcud ədəbiyyata yeni baxış bucağı əlavə edir.

Elmi və praktik əhəmiyyəti:

Tədqiqatın nəticələri boksçuların performansının artırılmasında psixoloji hazırlığın həlledici rolunu sübut edir və bu sahədə məşqçi-idmançı münasibətlərinin optimallaşdırılması üçün əsas verir. Əldə olunan nəticələr məşq prosesində psixoloji hazırlıq proqramlarının hazırlanmasına, stressin idarə olunması və fokusun gücləndirilməsi üçün effektiv metodların tətbiqinə kömək edə bilər. Eyni zamanda, bu araşdırma idman psixologiyası sahəsində çalışan mütəxəssislər, məşqçilər və idmançılar üçün praktik tövsiyələr təqdim edir. Tədqiqat həmçinin gələcək elmi işlər üçün baza rolunu oynayaraq, döyüş idmanlarında psixoloji faktorların daha dərinə öyrənilməsinə və fərdi yanaşmaların inkişafına şərait yaradır.

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POLITICAL SCIENCES

REGULATING ONLINE PRE-ELECTION CAMPAIGNING IN ARMENIA: LEGAL AND POLITICAL CHALLENGES IN THE AGE OF ARTIFICIAL INTELLIGENCE

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Abstract

This article examines the legal regulation of pre-election campaigning in the Republic of Armenia within a digitized information environment, in the context of global trends in the use of artificial intelligence (AI). The article demonstrates that the Electoral Code of the Republic of Armenia does not currently provide a sufficient regulatory toolkit to address contemporary challenges associated with online campaigning. These challenges include AI-generated political content, deepfakes, digital manipulation, and algorithmic influence on voter behavior. In response, the study proposes a number of amendments to the legal framework governing pre-election campaigning under Armenian electoral legislation.

Keywords: Electoral Code, pre-election campaigning, political communication, artificial intelligence, deep-fake

Introduction

Contemporary electoral processes are undergoing substantial structural transformations driven by the digitalization of the public sphere and the growing use of artificial intelligence (AI) in politics. Political communication is gradually moving into the online environment, where the circulation and visibility of information are shaped not only by political actors but also by platform algorithms. The Electoral Code of the Republic of Armenia does not currently provide a sufficient regulatory toolkit to address contemporary challenges associated with online campaigning. These challenges include AI-generated political content, deepfakes, digital manipulation, and algorithmic influence on voter behavior.

Methods

The study is grounded in an interdisciplinary political-legal methodology.

Results and Discussion

Viewed through Jean Baudrillard's media-philosophical framework, these transformations suggest that online pre-election campaigning increasingly takes the form of simulation. According to Baudrillard, modern media is no longer merely a channel for transmitting information; rather, it constitutes an environment for producing models of reality. In many instances, these models come to replace reality itself, while political campaigning begins to operate through simulacra. Digital technologies make it possible to rapidly create and disseminate targeted political signs, images, fictitious events, and even fabricated political personae. It is precisely in this context that Baudrillard's notion of hyper-reality becomes relevant: non-existent meanings become so persuasive and influential that they begin to shape political behavior.

Global digitalization trends have shifted a considerable share of pre-election campaigning to social media platforms and this tendency is clearly reflected in Armenian political reality. Political communication in Armenia underwent a fundamental transformation after

the so-called Velvet Revolution of 2018, moving away from traditional media toward new media platforms, including social networks and live-streaming tools. This shift strengthened the direct communication between political actors and the public. [1]

The OSCE/ODIHR report on the parliamentary elections of December 9, 2018 recorded a notable shift in the structure of political information consumption by voters. Although television remained the primary source of political information, the report emphasized the growing significance of online media. [5] In relation to the 2021 snap parliamentary elections, the OSCE/ODIHR report went further, noting that social media platforms had become one of the main instruments of political communication alongside television. International observers stressed that electoral contestants actively used social platforms for political campaigning and for direct interaction with voters. Some political actors, lacking sufficient access to traditional media, conducted their campaigns almost exclusively through social media channels. [6]

Thus, the nationwide elections of 2018 and 2021 were marked by the virtualization of pre-election campaigning; in other words, a significant part of campaign activity took place in the virtual sphere, namely on the Internet. According to Freedom House's 2024 analysis, 58 percent of the population uses social media platforms to access political information, which already exceeds television's share as a source of political information. [1]

The Digital 2026: Armenia report prepared by Kepios Analysis indicates that, as of October 2025, 2.3 million people in Armenia use the Internet, of whom 1.6 million are active users of social media. The study applies a deduplication method, meaning that it seeks, to the greatest extent possible, to avoid counting the same user multiple times across different social networks. The same report identifies Facebook, Instagram, and TikTok as the most widely used social media platforms in Armenia. [8]

Accordingly, both the 2018 and 2021 nationwide elections in Armenia were marked by the virtualization of pre-election campaigning, in the sense that a substantial proportion of campaign activity took place within the digital sphere. This trend has only intensified. As digital technologies become more deeply integrated into political processes, the question of legal regulation becomes increasingly urgent. However, the rapid development of artificial intelligence has significantly altered the risk environment. By the period preceding the 2026 parliamentary elections, these earlier practices have been supplemented by more sophisticated forms of digital manipulation, including AI-generated audiovisual content, synthetic speech, and algorithmically amplified messaging.

The year 2024 has often been described as a “global election year,” since elections were held in around 60 countries worldwide. It was also distinguished by the unprecedented use of AI-generated content in electoral processes. [7] During this electoral cycle, generated deepfake content had a negative impact both on voter behavior and on public trust in democratic institutions and procedures. [2]

Under these conditions, a number of states have sought to regulate the use of artificial intelligence in election campaigns through legislative reform. For example, the European Union adopted the Artificial Intelligence Act, which establishes the legal meaning of the concept of “deepfake” and addresses the risks posed by such content in electoral processes. The Act does not prohibit AI-generated political content as such, but it recognizes such content as a risk factor for elections and imposes certain requirements, including mandatory labeling and disclosure measures. In particular, in Germany, during election periods, social media platforms may be required to remove manipulative AI-generated political content within 24 hours. [2]

South Korea’s electoral legislation, by contrast, imposes a general prohibition on the use of deepfake content for political purposes. [3] In the United States, several states prohibit the use of deepfakes during election periods, while others regulate their use through specific legal requirements. [4] China, for its part, criminalized the dissemination of deepfake materials without proper disclosure labels as early as 2019.

In Armenia, AI-generated content is already being widely used for political purposes. Research indicates that such content is actively circulating within the Armenian media space through real users rather than solely through anonymous or automated networks. The public not only consumes but also shares and comments on AI-generated political content, often compelling public authorities to issue denials and clarifications. Illustrative examples include the allegedly fake account of Mariam Israelyan, presented as an applicant rejected by the Diplomatic Academy of the Ministry of Foreign Affairs, [5] as well as deepfake videos featuring the Prime Minister and other public officials. [6]

AI-generated political videos have been increasingly disseminated in the period preceding the 2026 parliamentary elections, often by users connected to major political actors. [7] These materials are frequently posted without subtitles, disclaimers, or any

AI-generated content labels provided by social media platforms. Given the relatively low level of media literacy among parts of the population, such content spreads widely and poses a direct threat to the fairness and integrity of the electoral process.

Online pre-election campaigning in Armenia is regulated by Article 20.1 of the Constitutional Law of the Republic of Armenia Electoral Code, as amended on 7 May 2021 (HO-202-N). The article provides:

1. “Mass media operating on the Internet, as well as persons who are right holders of Internet websites, shall ensure non-discriminatory and impartial conditions for candidates and political parties (party alliances) during the period of pre-election campaigning.

2. During the period of pre-election campaigning, paid advertising materials and videos related to pre-election campaigning published on the Internet, including through mass media, may be disseminated only on the basis of a written agreement concluded with the candidate, party, or its representative, and only at the expense of the resources of the pre-election fund.

3. The publication of pre-election campaign materials shall be accompanied by the label ‘Pre-Election Campaigning’, while campaign videos shall contain a continuously displayed on-screen caption reading ‘Pre-Election Campaigning’. Campaign materials and videos must also include information identifying the customer.” [8] The need to amend the law had already been acknowledged in 2021 in the Joint Urgent Opinion of the Venice Commission on the Electoral Code of Armenia and related legislative amendments. The Opinion highlighted the new and extensive possibilities for influencing voters through social media and microtargeting techniques, as well as the manipulative potential of algorithmic processes. It specifically emphasized the need to assess regulatory frameworks governing political communication and electoral processes in order to preserve the fairness and integrity of elections. [9]

Conclusion

An analysis of the Electoral Code in light of current AI-related developments and international regulatory practice makes it possible to identify the following major gaps:

1. The Electoral Code of the Republic of Armenia lacks a number of key legal definitions, including, inter alia, “deepfake,” “AI-generated political content,” “AI-generated political advertising,” and “algorithmic microtargeting.”

The Code does not provide a sufficiently detailed framework regulating the placement and dissemination of political advertising by owners or operators of Internet platforms and websites.

2. The Code does not establish co-responsibility mechanisms for social media platforms with regard to the prompt removal of anonymous manipulative political content.

3. The Code does not require mandatory labeling of AI-generated political content.

Therefore, the Electoral Code of the Republic of Armenia does not currently provide an adequate legal toolkit to regulate contemporary challenges associated with online pre-election campaigning. In the context of

the modern digital era, the above legislative amendments would contribute to the formation of a more transparent, balanced, and controllable electoral environment.

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SOCIAL SCIENCES

MODERN HUMAN CAPITAL SYSTEM FOR A DIGITAL KAZAKHSTAN: CHALLENGES, MECHANISMS AND STRATEGIC PATHWAYS

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Abstract

In the context of global digital transformation, Kazakhstan, long reliant on oil and minerals, aims to shift from a resource-based to an innovation-driven economy. This transition depends on building a modern human capital system aligned with digitalization, especially as industrialization accelerates. This paper examines the current state, structural challenges, operational mechanisms, and strategic pathways for human capital modernization in Kazakhstan, integrating quantitative data (2020–2025) and international best practices. Using the World Bank HCI, labor market statistics, and digital indicators, it finds notable progress—including a rise in HCI+ ranking, high internet penetration, strong education metrics, many innovative firms, and widespread digital transaction adoption—but persistent bottlenecks: skill mismatches, regional digital divides, brain drain, and weak industry-education links. A three-pillar framework is proposed: Digital Skill Ecosystems, Inclusive Digital Labor Markets, and Governance & Financing Mechanisms. Empirical analysis shows strong correlations between digital skill adoption and labor productivity, and between digital infrastructure and human capital outcomes. Actionable phased strategies are suggested, such as AI curriculum integration, scaling dual vocational education, digital social protection systems, and a talent retention ecosystem, to position Kazakhstan as a regional leader in human capital and digital innovation by 2035.

Keywords: Human Capital System; Digital Transformation; Kazakhstan; Skill Mismatch; Labor Market

1. Introduction

Kazakhstan, an upper-middle-income Central Asian nation with a projected GNI per capita of \$15,100 in 2025 (above the World Bank's upper-middle-income threshold of \$14,005), is experiencing robust economic growth—forecast at 5.5% by the Eurasian Development Bank and 5.6% by Kazakhstan's Ministry of National Economy in 2025. However, its economic growth remains overly dependent on natural resources, which account for over 40% of exports and 20% of GDP. To address this over-reliance, the Kazakh government is prioritizing economic diversification through strategic investments in automotive manufacturing, home appliances, and metallurgy in 2025, initiatives expected to create over 20,000 new jobs, secure \$30 billion in foreign direct investment (FDI), and raise fixed asset investment to 30% of GDP by 2025.

To achieve the *Kazakhstan 2050 Strategy* and *Digital Kazakhstan 2025* national goals, the country must transition to knowledge-intensive, digital, and inclusive growth, where human capital becomes the primary driver of productivity and competitiveness. The World Bank's 2020 Human Capital Index (HCI) scores Kazakhstan at 0.63, indicating a child born today will realize only 63% of their potential productivity by age 18—placing Kazakhstan ahead of most Central Asian peers (e.g., Uzbekistan: 0.55, Kyrgyzstan: 0.48) but lagging behind OECD economies (average: 0.76) and digital leaders like Singapore (0.88) and South Korea (0.85).

Digital transformation presents both opportunities and risks for Kazakhstan: artificial intelligence (AI) could boost productivity for 70% of the workforce but automate 29% of job functions by 2030. Success in this

transition hinges on reengineering the human capital system to equip citizens with future-proof digital, cognitive, and adaptive skills; bridge regional and social digital divides; ensure inclusive labor market participation; and strengthen institutional coordination across education, employment, health, and innovation sectors.

This paper addresses four core research questions: (1) What is the current state of Kazakhstan's human capital system and its key digital-era challenges? (2) What quantitative relationships exist between digital infrastructure, skill development, and labor market outcomes? (3) What operational mechanisms underpin effective digital human capital modernization? (4) What strategic pathways can accelerate Kazakhstan's transition to a modern digital human capital system? The study contributes empirical evidence on digital human capital gaps in Central Asia, providing a data-driven framework and policy recommendations aligned with global best practices and Kazakhstan's national context.

2. Current State, Challenges and Analytical Framework

This study combines quantitative (2020–2025) and qualitative data to analyze Kazakhstan's human capital system. Quantitative data includes World Bank HCI and labor statistics, Kazakhstan's Bureau of National Statistics (KBNS) metrics, Coursera's 2026 Global Skills Report, the UN E-Government Index (2024), and national innovation surveys. Qualitative data encompasses *Digital Kazakhstan 2025*, the *National Development Plan 2025–2029*, and international case studies (Singapore's SkillsFuture, Germany's dual VET, Finland's interdisciplinary education, South Ko-

rea's human capital strategy). Analysis methods include descriptive statistics, correlation and regression analysis, gap analysis, and policy scenario analysis.

Kazakhstan has made notable progress in human capital and digital transformation. Key human capital indicators include a 2025 HCI+ global ranking of 42nd (1st in Central Asia), 74 years of life expectancy, 12.5 years of expected schooling, 15–20% youth unemployment (down 2% since 2018), and 72% female labor force participation (25+). Digitally, the country boasts 90.9% internet penetration, 85% mobile broadband coverage, 89% digital transaction adoption, and a UN E-Government Development Index of 0.90 (24th globally), with the digital economy accounting for 6.1% of GDP in 2024 (up from 2.8% in 2018).

Despite this progress, critical gaps persist: a 22.3-percentage-point urban-rural digital literacy divide (90.5% vs. 68.2%), 3.5 million workers needing re-skilling by 2030, 57% of 2022 VET graduates in non-core sectors, and ~15,000 skilled professionals emigrating annually. Core structural challenges include misalignment between education and the digital economy, rural-urban disparities in education quality and infrastructure, youth employment and NEET crises, brain drain and talent scarcity, and fragmented governance with insufficient funding (human capital spending at ~12% of GDP vs. OECD's 18–25%).

To address these challenges, the study proposes a three-pillar analytical framework for a modern digital human capital system: (1) Digital Skill Ecosystems (encompassing early childhood to lifelong learning, with a focus on curriculum alignment and AI/STEM integration); (2) Inclusive Digital Labor Markets (covering youth employment, gender equity, rural development, and formalization); and (3) Governance & Financing Mechanisms (focused on institutional coordination, data governance, and diversified funding).

3. Operational Mechanisms and Strategic Pathways

Five interlocking operational mechanisms are critical to implementing the three-pillar framework, supported by phased strategic pathways (2026–2035) to position Kazakhstan as a regional human capital and digital innovation leader.

First, the Demand-Driven Digital Skill Formation Mechanism (Pillar 1) mandates 50% employer representation on VET/university boards for curriculum co-design, scales German-style dual VET to 100,000 places by 2028, integrates AI and data literacy into all K-12 and higher education curricula, and launches a national lifelong learning platform in partnership with Coursera (targeting 1 million users by 2028).

Second, the Inclusive Digital Labor Market Integration Mechanism (Pillar 2) implements a Youth Guarantee 4.0 (ensuring 15–29-year-olds access internships/jobs within 6 months with digital training), expands gender digital empowerment (500 subsidized nurseries by 2028, 75% female labor force participation target), establishes 2,000 rural digital service hubs by 2030, and simplifies formalization processes to reduce informal employment to <20% by 2035.

Third, the Health & Resilience for Digital Productivity Mechanism (Pillar 2) achieves 100% rural telemedicine coverage by 2028, modernizes 3,000 primary care clinics, mandates workplace wellness for digital workers, and launches the *Kazakhstan Talent* program (grants, tax breaks, housing) plus a \$500 million diaspora venture fund to reverse brain drain.

Fourth, the Digital Governance & Accountability Mechanism (Pillar 3) establishes a Presidential Human Capital Council for cross-ministerial oversight, launches a National Human Capital Observatory for real-time data-driven policy adjustments, and ties 70% of education/health funding to performance outcomes.

Fifth, the Sustainable Financing Mechanism (Pillar 3) increases public investment in education to 6% of GDP and health to 5% of GDP by 2030, scales public-private partnerships (PPPs), and introduces Individual Learning Accounts with government-matched savings for lifelong learning.

Phased strategic pathways prioritize short-term quick wins (2026–2028: digital infrastructure for schools, teacher training, youth internships), medium-term scaling (2029–2031: full AI curriculum integration, universal social protection, reverse brain drain), and long-term excellence (2032–2035: OECD-level HCI, global talent hub status, 18% of GDP in human capital spending).

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TECHNICAL SCIENCES

OPTIMIZATION ALGORITHMS FOR PROCESSING DOCUMENT FLOW DATA ON THE HADOOP PLATFORM

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Abstract

In the era of digital transformation, document flow systems generate rapidly increasing volumes of structured, semi-structured, and unstructured data. Traditional data processing approaches are insufficient to efficiently manage, analyze, and extract meaningful insights from such large-scale datasets. This paper explores the application of optimization algorithms for processing document flow data on the Apache Hadoop platform. The study examines the effectiveness of Greedy and Genetic algorithms, along with other optimization techniques including Simulated Annealing, Ant Colony Optimization, and Particle Swarm Optimization. A comparative analysis is conducted based on key performance metrics such as execution time, memory usage, accuracy, and scalability. The findings indicate that while Greedy algorithms provide faster results, Genetic algorithms achieve higher accuracy and better scalability. Furthermore, the integration of hybrid optimization models demonstrates significant potential in improving both efficiency and performance in distributed big data environments. The results highlight the importance of combining optimization techniques with scalable platforms like Hadoop for advanced document flow management systems.

In the digital transformation era, document flow systems generate large volumes of diverse data that require efficient processing. Traditional methods are insufficient for handling such data at scale. This study investigates the use of optimization algorithms on the Hadoop platform for document flow data processing. Greedy and Genetic algorithms, along with other techniques, are analyzed based on performance metrics such as execution time, memory usage, accuracy, and scalability. The results show that Greedy algorithms are faster, while Genetic algorithms provide better accuracy and scalability. The study highlights the effectiveness of hybrid approaches in improving performance in distributed big data environments.

Keywords: Hadoop, Greedy, Genetic, Simulated Annealing, Ant Colony, Particle Swarm

Introduction

Modern DMS provide functionalities such as capturing, storing, retrieving, indexing, classifying, and distributing digital documents. Key features include audit trails, version control, access management, and integration with ERP systems. Recent research focuses on the use of artificial intelligence, particularly natural language processing (NLP), for automated classification and summarization. However, many DMS still face challenges in scalability and integration with big data analytics.

However, despite the advanced capabilities of modern Document Management Systems (DMS), the rapid growth of data volume and complexity has exposed their limitations, particularly in terms of scalability and integration with big data analytics. As a result, there is a growing need for more powerful and distributed computing frameworks that can efficiently handle large-scale document flow data. In this context, Apache Hadoop emerges as a suitable solution, providing scalable and fault-tolerant infrastructure for processing and analyzing massive datasets. [2, p.256-257]

Hadoop platform and its components

Apache Hadoop is an open-source framework designed for distributed storage and processing of big data. Its core components—HDFS (Hadoop Distributed File System), MapReduce (for data processing), and YARN (for resource management)—provide a robust, scalable, and fault-tolerant system. Hadoop supports

both structured and unstructured data formats. Its ecosystem includes powerful tools such as Hive (for SQL queries), Pig (for data transformation), and Spark (for fast in-memory analytics). The modular and scalable architecture of Hadoop makes it suitable for integration with machine learning pipelines and real-time data streaming frameworks such as Kafka.

The Hadoop ecosystem includes the following core components:

- **HDFS:** Stores large files by dividing them into blocks across multiple nodes
- **MapReduce:** Enables parallel processing by splitting tasks across machines
- **YARN:** Manages computational resources and task scheduling
- **Hive and Pig:** Provide high-level data processing using SQL and scripting
- **Spark:** Enables fast analytics for real-time and iterative tasks

Studies in healthcare, e-government, and finance sectors have demonstrated the effectiveness of Hadoop in document-oriented analytics. [1, p.107-113]

Optimization Algorithms in Big Data

Optimization algorithms help improve execution time, resource utilization, and result quality in large-scale systems:

- **Greedy Algorithms:** Simple and fast, selecting locally optimal solutions at each step; suitable when speed is a priority
- **Genetic Algorithms:** Based on natural selection and evolution, effective in exploring large solution spaces; suitable for multi-objective problems
- **Simulated Annealing:** Can accept worse solutions probabilistically to escape local minima

- **Ant Colony Optimization:** Inspired by ant behavior, useful for path and routing optimization
 - **Particle Swarm Optimization:** Based on social behavior models, effective in clustering and classification problems
- Hybrid forms of these algorithms are increasingly being used. [4, p.314-315]



Fig. 1. Greedy vs Genetic Algorithm Comparison

The comparative performance graph of Greedy and Genetic algorithms for document flow optimization is presented above (Fig. 1). The comparison is based on the following criteria:

- **Execution Time:** Greedy is faster
- **Memory Usage:** Genetic requires more memory
- **Accuracy:** Genetic provides higher accuracy
- **Scalability:** Genetic is more flexible

Example-1. The following code implements a simple document ranking system in Java (Fig. 2).

It stores documents with their scores, then sorts them in descending order based on those scores, and prints the results. The logic follows a greedy approach, meaning it prioritizes the highest-scoring documents first without applying any complex optimization or constraints.

In short, the program's purpose is to rank and display documents from most relevant (highest score) to least relevant (lowest score).

```
// GreedyDocumentSorter.java (sorts documents based on simple scores)
public class GreedyDocumentSorter {
    public static void main(String [] args) {
        // Simulated List of document scores.
        Map<String, Integer> docScores = new HashMap<>();
        docScores.put("doc1.txt", 34);
        docScores.put("doc2.txt", 87);
        docScores.put("doc3.txt", 12);
        docScores.put("doc4.txt", 65);

        docScores.entrySet().stream()
            .sorted(Map.Entry.<String, Integer>comparingByValue().reversed())
            .forEach(e -> System.out.println(e.getKey() + " -> " + e.getValue()));
    }
}
```

Fig. 2. Greedy Algorithm with MapReduce (Java)

Example-2. The following code implements a Genetic Algorithm for optimizing document ordering using Apache Spark (PySpark).

It simulates a set of documents and tries to find the best possible arrangement (solution) based on a defined fitness function. The algorithm works by generating multiple candidate solutions (populations), evaluating

them, and iteratively improving them through genetic operations like selection, crossover, and mutation (Fig. 3).

In general, the program:

- Creates random document sequences (solutions)

- Evaluates how “good” each sequence is using a fitness function
- Selects the best solutions
- Combines them (crossover) and slightly changes them (mutation)

- Repeats this process over several generations
At the end, it outputs the best document sequence found.

```
import random
from pyspark.sql import SparkSession

spark = SparkSession.builder.appName('GeneticDocFlow').getOrCreate()

# Observed documents
documents = [f'doc{i}' for i in range(1, 11)]

# Fitness function
def fitness(solution):
    return sum(ord(c) for doc in solution for c in doc) % 100

# Generate initial population
def generate_population(size):
    return [random.sample(documents, len(documents)) for _ in range(size)]

# Crossover operation
def crossover(p1, p2):
    point = len(p1) // 2
    return p1[:point] + [x for x in p2 if x not in p1[:point]]

# Mutation operation
def mutate(solution):
    i, j = random.sample(range(len(solution)), 2)
    solution[i], solution[j] = solution[j], solution[i]
    return solution

population = generate_population(10)

for generation in range(20):
    population = sorted(population, key=fitness, reverse=True)
    parents = population[:2]
    children = [mutate(crossover(parents[0], parents[1])) for _ in range(8)]
    population = parents + children

# Best result
best_solution = max(population, key=fitness)
print('Best solution:', best_solution)
```

Fig. 3. Genetic Algorithm (Python with PySpark)

Simulated Annealing (SA)

A practical application of the Simulated Annealing approach involves optimizing the distribution of documents across nodes in a Hadoop cluster. The main objective of this problem is to allocate documents in such a way that the overall execution time is minimized while maintaining proper load balancing among the nodes (Fig. 4).

The process begins with an initial random distribution of documents across the available nodes. Then,

iterative improvements are performed by making small adjustments, such as transferring a document from one node to another. Unlike traditional optimization methods, Simulated Annealing allows the acceptance of worse solutions with a certain probability, especially at higher temperature levels. This mechanism helps the system avoid local optima and increases the likelihood of reaching a more optimal global solution over time. [3, p.137-144]

```

documents = [10, 20, 30, 40, 50] # sizes
nodes = 3

def cost(sol):
    loads = [0]*nodes
    for d, n in zip(documents, sol):
        loads[n] += d
    return max.loads) - min.loads) # imbalance

current = [random.randint(0, nodes-1) for _ in documents]
T = 100
for _ in range(1000):
    new = current[:]
    i = random.randint(0, len(documents)-1)
    new[i] = random.randint(0, nodes-1)
    delta = cost(new) - cost(current)
    if delta < 0 or random.random() < math.exp(-delta / T):
        current = new
    T *= 0.99 # cooling
print('Optimized': current)

```

Fig. 4. Simulated Annealing algorithm

Ant Colony Optimization (ACO)

A practical application of the Ant Colony Optimization approach involves finding the optimal processing path in document workflows. In this problem, documents are required to pass through multiple stages, such as parsing, classification, and storage. The main objective is to determine the shortest and most efficient path that minimizes processing time (Fig. 5).

The method is based on the behavior of ants exploring possible paths between nodes. During the process, ants probabilistically select different routes, and paths that lead to better results accumulate higher levels of pheromones. Over time, these pheromone trails guide subsequent selections toward more optimal solutions, while less efficient paths gradually lose their significance and disappear. This iterative process enables the system to converge toward an optimal or near-optimal processing path. [5, p.157-156]

```

import numpy as np
pheromone = np.ones(4,4))
distance = np.array([
    [0, 2, 2, 5],
    [2, 0, 3, 4],
    [2, 3, 0, 1],
    [5, 4, 1, 0]])
alpha, beta = 1, 2
def choose_path(currentt):
    probs = []
    for i in range(4):
        pheromone<current[i]*alpha) * ((1/distance(current)[i])**
        beta if distance(current[i] else 0))
    probs = probs / np.sum(probs)
    return np.random.choice(range(4), p=probs)
path = [0]
for _ in range(3)
    path.append(choose_path(path[-1]))

```

Fig. 5. Ant Colony Optimization (ACO) algorithm

Particle Swarm Optimization (PSO)

A practical application of the Particle Swarm Optimization approach involves determining the optimal allocation of computational resources, such as CPU and

RAM, for document processing tasks. The primary objective is to minimize latency while maximizing system throughput (Fig. 6).

In this approach, each particle represents a potential resource allocation configuration within the system.

The particles move through the solution space by continuously updating their positions based on both their individual best-known solutions and the globally best solution found by the swarm. This collective behavior

enables the system to efficiently converge toward an optimal or near-optimal resource distribution, improving overall system performance in distributed environments. [6, p.2-3]

```
import random
particles = [random.uniform(0, 10) for _ in range(10)]
velocity = [0]*10
best_personal = particles[:]
best_global = min(particles)
def cost(x):
    return (x-5)**2 # optimal resurs 5
for _ in range(100):
    for i in range(10):
        velocity[i] = 0.5*velocity[i] + 0.8*(best_personal[i]-particles[i])
        particles[i] += velocity[i]
        if cost(particles[i]) < cost(best_personal[i]):
            best_personal[i] = particles[i]
    best_global = min(best_personal, key=cost)
print("Optimal resource value:." best_global)
```

Fig. 6. Particle Swarm Optimization (PSO) algorithm

Results

The results of this study demonstrate that optimization algorithms play a crucial role in improving the efficiency of document flow data processing on the Hadoop platform. The comparative analysis of Greedy and Genetic algorithms, along with other optimization techniques, highlights significant differences in performance based on key evaluation metrics such as execution time, memory usage, accuracy, and scalability.

The findings indicate that the Greedy algorithm performs efficiently in terms of execution time and computational simplicity. It is particularly suitable for scenarios where quick decision-making is required. However, its limitation lies in its tendency to reach only locally optimal solutions, which may reduce overall system performance in complex problem spaces.

In contrast, the Genetic algorithm provides higher accuracy and better scalability, making it more suitable for large-scale and complex optimization problems. Despite its advantages, it requires greater computational resources and memory usage, which may affect system efficiency in resource-constrained environments.

Additionally, optimization techniques such as Simulated Annealing, Ant Colony Optimization, and Particle Swarm Optimization have shown promising results in addressing specific challenges such as load balancing, routing optimization, and resource allocation in distributed systems. These methods are particularly effective in dynamic environments where adaptive solutions are required.

Overall, the results suggest that relying on a single optimization algorithm is not sufficient to address all

challenges associated with large-scale document flow processing. Hybrid approaches that combine multiple algorithms can significantly enhance both performance and accuracy while ensuring better resource utilization.

In conclusion, the integration of optimization algorithms within the Hadoop ecosystem provides an effective solution for managing and processing large-scale document flow data. The use of hybrid optimization models, combined with scalable distributed frameworks, offers a promising direction for improving system performance and supporting advanced data-driven decision-making processes.

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ABSORPTION OF NITROGEN OXIDES AND SULPHUR DIOXIDE UNDER INTENSIVE BARBOTAGE CONDITIONS**Zhuha O.***phD student**National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine*<https://orcid.org/0009-0000-9748-9129>**Davydov D.***phD student**National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine*<https://orcid.org/0000-0003-0712-0358><https://doi.org/10.5281/zenodo.19573273>**Abstract**

This study investigates the efficiency of gas purification from nitrogen oxides (NO_x) and sulfur dioxide (SO_2) using jet-bubbling contact devices under intensified hydrodynamic conditions. The aim is to enhance mass transfer and improve removal efficiency in gas–liquid systems applied in industrial emission control. The research combines theoretical analysis and experimental validation of absorption and oxidation processes. Particular attention is given to the oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2), which significantly increases absorption efficiency. Experimental studies were performed using water and alkaline absorbents, considering the influence of gas concentration, oxidation degree, and physicochemical properties of the liquid phase. Results show that jet-bubbling devices provide high turbulence and interfacial surface development, leading to improved mass transfer compared to conventional equipment. The removal efficiency of nitrogen oxides increases with higher oxidation levels, while sulfur dioxide absorption reaches up to 98.9% under optimal conditions using alkaline solutions. The findings confirm that jet-bubbling contact devices are an effective and compact solution for industrial gas treatment, offering reduced hydraulic resistance, lower energy consumption, and fewer technological stages. The proposed approach demonstrates strong potential for application in modern environmental protection systems.

Keywords: process intensification, absorption, mass transfer, hydrodynamic parameters, scrubber, contact devices, gas purification, operating parameters, nitrogen monoxide, nitrogen dioxide, absorbent, scrubbing, sulphur dioxide, degree of purification of the gas mixture

Introduction

The problem of environmental pollution caused by chemical toxins remains as acute as ever.

Emissions of nitrogen oxides into the atmosphere remain one of the environmental problems. Nitrogen oxides are formed as a result of the combustion of organic fuels in industries such as power generation, metallurgy, mechanical engineering, the chemical and petrochemical industries, road and rail transport, and others [1-2].

Over the past two decades, it has been established that the NO molecule has a wide range of biological effects, which can broadly be divided into regulatory, protective and harmful effects. Disorders of NO biosynthesis and metabolism are associated with conditions such as essential hypertension, ischaemic heart disease, myocardial infarction, primary pulmonary hypertension, bronchial asthma, neurotic depression, epilepsy, neurodegenerative diseases (Alzheimer's disease, impotence, etc.) [3].

Sulphur dioxide (sulphuric anhydride) also occupies a special place, due to its significant gross emissions and harmful properties [4]. This substance has a negative impact on the human body, flora and fauna, and possesses strong corrosive properties; consequently, it has a detrimental effect on the metal structures of buildings and structures, causing significant damage to property.

Furthermore, when sulphur dioxide combines with moisture, it forms sulphuric acid, which damages the lung tissue of humans and animals. This link is

particularly evident when analysing childhood lung conditions and the concentration of sulphur dioxide in the atmosphere of large cities. According to research by American scientists, at SO_2 pollution levels of up to 0.049 mg/m^3 , the morbidity rate (in person-days) among the population of Nashville (USA) was 8.1%, at $0.150\text{--}0.349 \text{ mg/m}^3$ – 12%, and in areas with air pollution levels above 0.350 mg/m^3 – 43.8%. Sulphur dioxide is particularly dangerous when it settles on dust particles and, in this form, penetrates deep into the respiratory tract [5].

Industrial production mainly emits sulphur dioxide when burning organic fuels containing sulphur. The main sources of SO_2 are the energy sector, metallurgical and engineering enterprises, as well as the petrochemical industry [6-7].

Research into the absorption of nitrogen oxides

To date, there are numerous methods for controlling nitrogen oxides, but they are only suitable for specific production processes and situations. In its own 'niche', the liquid absorption method for NO_x removal is of particular interest. The process of nitrogen oxide absorption has been studied quite thoroughly in both scientific research and industrial practice. The problem lies in the fact that, given the varying characteristics of exhaust gases, a specific technology must be developed for each absorption process.

In many industrial processes, it is not a single nitrogen oxide but a mixture of several that is emitted into the atmosphere – typically $\text{NO} + \text{NO}_2$. Moreover,

as is well known, NO_2 is highly soluble in water, whereas NO is poorly soluble in the liquid phase. This raises the question of converting NO to NO_2 in terms of the qualitative absorption of the gas mixture by the absorbent.

For cold nitrous gases, a study was conducted on the absorption of nitrogen oxides in plate-type contact apparatus.

The oxidation of NO to NO_2 mainly takes place in the liquid phase, which accelerates the conversion of nitrogen oxides into HNO_3 . Previous studies have shown that in reactors with mesh trays, this process occurs several times more intensively than in packed towers [8, 9]. It can therefore be assumed that in apparatuses with jet-bubbling phase contact, this process will be even more efficient. To evaluate this hypothesis, theoretical calculations were performed, which showed that to achieve high degrees of nitrogen oxide absorption from gases containing approximately 0.5% $\text{NO} + \text{NO}_2$, a column with 10–12 jet-bubble contact devices is required. To verify this assumption, the experiments described were carried out.

The experiment used a column with a diameter of 80 mm containing 10 contact devices with perforations ranging from 6 to 17 mm. The live cross-sectional area was 25%.

Nitrogen oxides were absorbed by water, which was fed through a rotameter to the upper part of the contact device. The experiments were conducted at gas flow rates in the column ranging from 0.65 to 0.70 m/s. The temperature of the gas-liquid layer was 15–17°C.

Depending on the initial nitrous oxide content of the gas and the level of NO oxidation, the degree of gas absorption was determined using the following formula:

$$\eta = \frac{C_1 - C_2}{C_1} \cdot 100$$

where C_1 and C_2 - the initial and final concentrations of nitrogen oxides, (vol. %).

To assess the extent to which NO is oxidized to NO_2 , the theoretically possible degree of NO_2 absorption by water was also calculated

$$A = \frac{\frac{2}{C} C_{\text{NO}_2}}{C_1} \cdot 100,$$

where C_{NO_2} - NO_2 concentration in the exhaust gas (%).

The ratio η/A indicates how much of the nitrogen monoxide oxidized in the column is absorbed by water and converted to HNO_3 .

The effect of gas oxidation on the degree of absorption was studied at a spray density $L = 2 \text{ m}^3/\text{m}^2 \cdot \text{h}$. The concentration of the initial gas mixture ranged from 0.55 to 0.65% $\text{N} + \text{NO}_2$.

The degree of NO oxidation ranged from 0.34 to 0.72, and the absorption level of $\text{NO} + \text{NO}_2$ increased as the gas oxidation $\alpha_1 = \frac{\text{NO}_2}{\text{NO} + \text{NO}_2}$ increased. In our experiments, it ranged from 35% to 50%.

As the gas oxidation increases, the theoretical absorption coefficient A also increases, but to a greater extent than η . Therefore, the value of η/A decreases.

If, at an oxidation state of $\alpha_1 = 0.34$, the ratio η/A averages 140%, then at $\alpha_1 = 0.7$ it is 106%. This indicates that the less oxidized the gas is, the more NO is converted to NO_2 , and the greater the amount converted to nitric acid.

However, not all of the nitrogen dioxide that was present in the gas and has been re-formed is absorbed by water in time. This is indicated by the oxidation state of the gas leaving the column—it remains quite high and depends on the oxidation state of the feed gas α_1 .

Thus, at $\alpha_1 \sim 0.6$, the degree of NO oxidation in the gas leaving the column remains approximately constant ($\alpha_2 \sim 0.35\text{--}0.4$). Then α_2 begins to increase. At a degree of oxidation of the feed gas of $\alpha_1 \sim 0.7$, despite the high degree of NO_2 absorption $\alpha_1 \approx \alpha_2$. Exclusively in the gas phase, the conversion of NO to NO_2 could not occur during the short contact time upstream of the apparatus; therefore, it is achieved on the developed phase contact surface, i.e., up to 90–95% of the total amount of nitrogen monoxide is oxidized in the liquid. The experiments were conducted at a spray density of $L = 2 \text{ m}^3/\text{m}^2 \cdot \text{h}$. The gas oxidation level ranged from 0.59 to 0.65, indicating that the degree of nitrogen oxide absorption $\text{NO} + \text{NO}_2$ increases from 16% to 42% as the nitrous content of the gases changes from 0.17% to 0.30%.

As the concentration of nitrogen oxides in the gas increases further, absorption increases only slightly. Conversely, as the concentration of $\text{NO} + \text{NO}_2$ decreases, the degree of absorption decreases. The following relationship is observed: when the gas contains $\text{NO} + \text{NO}_2$ up to 0.3% – ($\eta/A < 100\%$); if this mixture exceeds 0.3%, the ratio $\eta/A = 100$ or higher. In this case, a portion of the NO_2 formed during the oxidation of NO is absorbed as the gas passes through the column. In the column with a jet-bubbling contact device, the gas-liquid system becomes turbulent, which promotes the oxidation of NO to NO_2 - an absorption rate of over 50% was achieved across 10 contact device blocks. Thus, as the concentration of nitrogen oxides in the outlet gas decreases, the efficiency drops sharply.

In addition to the absorption of nitrogen oxides by water, studies were conducted on alkaline absorption (using an aqueous solution of sodium carbonate as the absorbent). The experiments showed that the efficiency of the $\text{NO} + \text{NO}_2$ chemisorption process is greatly influenced by the time since the solution was prepared (the so-called “freshness of the solution”). This effect is apparently explained by the fact that in a fresh solution there are no intermediate compounds that inhibit the absorption process.

Analyses were conducted in both the gas and liquid phases, with the balance of gas and liquid absorption falling within the margin of error.

The experimental results are shown in Table 1. The table also includes, for comparison, three sets of

experimental data obtained using 15 perforated sieve plates [10].

Table 1.

Absorption of nitrogen oxides in an absorber with a jet-bubble contact device

Gas inlet		Gas outlet		Degree of absorption in the gas phase, η_1 , %	Degree of absorption in the liquid phase, η_2 , %	Cleansing effect, %	Absorption coefficient, K
$NO + NO_2$	α_1	$NO + NO_2$	α_2				
15 Perforated Plates							
0.64	0.47	0.35	0.35	45.8			
0.61	0.48	0.34	0.34	44.3	-	3.9	68
0.61	0.49	0.34	0.34	44.3			
10 jet-bubble contact devices							
0.53	0.50	0.25	0.52	52.6			
0.46	0.56	0.29	0.38	38.1			
0.30	0.63	0.13	0.67	60.0	44.3	13.4	883
0.46	0.65	0.20	0.35	56.6			
0.54	0.65	0.25	0.50	58.6			
0.61	0.58	0.26	0.42	57.5			
0.59	0.61	0.24	0.37	59.4			
0.68	0.48	0.26	0.46	59.8			
0.26	0.50	0.27	0.48	51.8			
0.57	0.49	0.27	0.48	52.6	56.4	14.2	403
0.54	0.54	0.25	0.50	51.9			
0.58	0.50	0.26	0.54	51.0			

The data presented indicate that jet-bubble contact devices achieved approximately the same degree of nitrogen oxide absorption as 15-pass sieve plates. A comparison of these data shows that the efficiency of the jet-bubble contact devices is approximately 3.5 times higher, and the absorption coefficient is 5.5-6.0 times higher than that of the perforated sieve plates.

Thus, to achieve the same degree of absorption, jet-bubble contact devices will require several times fewer units, which will lead to a reduction in the overall column resistance and a decrease in capital costs.

The following main conclusions can be drawn from the studies conducted.

The degree of absorption depends on the initial nitrogen oxide content of the gas;

When nitrogen oxides in the feed gas are reduced below 0.3% $NO + NO_2$, the degree of absorption decreases sharply;

Along with the absorption of nitrogen oxides in the column, there is simultaneous intensive oxidation of NO to NO_2 , which occurs mainly in the liquid phase.

Sulfur dioxide absorption under conditions of intense bubbling

Methods and techniques for sulfur dioxide purification have been under development by the scientific and industrial communities for quite some time. Among the existing methods, the following should be highlighted: wet (without sulfur recovery, cyclic with sulfur recovery, and with the production of new sulfur-containing chemicals) and dry (with a similar classification of processes for removing sulfur dioxide from gas) [11-13].

However, it should be noted that there is no universal method suitable for every type of production [14]. For instance, wet scrubbing is of particular interest for the purification of sulfur-containing gases at oil refineries, specifically in absorption units operating under enhanced bubbling conditions [15-16].

One of the main objectives in developing technology for the absorption of contaminated gas in an absorption unit is to select a hydrodynamic regime that ensures the greatest possible contact surface area between the gas and liquid phases and, as a result, enables the removal of toxic components from the gas with high efficiency, which is achieved by absorbers operating under intensive hydrodynamic conditions. In addition, such units are compact in size and feature a simple design [17-18].

The scope of application for intensified devices in industry can be very diverse: they can be used for processes such as gas absorption and desorption, dust collection, flue gas cleaning, mist removal, and others.

Absorbers operating under intense hydrodynamic conditions are columns with rectangular or circular cross-sections and horizontally arranged packing elements. The number of packing elements and their configuration depend on the unit's process purpose.

The contact devices in such units are block elements of jet-bubble contact devices with uniformly spaced holes, the total area of which i.e., the free cross-sectional area – typically ranges from 10 to 60% of the total cross-sectional area of the column. The diameters of the contact device's holes are 3-6 mm or more, and the distance between the centers of the holes (pitch) depends on the size of the device's individual cells, as well as the required free cross-sectional area.

By maintaining the velocity of the gas entering the unit through the diffuser within the range of 0.5–3.5 m/s, a fully developed bubbling regime can be achieved through the kinetic effect on the entire gas-liquid system. In this process, the liquid, passing through the distribution device and reaching the contact device in the form of moving foam, and having passed through the contact stages required by the process parameters, is discharged into a drain tank-defoamer, where the

foam is broken down and the liquid is removed from the apparatus via a pipeline.

The height of the moving foam on the contact devices can be adjusted within the range of 30 to 50 mm by varying the inter-contact distance, the gas velocity, and the amount of liquid fed into the unit. The purified gas exits through a fitting at the top of the unit, while the liquid, which has captured harmful impurities in the gas, is drained through a hopper and a fitting at the bottom of the unit.

The aim of the study was to investigate the feasibility of using jet-bubble contact devices in an extended bubbling mode for the capture of sulfur dioxide from process off-gases.

The experiments were conducted on single- and double-block jet-bubble contact devices in an extended bubbling mode.

For the sulfur dioxide experiments, the optimal hydrodynamic operating mode of the apparatus for the air-water system was selected in advance. Experiments showed that the developed bubbling mode and the most stable foam are achieved at a gas-air mixture velocity of 1-3.5 m/s. When using different chemical reagents for sulfur dioxide capture, the gas velocity can be varied within certain limits to optimize the purification process.

The unit operated according to the following scheme: sulfur dioxide from the cylinder flowed through a pressure reducer to the mixer, where air from the compressor was fed. The flow rate of the gas-air mixture was taken to be equal to the air flow rate and was measured using a rotameter. From the mixer, the gas-air mixture was fed into the apparatus from below and, foaming the absorbent, was discharged through the upper part of the apparatus. The absorbent was supplied

from a pressure vessel to the upper block of the contact device.

The following were tested as absorbents: triethanolamine, 4% and 8% solutions of caustic soda, and a 3–5% aqueous solution of soda ash.

The absorption capacity of the absorber, or the degree of absorption, was determined as the ratio of the difference between the initial and final concentrations of sulfur dioxide to its initial concentration. Experiments on sulfur dioxide capture were conducted at a normal temperature of 15–35°C, with a gas-air mixture velocity of 0.6–3.5 m/s. The initial concentration of sulfur dioxide in the gas-air mixture ranged from 0.206–1.000%.

The results of the experiments are presented in Table 2. The table shows that triethanolamine proved to be an ineffective absorbent.

The highest degree of purification was achieved using a 5.8% solution of soda ash and an 8% solution of caustic potash, which ensure the capture of sulfur dioxide up to 98.9%.

The tabulated data also indicate that a sulfur dioxide absorption rate of 87.7–90.0% was achieved in the single-block model, and 92.7–98% in the two-block model. Therefore, if a high degree of purification is required, a greater number of block sections must be installed in the apparatus.

When using a two-block contact device in an enhanced bubbling mode with chemical reagents such as a 5.3% aqueous solution of soda ash and 4% and 8% caustic potash, the capture of sulfur dioxide from the gas was 92.3–96%. At the same time, the sulfur dioxide content at the outlet of the bubbling apparatus was 0.0137–0.0150%.

Table 2.

Sulfur dioxide capture efficiency in bubbler columns

Name of the absorber	Experimental conditions				Concentration SO ₂		Degree of absorption
	gas-air mixture velocity, m/s	gas-air mixture flow rate, m/s	duration of the experiment, s	temperature, °C	at the device's input	at the output of the device	
Single-block contact device							
Trimethylamine	2.6	13.1	13	17	0.9800	0.2400	75.5
-//-	2.6	13.1	10	17	0.5900	0.215	63.5
Sodium carbonate 5.3% aqueous solution	2.0	10.0	30	16	0.2270	0.0217	90.4
Sodium carbonate 5.3% aqueous solution	2.0	10.0	30	16	0.2270	0.0213	90.6
Caustic soda 4% aqueous solution	2.0	10.0	20	17	0.2070	0.0270	86.9
Caustic soda 8% aqueous solution	2.0	10.0	20	15	0.2620	0.0310	88.1
Caustic soda 8% aqueous solution	2.0	10.0	20	15	0.2620	0.0380	85.5
Two-block contact device							
Caustic soda 8% aqueous solution	3.5	17.6	30	16	0.3190	0.0132	95.86
Caustic soda 8% aqueous solution	3.5	17.6	32	16	0.4280	0.017	96
Sodium carbonate 5.3% aqueous solution	3.7	18.7	60	16	0.2100	0.0158	92.5
Sodium carbonate 5.3% aqueous solution	3.7	18.7	60	16	0.2060	0.0150	92.7

Conclusions

Thus, it has been established that sulfur dioxide can be captured by connecting an absorption unit equipped with a jet-bubbling contact device, operating in an enhanced bubbling mode, to the treatment plant. The results demonstrate that the oxidation process predominantly occurs in the liquid phase due to increased turbulence and developed interfacial contact. The findings indicate that jet-bubbling contact devices achieve comparable or higher efficiency than traditional plate columns while requiring fewer stages, thus reducing hydraulic resistance and capital costs.

To achieve the same degree of absorption, jet-bubble contact devices will require several times fewer units, which will lead to a reduction in the overall column resistance and a decrease in capital costs. Jet-bubbling contact devices represent an effective and compact solution for industrial gas purification, providing enhanced mass transfer, high removal efficiency, and reduced operational costs. The proposed approach can be widely applied in modern environmental protection systems.

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STUDY TO DEVELOP A SCIENTIFIC NARRATIVE TO ILLUSTRATE THE FATE OF THE UNIVERSE WITH THE HELP OF MODERN ASTROPHYSICS AND QUANTUM COSMOLOGY

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Abstract

Astrophysicists model the lifecycles of stars, perceiving that in the distant future, no new stars will form, leading to a dark universe. Astrophysics suggests the universe will likely end in a Heat Death or Big Freeze, and that is driven by accelerating expansion from dark energy. However, modern cosmology holds that the universe began around 13.8 billion years ago with the Big Bang, has been growing since, and is presently dominated by dark energy, causing accelerated expansion. Data from the Planck mission and other observatories suggest the universe is spatially flat and will continue expanding, supporting the Big Freeze scenario. The cosmos will become cold, dark, and empty as galaxies drift apart, stars burn out, and matter eventually breaks down. Other theoretical fates include a Big Rip or a Big Crunch. The most widely accepted scenario, driven by dark energy accelerating the universe's expansion, is that the universe will continue to expand until all stars burn out and black holes evaporate, reaching maximum entropy. However, if the universe's density were high enough, gravity could overcome the current expansion, causing the universe to stop expanding and eventually collapse back into a singular point. On the other hand, if the density of dark energy increases over time, it could become strong enough to tear galaxies, stars, planets, and eventually atoms apart. Again, a theory suggesting a cyclical scenario where a Big Crunch is followed by a new Big Bang, implying a series of universes. Actually, the future of the universe is still a subject of research, with its final state depending heavily on the precise nature of dark energy and the total amount of matter (dark and baryonic) in the cosmos. This is an investigative study to illustrate a probable scenario of the fate of the universe based on modern astrophysics and cosmology.

Keywords. Astrophysics, cosmos, WUM, BBM, dark energy, black hole, Big Freeze, Big Crunch

1. Introduction

Modern Astrophysics is the branch of science that uses physics and chemistry to understand the formation, evolution, and demise of stars, planets, galaxies, nebulae, and other cosmic objects.¹ Unlike classical astronomy, which focuses on the positions and motions of celestial bodies, astrophysics seeks to understand their physical nature—what they are and how they work.² The field of Astrophysics is broad, encompassing phenomena from tiny subatomic particles to the largest cosmic structures. Cosmology, a key branch of Astrophysics, studies the universe's origin and development, including the Big Bang, dark matter, and dark energy.³ Stellar Astrophysics focuses on the life cycles of stars, from their formation in nebulae to their end states as white dwarfs, neutron stars, or black holes. Galactic Astrophysics explores the structure and evolution of our Milky Way and other galaxies. Meanwhile, High-Energy Astrophysics investigates extreme phenomena

such as quasars, gamma-ray bursts, and active galactic nuclei.⁴

Quantum cosmology is the attempt in theoretical physics to develop a quantum theory of the universe.⁵ This approach seeks to address open questions in classical physical cosmology, particularly those related to the universe's early phases.⁶ Classical cosmology is based on Albert Einstein's general theory of relativity (GTR or simply GR), which describes the evolution of the universe very well, as long as you do not approach the Big Bang. It is the gravitational singularity and the Planck time where the theory of relativity fails to provide what must be demanded of a final theory of space and time. Therefore, a theory is needed that integrates relativity and quantum theory.⁷ Such an approach is attempted, for instance, in loop quantum cosmology, loop quantum gravity, string theory,

¹ Zeilik, M. and Gregory, S.A. (1998) *Introductory Astronomy and Astrophysics*. 4th Edition, Saunders College Publishing, Philadelphia, accessed on 11 Mar 2026

² Keeler, James E. (November 1897). "The Importance of Astrophysical Research and the Relation of Astrophysics to the Other Physical Sciences". *The Astrophysical Journal*. 6 (4): 271–288, doi:10.1086/140401, accessed on 11 Mar 2026

³ <https://www.cambridge.org/highereducation/books/an-introduction-to-modern-astrophysics/140DDF8A480C3841DCCD76D66984D858/contents/351D92F23E4D4016D6261254E763B10E>, accessed on 11 Mar 2026

⁴ Maoz, Dan (2016). *Astrophysics in a Nutshell*. Princeton University Press. p. 272. ISBN 978-1400881178, accessed on 11 Mar 2026

⁵ Bojowald, Martin (2015). "Quantum cosmology: A review". *Reports on Progress in Physics*, 78 (2): 023901. arXiv:1501.04899, doi:10.1088/0034-4885/78/2/023901. PMID 25582917. S2CID 18463042, accessed on 11 Mar 2026

⁶ Chiou, Dah-Wei (2015). "Loop quantum gravity". *International Journal of Modern Physics D*. 24 (1): 1530005–1530331. arXiv:1412.4362, doi:10.1142/S0218271815300050. S2CID 16655619, accessed on 11 Mar 2026

⁷ Stephen Hawking wrote 1999: So what the singularity theorems are really telling us, is that the universe had a quantum origin, and that we need a theory of quantum cosmology, if we are to predict the present state of the universe. "Quantum Cosmology, M-theory and the Anthropic Principle – Stephen Hawking". Archived from the original on 2015-02-14. Retrieved 2015-02-14, accessed on 11 Mar 2026

and causal set theory.⁸ In quantum cosmology, the universe is treated as a wave function instead of classical spacetime.⁹ However, the most likely long-term fate of the universe is Heat Death, in which expansion continues, leaving a cold, dark, and empty universe.

Because full gravity is complex, investigations that avoid symmetry assumptions or perturbative methods typically address conceptual issues. As mentioned earlier, cosmology is unique in physics because no external observer can exist. This fact affects how we interpret observations classically, but its significance is clearer in quantum cosmology. Traditional interpretations of quantum mechanics often depend on external observers, making them unsuitable for cosmological scenarios.¹⁰ Quantum cosmology involves studying the universe as a whole as a quantum system. It encompasses two main challenges. The first concerns developing a quantum version of the universe's dynamics, particularly examining the quantum features of the simplified dynamical systems, assuming the universe is homogeneous. Classical models, such as the Friedmann-Robertson-Walker model, are vital in cosmology and are thought to describe the universe's large-scale structure accurately. Quantizing these models is valuable for several reasons: it offers a simplified setting to explore conceptual issues in Quantum Gravity (QG) and test potential solutions, and it provides a means to investigate what a quantum theory of gravity might reveal about the physics near and at the Big Bang, where quantum gravitational effects are expected to be significantly dominant.

The advent of Einstein's general theory of relativity revitalized interest in and research on cosmology, the study of the universe on its largest scale. Under Newtonian theory, cosmology primarily focused on one question: how matter is spread out in an infinite, Euclidean space. Einstein's theory, however, significantly expanded this question. Cosmologists now had to consider numerous possible matter distributions, geometries, and dynamics for each. All these possibilities were linked through Einstein's gravitational field equations, which determined which matter arrangements could correspond with specific geometries and how the entire system might change over time.¹¹ Understanding the structure and evolution of the universe comes through Nuclear Physics and the Physics of Ionizing Radiation. These fields explain how matter forms, how stars produce energy, and how elements are synthesized over time. By analyzing the behavior of protons and neutrons in atomic nuclei and examining the radiation

emitted during stellar processes, scientists can piece together the universe's history from the Big Bang to today and make predictions about its final fate.¹² The formation and development of stars, gravitational collapse, neutron stars and black holes, the structure and formation of galaxies, the expansion of the universe, the very early universe, primordial and stellar nucleosynthesis, and the unification of interactions in unitary field theories are discussed in those two parts of Physics.¹³

The end of the universe remains a complex issue in both science and philosophy, with no definitive answer. Scientists have proposed various hypotheses about the ultimate fate of the universe, including Big Rip, Big Crunch, and Heat Death. All those possibilities will discuss in this article later. Regardless of where the universe ultimately leads, it has no direct bearing on the purpose of biological evolution. All this is certainly very beautiful and beneficial from the point of view of our knowledge of nature, the universe and the possibilities of technological applications for the benefit of enlightening life here on Earth and possibly its expansion into space.¹⁴ However, for fair neutrality, it is probably worth mentioning the other side of the coin. Humans are still deficient in ample knowledge. Willingly admit what we do not know about the universe and the nature of matter until now. Humans can pose many questions about the universe and the physical nature of matter that our scientific knowledge cannot yet answer. And the number of questions is certainly incomplete. A few primary but important questions need to be answered. Astrophysics in general and quantum cosmology in particular will continue to try to find the answers to those questions. Author will try to illustrate the whole scenario and narrate the story of creation and ultimate fate of universe in light of modern concept and advancement of Astro Physics.

a. How did the universe create? We have no idea yet about the "mechanism" of the origin or creation of the universe. It is only known that in the beginning the universe was very hot and dense. And we know most of the mechanisms of how it gradually cooled and transformed its material content to its current cold state with a very low average material content. This is supported by astronomical observations and laboratory experiments on particle accelerators.¹⁵ However, we cannot say anything about the very beginnings in the first approximately 10^{-43} to 10^{-36} seconds.

b. What is the core of gravity? The classical Newtonian concept of gravity, which works well in practice, has been generalized in the general theory of relativity.

⁸ Klebanov, Igor & Maldacena, Juan (2009). "Solving Quantum Field Theories via Curved Spacetimes", *Physics Today*. 62 (1): 28, doi:10.1063/1.3074260, accessed on 11 Mar 2026

⁹ He, Dongshan; Gao, Dongfeng; Cai, Qing-yu (2014). "Spontaneous creation of the universe from nothing". *Physical Review D*. 89 (8): 083510, doi:10.1103/PhysRevD.89.083510, S2CID 118371273, accessed on 11 Mar 2026

¹⁰ https://www.researchgate.net/publication/358918610_Lectures_on_classical_and_quantum_cosmology, accessed on 11 Mar 2026

¹¹ https://sites.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/relativistic_cosmology/index.html, accessed on 11 Mar 2026

¹² Mayer, Maria Goeppert (1949). "On Closed Shells in Nuclei. II". *Physical Review*. 75 (12): 1969–1970, doi:10.1103/PhysRev.75.1969, accessed on 12 Mar 2026

¹³ Rugh, S. and Zinkernagel, H. (2001) *Studies in History and Philosophy of Modern Physics*, 33, 663–705,

¹⁴ Feynman, R.P. (2011) *Six Easy Pieces: Essentials of Physics by Its Most Brilliant Teacher*. Basic Books, New York.

¹⁵ Chow, T.L. (2008) *Gravity, Black Holes, and the Very Early Universe: An Introduction to General Relativity and Cosmology*. Springer, New York.

And that works perfectly in the entire universe, and describes it as curved spacetime. Again, the curvature of spacetime caused by mass and energy, rather than just a traditional force acting at a distance.¹⁶ It dictates that objects (and light) follow paths through this warped geometry, bringing them together. While weak on atomic scales, it shapes the large-scale universe. However, the reason why matter curves spacetime in its surroundings is not known. So far, we do not know what gravity is, only how it works. Perhaps the future complete unitary field theory will answer this, but from the opposite side: how do "condensations" in the geometry of spacetime create what appears to us as matter?

c. Why is there a huge amount of matter and almost no antimatter in the universe? According to the laws of the symmetrical formation of particles and antiparticles, at the beginning of the universe both should have been created in the same ratio (or 1:1). And that would lead to complete annihilation and the universe would contain only radiation. The observable universe is dominated by matter, with a tiny, crucial asymmetry, as antimatter is effectively absent in large quantities. It is estimated that for every billion antimatter particles, a billion-and-one matter particles were created, leaving a ratio of roughly 1 leftover matter particle for every 10^9 annihilation events.¹⁷ All the matter that exists in the universe resulted from this slight excess after annihilation. We do not know for sure why this asymmetry of matter and antimatter occurred.¹⁸

d. What is the internal structure of the elementary particles of the microworld? According to the Standard Model of particle physics, true elementary particles—such as quarks, leptons (including electrons and neutrinos), and bosons—do not have an internal structure. They are considered point-like, zero-dimensional objects, meaning they are not made of smaller components and cannot be broken down further. Direct investigation of the inside of particles of the microworld is not possible. This is possible only by the destructive method of mutual collisions of particles in accelerators, while studying new particles that fly out. In this way, it was possible to reveal the internal quark-gluon structure of hadrons, especially protons and neutrons. For other hadrons - pions, kaons, hyperons - their quark structure is assumed in a model, based on analogy. For leptons, such as electrons or muons, no internal structure has been discovered, they are considered to be "point". Their observed properties, such as spin or magnetic moment, are considered to be their inherent characteristics, without proper explanation. So, we have to admit that we do not yet know the nature of most of the particles that make up our world. This explanation is expected; probably in the more distant future, from unitary field theories.

e. What is the ultimate fate of the universe? Based on existing observational evidence, determining the universe's future and evolution has become a legitimate cosmological question, beyond the largely untestable constraints of mythological or theological beliefs. Several potential futures have been proposed by various scientific hypotheses, including that the universe could have existed for a finite or infinite amount of time, and attempts to explain the manner and circumstances of its origin. Observations by Edwin Hubble during the 1930s–1950s revealed that galaxies were moving away from each other, leading to the currently accepted Big Bang theory. This implies that the universe began very dense approximately 13.787 billion years ago and has been expanding and, on average, decreasing in density ever since.¹⁹ Most cosmologists agree that the universe is flat in shape and will keep expanding indefinitely. To understand its origin and final destiny, one must consider factors such as the average motion of galaxies, the overall shape and structure of the universe, and the quantities of dark matter and dark energy present contains.^{20,21}

2. Historical Chronology and Literature Review

2.1 Incomprehensible Incomprehensibility of Quantum Physics

In contemporary physics, there are several findings, theories, and hypotheses that deal with phenomena in the deep microworld or very distant universe - in areas inaccessible to our direct observation and experience. In attempts to understand and explain them, ideas and concepts appear that are difficult for our "common sense". And that has developed from observing the surrounding macro world to understand. One such area is the special and especially general theory of relativity. And that is sometimes said to be "incomprehensibly-incomprehensible", to which this entire book of ours "Gravity, Black Holes and the Physics of Spacetime", is essentially dedicated. Even less understandable for us is quantum physics, and that is sometimes said to be 'incomprehensibly incomprehensible.' These hidden aspects are discussed from various perspectives in the branch of 'Nuclear Physics and Physics of Ionising Radiation'. Astro Physics in general and Quantum Physics in particular are extremely successful for investigating the structure of matter, as well as in applications, but their fundamental inner nature is hidden from our understanding by a mystery.

2.2 World Universe Model (WUM)

In 1937, Paul Dirac introduced the large number hypothesis and the hypothesis of a 'variable gravitational constant,' later adding the idea of 'continuous creation of matter' in the universe. The Hypersphere

¹⁶ Einstein, A. (1905) *Annalen der Physik*, 17, 891-921, accessed on 12 Mar 2026

¹⁷ Segal, I. E. (December 1993). "Geometric derivation of the chronometric redshift". *Proceedings of the National Academy of Sciences USA*. 90 (23): 11114–11116, doi:10.1073/pnas.90.23.11114

¹⁸ <https://home.cern/science/physics/matter-antimatter-asymmetry-problem>, accessed on 12 Mar 2026

¹⁹ Wollack, Edward J. (10 December 2010). "Cosmology: The Study of the Universe". *Universe 101: Big Bang Theory*. NASA. Archived from the original, accessed on 12 Mar 2026

²⁰ <https://science.nasa.gov/dark-matter/>, accessed on 12 Mar 2026

²¹ Tegmark, Max (2014). *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality* (1 ed.). Knopf. ISBN 978-0-307-59980-3, accessed on 12 Mar 2026

World Universe Model (WUM) builds on these concepts but proposes a different mechanism for matter creation. This model suggests that the universe is a 3D hypersphere surface expanding into a fourth spatial dimension, maintaining a constant energy density equal to the critical energy density.²² WUM suggests that dark matter particles (DMPs) are continuously created from the 4D nucleus, thereby producing luminous matter via annihilation, and provides a framework for calculating cosmological parameters that match observations, such as the Hubble parameter and the cosmic microwave background temperature.²³

However, WUM is a natural extension of classical physics. It is proposed as an alternative to the dominant Big Bang Model (BBM), which is based on General Relativity (GR). WUM and BBM are fundamentally different models. First, instead of the initial singularity with infinite energy density and rapid spacetime expansion (Inflation) in BBM, WUM suggests there was a fluctuation- specifically, a 4D nucleus of the universe with an extrapolated radius equal to the basic size unit of 'a'- existing in an eternal universe with finite energy density (about 10^4 times less than nuclear density) and a finite expansion of the nucleus in its fourth spatial dimension at the speed of light, which is the gravitodynamic constant. Second, while BBM implies a virtually infinite, homogeneous, and isotropic universe around the initial singularity, WUM describes a three-dimensional, finite, yet unbounded universe and that is an hypersphere of a 4D nucleus- featuring a patchwork of luminous superclusters (≥ 103), which formed in various locations at different cosmological times. The universe's medium, composed of protons, electrons, photons, neutrinos, and dark matter particles, is homogeneous and isotropic, but the distribution of macro-objects is spatially inhomogeneous, anisotropic, and varies over time non-simultaneously.²⁴

The strongest observational evidence supporting the validity of WUM includes: first, the Microwave Background Radiation and Intergalactic Plasma indicate the presence of a Medium. Second, the Laniakea Supercluster, with a binding mass of approximately $10^{17} M_{\odot}$, contains the Milky Way (MW) and about 105 nearby galaxies, which did not originate from the Initial Singularity. Third, the MW is gravitationally bound to the Virgo Supercluster (VS) and possesses an Orbital Angular Momentum that greatly surpasses its

rotational angular momentum.²⁵ Furthermore, the mass-to-light ratio of VS is about 300 times greater than the Solar ratio. Similar ratios are observed in other superclusters, supporting the presence of significant Dark Matter in the universe. Additionally, astronomers have identified the most distant galaxy, HD1, approximately 13.5 billion light-years away. WUM forecasts the discovery of galaxies at a distance of around 13.8 billion light-years. The three main pillars of the universe are Dark Matter, the Medium of the universe, and Angular Momentum WUM.²⁶

Today, many researchers feel a sense of stagnation in Physics. In some ways, the current situation mirrors the end of the 19th century, when the prevailing view was that Physics was nearly complete. Discoveries in special and general relativity, quantum physics, and elementary particles challenged that belief, sparking a century-long era of progress in physics. The brilliant minds of Einstein, Planck, Bohr, Dirac, Heisenberg, and Schrödinger led to the development of groundbreaking theories based on limited experimental evidence.²⁷ During the 20th century, their theories were confirmed and expanded through new experimental data. Today, the pendulum might have swung too far, with all results needing to align within the current framework. Adjustments to the frameworks are made as needed, and especially inconvenient results may even be discarded at times.²⁸ It might be the right moment to suggest new fundamental models that are simpler than existing ones, and also to explore new research fields.

WUM is suggested as an alternative to the dominant BBM. In BBM, the universe's beginning links to the Initial Singularity—an infinitely dense point—and to Cosmological Inflation, which describes a rapid exponential expansion of spacetime. This expansion, occurring at nearly infinite speed in the early universe, stretched the universe to about 93 billion light-years across in less than 10^{-32} seconds. The total size of the universe remains unknown and could be of infinite extent.²⁹ The initial singularity is a gravitational singularity anticipated by General Relativity to have existed before the Big Bang (BB), containing all the energy and spacetime universe.³⁰ From a physical perspective, the presence of a mathematical singularity is a flaw in any theory. It indicates that the model fails to account for

²² D. Valev (2019). "[Evidence of Dirac large numbers hypothesis](#)" (PDF). Proceedings of the Romanian Academy. 20 (+4): 361–368, accessed on 12 Mar 2026

²³ Poulin, V., Smith, T.L., Karwal, T. and Kamionkowski, M. (2019) Early Dark Energy Can Resolve the Hubble Tension. Physical Review Letters, 122, Article ID: 221301, accessed on 12 Mar 2026

²⁴ <https://phas.ubc.ca/quantum-gravity-and-cosmology>, accessed on 12 Mar 2026

²⁵ Netchitailo, V. (2017) Mathematical Overview of Hypersphere World-Universe Model. Journal of High Energy Physics, Gravitation and Cosmology, 3, 415–437, accessed on 12 Mar 2026

²⁶ <https://www.scirp.org/journal/paperinformation?paperid=120558>, accessed on 12 Mar 2026

²⁷ Case, Stephen (2015). "'Land-marks of the universe': John Herschel against the background of positional astronomy". Annals of Science. 72 (4): 417–434, [doi:10.1080/00033790.2015.1034588](https://doi.org/10.1080/00033790.2015.1034588), accessed on 12 Mar 2026

²⁸ Hearnshaw, J.B. (1986). The analysis of starlight. Cambridge: Cambridge University Press. pp. 23–29. ISBN 978-0-521-39916-6, accessed on 12 Mar 2026

²⁹ Hetherington, Norriss S., (2015), McCray, W. Patrick, Weart, Spencer R. (ed.). Spectroscopy and the Birth of Astrophysics. American Institute of Physics, Center for the History of Physics. Archived from [the original](#) on September 7, 2015, accessed on 12 Mar 2026

³⁰ Ricard, Y. (2007) 7.02—Physics of Mantle Convection. In: Bercovici, D. and Schubert, G., Eds., Treatise on Geophysics: Mantle Dynamics, Vol. 7, Elsevier Science, Amsterdam, 31–87, accessed on 12 Mar 2026

certain important physical phenomena that would prevent such a situation from occurring singularity.³¹

However, preventing the initial singularity in BBM is not possible. A finite universe likely began through a different process—a fluctuation in the eternal universe at a finite size and energy density. This fluctuation's size can grow at a finite rate, eliminating the need for cosmological inflation. Nonetheless, this raises questions about the mechanism of continuous matter creation. In 1964, F. Hoyle and J. V. Narlikar proposed explaining new matter's appearance via a "Creation field" or "C-field." In 1974, P. Dirac discussed continuous matter creation through two mechanisms: an additive process, spreading uniformly across space, and a multiplicative process, proportional to the existing amount matter.³² WUM adheres to the concept of continuous matter creation through an additive process but introduces a different mechanism for matter generation. The key distinctions between BBM and WUM are the presence of the Medium of the World—which includes protons, electrons, photons, neutrinos, and dark matter particles—and the source of the World's energy, the Eternal Universe.³³

We believe that incorporating a range of hypotheses that are currently unknown or overlooked by mainstream science is essential for developing a new cosmology. Below, we will discuss hypotheses from classical physicists like Newton, Le Sage, McCullagh, Riemann, Heaviside, Tesla, Dirac, and Sakharov, and expand on them within this framework WUM.³⁴ The hypotheses presented are not original, nor do we claim ownership of them. Instead, we expand on existing hypotheses and introduce new ones within the WUM framework. The primary goal of the model is to unify and clarify existing results in Classical Physics into a cohesive view of a New Cosmology. Numerous findings from WUM are cited in this work without detailed explanation or justification.^{35,36,37}

2.3 History of Dark Matter

The history of Dark Matter (DM) dates back to at least the mid-1800s. G. Bertone and D. Hooper offer an excellent overview of this history. In 1844, F. Bessel suggested that the proper motion of stars like Sirius and Procyon could only be explained by faint companion

stars exerting gravitational influence. Two years later, in 1846, U. Le Verrier and J. C. Adams proposed the existence of a new planet to account for anomalies in Uranus's motion. Besides dark stars and planets, 19th-century astronomers also considered DM in the form of dark "nebulae". In 1877, A. Secchi wrote, 'Among these studies there is the interesting probable discovery of dark masses scattered in space, whose existence was revealed thanks to the bright background on which they are projected. Until now they were classified as black cavities, but this explanation is highly improbable, especially after the discovery of the gaseous nature of the nebular masses.' As soon as astronomical photography was invented, scientists began to notice that stars were not evenly distributed across the sky. Dark regions were observed in dense stellar fields.³⁸ In 1904, Lord Kelvin was among the first to estimate the amount of dark matter in the Milky Way (MW) using a dynamical approach. His reasoning was straightforward yet impactful: if stars in the MW can be viewed as a gas of particles influenced by gravity, then one can relate the system's size to the stars' velocity dispersion. H. Poincare was intrigued by Kelvin's idea of applying the "theory of gases" to the MW's stellar system. By 1906, he explicitly mentioned "dark matter" and noted that because Kelvin's predicted velocity dispersion is roughly the same as observed, the dark matter amount was likely less than or comparable to the visible matter.³⁹

Nebular Hypothesis. The most widely accepted model for the formation of the Solar System (SS) is the Nebular hypothesis, first proposed in 1734 by E. Swedenborg and further developed by I. Kant in 1755. According to this hypothesis, about 4.6 billion years ago, the SS formed from the gravitational collapse of a massive molecular cloud spanning light-years. Most of the mass concentrated at the centre, becoming the Sun, while the remaining material flattened into a protoplanetary disc from which planets and other SS bodies originated formed.^{40, 41} The Nebular hypothesis is not without its critics. In his "The Wonders of Nature", V. Ferrell outlined the following counter-arguments:

³¹ J. P. Uzan (2003). "The fundamental constants and their variation, Observational status and theoretical motivations". *Reviews of Modern Physics*, 75 (2): 403, doi:10.1103/RevModPhys.75.403, accessed on 12 Mar 2026

³² Dirac, P.A.M. (1974) Cosmological Models and the Large Numbers Hypothesis. *Proceedings of the Royal Society of London*. A338, 439, accessed on 12 Mar 2026

³³ Netchitailo, V. (2020) World-Universe Model—Alternative to Big Bang Model. *Journal of High Energy Physics, Gravitation and Cosmology*, 6, 133-258, accessed on 15 Mar 2026

³⁴ Netchitailo, V. (2020) World-Universe Model Predictions. *Journal of High Energy Physics, Gravitation and Cosmology*, 6, 282-297, accessed on 15 Mar 2026

³⁵ Netchitailo, V.S. (2013) Fundamental Parameter Q. Recommended Values of the Newtonian Parameter of Gravitation, Hubble's Parameter, Age of the World, and Temperature of the Microwave Background Radiation. viXra:1312.0179v2, Available from: <https://vixra.org/abs/1312.0179>, accessed on 15 Mar 2026

³⁶ Netchitailo, V.S. (2015) 5D World-Universe Model. Multicomponent Dark Matter. *Journal of High Energy Physics, Gravitation and Cosmology*, 1, 55-71, accessed on 15 Mar 2026

³⁷ Netchitailo, V.S. (2016) 5D World-Universe Model. Neutrinos. *The World. Journal of High Energy Physics, Gravitation and Cosmology*, 2, 1-18, accessed on 15 Mar 2026

³⁸ Netchitailo, V.S. (2022) Unidentified Infrared Discrete Emission Bands. *Journal of High Energy Physics, Gravitation and Cosmology*, 8, 243-253, accessed on 15 Mar 2026

³⁹ Netchitailo, V.S. (2019) High-Energy Atmospheric Physics: Ball Lightning. *Journal of High Energy Physics, Gravitation and Cosmology*, 5, 360-374, accessed on 14 Mar 2026

⁴⁰ Netchitailo, V.S. (2016) Overview of Hypersphere World-Universe Model. *Journal of High Energy Physics, Gravitation and Cosmology*, 2, 593-632, accessed on 14 Mar 2026

⁴¹ Netchitailo, V.S. (2019) Solar System. Angular Momentum. *New Physics. Journal of High Energy Physics, Gravitation and Cosmology*, 5, 112-139, accessed on 14 Mar 2026

- It contradicts the basic physical principle that gas in outer space never clumps together; it always disperses outward;

- Every planet and moon in SS possess distinct structures and features. How can each one differ if they all originated from the same nebula?

- In SS, 98 per cent of the total angular momentum is held by the planets, while an overwhelming 99.8 per cent of all the mass lies with our Sun;

- Jupiter holds 60 percent of the planet's angular motion, a fact that evolutionary theory cannot explain. This unusual distribution was the main reason for the failure of the Nebular hypothesis.

- It is impossible for the Sun to transfer angular momentum to the planets. However, this transfer would be necessary if any evolutionary theories about the Solar System's origin are to hold accepted.

The Lunar Origin Fission Hypothesis was proposed by G. Darwin in 1879 to explain the origin of the Moon by rapid rotation of the Earth, on which the equatorial gravitational attraction was nearly overcome by centrifugal force.

2.3 Bing Bang Model (BBM)

Special Relativity. The principle of relativity originates from Galileo and was integrated into Newtonian physics. By the late 19th century, the discovery of electromagnetic waves prompted some physicists to propose the existence of a substance called "Aether". They believed this Aether served as the medium for wave propagation and provided an absolute reference frame for measuring speeds, which they thought were fixed and motionless relative to Earth or other fixed points. The Aether was envisioned to be elastic enough to support electromagnetic waves, which could interact with matter, yet offered no resistance to bodies moving through it.⁴² The results from various experiments, including the 1887 Michelson–Morley experiment, led to the development of the theory of Special Relativity (SR), which describes the relationship between space and time. In 1905, A. Einstein formulated SR based on two postulates: (1) The laws of physics are the same in all inertial frames—which are frames of reference moving at constant velocity—and the light source must also be in that frame. (2) The speed of light in a vacuum is constant for all observers, regardless of the motion of the light source. Lorentz invariance is fundamental to SR. Einstein's approach was to reject the concept of an "Aether" and the notion of absolute rest. In relativity, any frame moving uniformly observes the same physical laws, and the speed of light in a vacuum is always measured as c , even by different systems moving at constant velocities.

General Relativity. General Relativity (GR), introduced by A. Einstein in 1915, is a geometric theory of gravitation and a foundational framework in modern

physics. It extends Special Relativity (SR) and refines Newton's universal law of gravitation, describing gravity as a feature of four-dimensional spacetime. Einstein's field equations are nonlinear and complex to solve, but in 1916, K. Schwarzschild derived the first exact solution—the Schwarzschild metric—paving the way for understanding the late stages of gravitational collapse and the formation of objects now known as Black Holes (BHs). In 1917, Einstein applied his theory to the universe, initiating relativistic cosmology. He assumed a static universe and added the cosmological constant to his equations to align with this presumption. By 1929, observations by Hubble and others proved the universe is expanding, a phenomenon explained by Friedmann's 1922 solutions, which do not need a cosmological constant. Einstein later called the cosmological constant his "biggest blunder." It's important to note that Aether was discarded in 1905 with SR, and the Friedmann equations were first derived in 1922 from Einstein's gravitational field equations for the Friedmann–Lemaître–Robertson–Walker metric, describing a universe filled with a perfect fluid characterised by density ρ and pressure p .

Big Bang Model. The BBM framework is based on General Relativity and simplifications like space homogeneity and isotropy. The Lambda Cold Dark Matter (Λ CDM) model describes BBM by including three main components: a Cosmological constant Λ linked to dark energy, hypothesized Cold Dark Matter, and Ordinary matter.^{43, 44, 45} Dark Matter: G. Bertone and D. Hooper offer a comprehensive review of dark matter alongside Big Bang model insights. Following the failures of hot dark matter, it became evident that cold dark matter better explains the patterns observed in large-scale structures. The term WIMPs, introduced by G. Steigman and M. Turner in 1984, originally encompassed all particle dark matter candidates, including axions and gravitinos. However, its definition has since narrowed to particles interacting via the weak force. By the late 1980s, it was widely accepted among astrophysicists and particle physicists that most of the universe's mass consists of cold, nonbaryonic particles, positioning cold dark matter of an unknown elementary particle as the leading paradigm. The Λ CDM model relies on six key parameters: baryon density, dark matter density, dark energy density, scalar spectral index, curvature fluctuation amplitude, and reionisation optical depth. These parameters are mostly not derived from current theories; others are set to "natural" values, such as a total density of 1.00 and negligible neutrino masses. The model can be extended to include cosmological inflation and is often called the Standard Model of Big Bang cosmology. The Four Pillars of Standard

⁴² Netchitailo, V.S. (2021) Hypersphere World-Universe Model: Evolution of the World. *Journal of High Energy Physics, Gravitation and Cosmology*, 7, 508-530, accessed on 14 Mar 2026

⁴³ Netchitailo, V.S. (2020) World-Universe Model—Alternative to Big Bang Model. *Journal of High Energy Physics, Gravitation and Cosmology*, 6, 133-258, accessed on 14 Mar 2026

⁴⁴ Netchitailo, V.S. (2022) Decisive Role of Dark Matter in Cosmology. *Journal of High Energy Physics, Gravitation and Cosmology*, 8, 115-142, accessed on 14 Mar 2026

⁴⁵ Netchitailo, V.S. (2022) Hubble Tension. *Journal of High Energy Physics, Gravitation and Cosmology*, 8, 392-401, accessed on 14 Mar 2026

Cosmology are: universe expansion, the origin of cosmic background radiation, light-element nucleosynthesis, and galaxy and large-scale structure formation.

Expansion of the Universe. Recent evidence strongly confirms Hubble's law, indicating that a galaxy's recessional velocity v is proportional to its distance d , expressed as $v=Hd$, with H being Hubble's constant. Rewinding galaxy movements suggests they originate from a single point at $t = 0$, a cosmological Singularity characterized by infinite energy density. This highlights one of the limitations of Standard Cosmology—the Horizon problem. "Why does the universe look the same in all directions when it arises out of causally disconnected regions? This problem is most acute for the very smooth cosmic microwave background radiation". This issue was addressed by introducing Cosmological Inflation, a theory proposing an extremely rapid, exponential expansion of space in the early universe. This swift expansion enlarged the universe's linear dimensions by at least a factor of 10^{26} , increasing its volume by at least 10^{78} . The inflationary period lasted less than 10^{-32} seconds after the singularity. After this epoch, the universe continued expanding but at a slower pace. L. Verde, T. Treu, and A. G. Riess summarized the 'Workshop at Kavli Institute for Theoretical Physics, July 2019'. It remains uncertain whether the observational discrepancy results from systematics or poses a significant challenge to the Standard Model.

Origin of Cosmic Background Radiation.

According to BBM, approximately 380,000 years after BB, the universe's temperature dropped enough for nuclei to combine with electrons, forming neutral atoms. Consequently, photons interacted less frequently with matter, causing the universe to become transparent and leading to the creation of Microwave Background Radiation (MBR). This event, known as Decoupling, marked the moment when photons began to travel freely. These photons have continued to propagate, though they have become fainter and less energetic as the universe's expansion stretches their wavelengths. The photons present at decoupling are the same ones we observe in MBR today. So, why is MBR a perfect blackbody? WUM states that wavelength is a classical concept, whereas photons are quantum objects, which only four-momenta.⁴⁶ They do not possess specific wavelengths, by definition. Within the WUM framework, the black-body spectrum of MBR results from the thermodynamic equilibrium of photons with the Intergalactic Plasma (IGP), whose existence has been confirmed experimentally proved.

Nucleosynthesis of Light Elements. Big Bang Nucleosynthesis (BBN) describes the formation of nuclei other than hydrogen during the early universe stages. It is believed that primordial nucleosynthesis occurred roughly between 10 seconds and 20 minutes after the Big Bang, leading to the creation of most of

the universe's helium, primarily as helium-4, along with small amounts of deuterium, helium-3, and a tiny fraction of lithium-7. All elements heavier than lithium were produced much later through stellar nucleosynthesis in the evolution and explosion of stars.⁴⁷ The history of BBN starts with R. Alpher's calculations in the 1940s. In the 1970s, efforts intensified to identify processes that could generate deuterium. Although the universe's deuterium concentration aligns with the Big Bang Model (BBM), it's too high for models assuming the universe is mostly protons and neutrons. Currently, the standard explanation is that non-baryonic dark matter, rather than baryons, constitutes most of the universe's mass. Modern cosmology states that lithium was synthesized in the Big Bang. However, a discrepancy exists: older stars have less lithium than expected, while some younger stars have more. M. Anders et al. reported the first measurement of the $2H(\alpha, \gamma)6Li$ cross section at Big Bang energies, ruling out BBN lithium production as an explanation for observed $6Li$. In the WUM framework, nucleosynthesis of all elements, including light ones, occurs inside dark matter cores of macro-objects during their evolution. Stellar nucleosynthesis is well understood, originating from the renowned B2FH paper. Within WUM, this theory should also consider self-annihilation of heavy dark matter fermions in macro-object cores.

Formation of Galaxies and Large-Scale Structures. The formation and evolution of galaxies can only be explained through gravity within an inflationary framework combined with dark matter and dark energy. The standard Hot Big Bang Model offers a foundation for understanding how galaxies form. Around 10,000 years after the Big Bang, the universe's temperature had decreased enough that the energy density became dominated by massive particles, overtaking the radiation and light that had previously held sway.⁴⁸ This change in the form of the main matter density meant that the gravitational forces between the massive particles could begin to take effect, so that any small perturbations in their density would grow. This highlights one of SC's shortcomings—a density fluctuation problem. The analysis shows that the Four Pillars of SC are model-dependent and insufficient to support BBM. BBM violates the law of angular momentum conservation. BBM relies on the following assumptions.

- Homogeneity and isotropy of space.
- Physical laws are invariant across all inertial frames.
- The speed of light in a vacuum remains constant for all observers.
- Photons have zero mass.
- Cold Dark Matter's existence is a key aspect of BBM.

Angular Momentum Problem. The angular momentum problem is one of the most critical problems in BBM that must be solved. Any theory of the evolution

⁴⁶ Netchitailo, V.S. (2021) Solar System. Angular Momentum. Dark Matter Reactors. Journal of High Energy Physics, Gravitation and Cosmology, 7, 1353-1372, accessed on 14 Mar 2026

⁴⁷ Netchitailo, V.S. (2021) From the Beginning of the World to the Beginning of Life on Earth. Journal of High Energy

Physics, Gravitation and Cosmology, 7, 1503-1523, accessed on 14 Mar 2026

⁴⁸ Netchitailo, V.S. (2020) World-Universe Model Predictions. Journal of High Energy Physics, Gravitation and Cosmology, 6, 282-297, accessed on 14 Mar 2026

of the Universe that is not consistent with the Law of Conservation of Angular Momentum should be promptly ruled out. SC cannot answer the following questions.⁴⁹

- Sun accounts for approximately 0.3% of the total angular momentum of SS, while about 60% is attributed to Jupiter;
- SS has an orbital angular momentum that far exceeds its rotational angular momentum;
- MW galaxy is gravitationally bound with Virgo Supercluster (VS) and has an orbital momentum, which far exceeds its rotational angular momentum;
- How did MW galaxy and SS obtain their substantial orbital angular momenta?
- To the best of our knowledge, the Standard Model does not answer these questions. WUM is the only cosmological model in existence that is consistent with this Fundamental Law.

3.5 Black Holes

Einstein's field equations for gravity in 3 + 1 dimensions spacetime are mathematically solved by BH. The Schwarzschild solution, which characterizes the gravitational field in the spherically symmetric, static, vacuum condition, is the most basic BH solution. The mass of an object that generates the same gravitational field is the only characteristic that characterizes this solution. It is now widely acknowledged that supermassive compact objects exist at galactic centers. It is commonly believed that the central mass is a Supermassive Black Hole (SBH).⁵⁰ However, there is evidence indicating the contrary. N. Hurley-Walker discovered the previously unidentified radio galaxy NGC1534 in 2013. Although it is somewhat close to Earth, it is far fainter than it should be if the core black hole was accelerating the electrons in the jets. Another possibility is that there was never a BH at all.

In 2014, L. Mersini-Houghton claimed to have shown mathematically that existing theories of BH generation are incorrect given specific assumptions regarding BH firewalls. According to her, the star loses mass due to Hawking radiation at a rate that makes it insufficiently dense to form a black hole. Outstanding 1.3 mm measurements of the radio source at the location of the supermassive black hole Sgr A* were presented by the Event Horizon Telescope (EHT) Collaboration in 2022. Sgr A* was simultaneously monitored at near-infrared and X-ray wavelengths as well as 22, 43, and 86 GHz. Astronomers published the first picture of the accretion disk surrounding Sgr A* using EHT. The EHT Collaboration asserted that Sgr A* is an SBH based on the results collected. Astronomers must provide answers to a few key questions:

- The Age of the World and the Age of MW are comparable. Methuselah, the oldest star in MW, is almost as ancient as the Earth. How might Sgr A* grow so rapidly if it is an SBH?

➤ Where did the purported SBH favorable spin come from?

➤ Their models in the "best-bet region" feature low inclinations of 30° and 10°, which are at odds with the MW galaxy's disk shape and bipolar astrophysical jets—astronomical phenomena in which matter outflows are released as extended beams along the axis of rotation;

➤ The MW galaxy, which includes Sgr A*, has a large orbital angular momentum and is gravitationally confined by VS (Section 2.4). How was this significant orbital angular momentum acquired by the MW galaxy?

➤ What is the process by which the Galactic Centre emits gamma rays?

The EHT Collaboration's results can be described as follows within the context of WUM. Nonetheless, all of the acquired experimental data support the existence of the supermassive compact object composed of DMPs at MW Center.⁵¹

➤ The dense, brilliant ring with a radius of 3.17×10^{10} m dominates the photograph. The extra gamma-ray emission from Sgr A* is caused by the relatively dim interior of the ring, which is composed of DM Fermions DMF1 (1.3 TeV) and DMF2 (9.6 GeV).

➤ The inside of Sgr A* continuously absorbs Dark Matter Particles (DMPs). The result of DMPs self-annihilation is Ordinary Matter. The Interior continuously re-emits it into a shell surrounding it.

➤ In the area of the Shell's atomic nuclei, strong gamma quanta with an energy of at least 1.02 MeV generate highly concentrated electron-positron couples;

➤ The brilliant, dense region is made up of Ordinary Matter and Electron-Positron plasma, a compact nonthermal radio entity with a radius of 2.9×10^{10} m that produces the strongest radio emission.

➤ The area between 3.17×10^{10} m and 1.88×10^{12} m is filled with DM Fermions DMF3 (3.7 keV), which self-annihilate and cause X-rays from the center of MW; the enclosed mass of the Supermassive Compact Object of $4.154 \times 10^6 M_{\odot}$ is the mass of the MW DM Core, which is composed of DMF1 and DMF2 with the Ordinary Matter and Electron-Positron Shell and DMF3 Shell; Sgr A* has obtained the orbital angular momenta as a result of the rotational fission of VS;

➤ The angle of inclination between Sgr A* rotational angular momentum vector and line of sight is approximately 90°.

3. Methodology

The contemporary relativistic cosmology has already emerged from the stage of unfounded speculations and idle theorizing. So, it is no longer "mythology" and has become an important part and extension of astrophysics and the natural sciences. It can give a consistent picture of the structure and evolution of the universe as a whole, and this picture is built on

⁴⁹ Netchitailo, V.S. (2021) Hypersphere World-Universe Model. *Journal of High Energy Physics, Gravitation and Cosmology*, 7, 915-941, accessed on 14 Mar 2026

⁵⁰ Netchitailo, V.S. (2022) Center of Milky Way Galaxy. *Journal of High Energy Physics, Gravitation and Cosmology*, 8, 657-676, accessed on 14 Mar 2026

⁵¹ Ludwig, G.O. (2021) Galactic Rotation Curve and Dark Matter According to Gravitomagnetism. *The European Physical Journal C*, 81, Article No: 186, accessed on 14 Mar 2026

the proven laws of physics, and its predictions agree well with the observations. Let us therefore consider some general aspects of the relationship between cosmology and physics.⁵² The methodology of physical cognition consists of three main elements like observation, experiment and theory. In the early stages of the development of physics, the first of these methods like observation played a decisive role. For example, let us recall only Newton's law of gravitation based on astronomically observed Kepler's laws of planetary motion. However, Newton was already doing mechanical experiments that resulted in his three basic laws of motion. With the further development of physics, accompanied by a profound improvement in experimental techniques. The role of observation declined rapidly, especially since the early 20th century, when for the reveal the laws of the microstructure of matter.

It was necessary to conduct increasingly sophisticated and costly experiments.⁵³ It is powerful yet accurate accelerators in conjunction with subtle detection electronics. The method of observation seemed already entirely historic and the relationship between physics and astronomy is one-way: physics in its laboratories reveals the fundamental laws of nature, and that allow to explain and predict astronomically observed phenomena in space. In recent years, however, this relationship has begun to change. Indeed, contemporary relativistic cosmology has shown that the universe, in its very hot and dense initial phase, was a kind of unique "laboratory" of high-energy physics, in which the processes took place intensively, that we are now trying to observe with the greatest effort on massive accelerators, and even those phenomena whose laboratory implementation is not hopeful in the foreseeable future.⁵⁴ The cosmological consequences of current theories of elementary particles especially unitary theories have proven to be so clear and obvious, that their confrontation with astronomical observations distant universe makes it possible to set strong constraints on the parameters of these theories of elementary particles, and sometimes even their verification or rejection.

In addition to optical observations (including spectroscopic) with increasingly larger and more powerful telescopes and radio telescopic observations using large antenna systems (interconnected), it is primarily a detailed measurement of the properties of microwave relic radiation - its homogeneity, fluctuations (depending on the angular distance and wavelength), polarization. Already at the time of the separation of radiation from matter, there were germs of future structures in the universe, so these photons passed through places with different gravitational potentials, which led

to small changes in their energy and wavelength - a slight cooling or heating.⁵⁵ These fluctuations should be visible even now, as slightly warmer and colder "spots" in the otherwise isotropic distribution of relic radiation - they represent a kind of "paleontological imprint" of the structures of the early universe. The temperature difference is very small, of the order of 10^{-5} degrees, so the relevant methods of their data measurement are constantly being improved. In the future, then the detection of primordial gravitational waves or detection of relict neutrinos.⁵⁶

For a detailed study of relic radiation, the COBE satellite (Cosmic Background Explorer) was launched in 1989, the WMAP satellite (Wilkinson Microwave Anisotropy Probe) in 2001, an even more sensitive PLANCK probe in 2007 was launched. NASA's Cosmic Background Explorer (COBE) satellite was launched on November 18, 1989, via a Delta rocket to study the cosmic microwave background (CMB) and early universe. It operated until December 1993, confirming the Big Bang theory with precise measurements of the CMB's blackbody spectrum and finding early evidence of structural anisotropy.⁵⁷ WMAP was a NASA spacecraft operating from 2001 to 2010 which measured temperature differences across the sky in the cosmic microwave background (CMB) – the radiant heat remaining from the Big Bang.⁵⁸ Planck was a space observatory operated by the European Space Agency (ESA) from 2009 to 2013. The project aimed to map the anisotropies of the cosmic microwave background (CMB) at microwave and infrared frequencies, with high sensitivity and angular resolution. The mission provided data that substantially improved upon previous observations by NASA's WMAP.⁵⁹ At first glance, it might seem that nuclear and particle physics, dealing with the smallest known particles of matter, has very little to do with cosmology, which, on the other hand, examines the largest possible objects in the universe. However, current research refutes this view. Both in the form of elementary particles and in cosmology, it was possible to develop so-called standard models, which explain very well the results of almost all physical experiments and astronomical observations. On the other hand, they raise new questions and problems - how to "find common ground of things"?

At present, in the mutual interest of physics and cosmology are the fundamental principles of our world. In cosmology, these are questions of the origin of our universe, the basic laws which control him, his ultimate destiny. In particle physics, these are questions of the nature of matter: how did matter originate? what is its structure - what are its basic building "stones" and

⁵² <https://www.cambridge.org/core/books/relativistic-cosmology/7CBB180DDF5B86C0BDB11390CC9FDEED>,

⁵³ Qian, W.H. (2023) *Journal of Modern Physics*, 14, 271-286, accessed on 14 Mar 2026

⁵⁴ Netchitailo, V. (2019) *Solar System. Angular Momentum. New Physics. Journal of High Energy Physics, Gravitation and Cosmology*, 5, 112-139, accessed on 14 Mar 2026

⁵⁵ Qian, W.H. (2022) *Journal of High Energy Physics, Gravitation and Cosmology*, 8, 417-431, accessed on 14 Mar 2026

⁵⁶ Netchitailo, V. (2018) *Analysis of Maxwell's Equations. Cosmic Magnetism. Journal of High Energy Physics, Gravitation and Cosmology*, 4, 1-7, accessed on 14 Mar 2026

⁵⁷ Arny, Thomas T. (2002). *Explorations: An Introduction to Astronomy* (3rd ed.). Dubuque, Iowa: McGraw-Hill. ISBN 978-0-07-241593-3, accessed on 14 Mar 2026

⁵⁸ Beringer, J.; et al. (Particle Data Group) (2013). "Astrophysics and Cosmology". *Review of Particle Physics*. This article incorporates text from this source, which is in the public domain, accessed on 14 Mar 2026

⁵⁹ https://www.nasa.gov/mission_pages/planck/overview.html, accessed on 14 Mar 2026

how do these interact? what are the mechanisms of these building blocks that create such complex objects as galaxies, stars, planets - and ultimately living matter? This creates a very remarkable connection between the microworld and the mega-world. All the most basic aspects of matter and the universe seem to be rooted in those first prime fractions of a second after the Big Bang, when the properties of the physical interactions themselves were formed. The laws of physics that prevailed in these extreme conditions are not yet well known - we do not know what the structure of space and time was then, what was the number of dimensions, how matter was formed. At that time, the macroworld and the cosmos, then non-existent in the present sense, intertwined with the microworld of quantum laws.⁶⁰

However, some current (and especially future) concepts of unitary theories of fields, interactions and elementary particles could shed some light here, in co-production with experiments of high-energy particle interactions on successively built large accelerators. The finer the details of the structure of matter we want to penetrate - and thus also the greater the depth of knowledge of the structure of the universe - the higher the energy of the particles we must use. It can be said that high-energy particles are certain "probes" into the deepest details of the structure of matter and at the same time into the earliest moments of the evolution of the universe.⁶¹ Two seemingly very remote parts of physics: the theory of elementary particles examining the smallest objects and cosmology examining the largest of the whole universe; thus, combine to form a unified picture of the world. The successes of research in one area can be very penetrating in the other area of knowledge. It is this dialectical unity of the microworld, macroworld and mega-world that is the characteristic trend in contemporary fundamental physics.⁶² Physically, we humans are just a tiny powder in the universe. Spiritually, however, we go far beyond this insignificance. We are able to know and understand the vast universe and its structure, functioning, and evolution. In this article scientific narration of creation and end story of universe will be illustrated on the basis of history, chronological development of astro physics with special emphasis on quantum cosmology.

4. Formation of First Galaxies and Large Black Holes

The current standard astrophysical mechanisms for the formation of the first galaxies are based on the situation after the end of the "dark ages" in the universe

about 200 million years after the big bang, when clouds of hydrogen + helium gas began to cluster around the initial inhomogeneities (originating from density fluctuations of the post-inflationary period) by gravitational attraction. A large-scale structure of the network concentration of matter around large voids was gradually formed. In them, gravitational contraction then produced the first large protostars that transformed into 1st generation stars - galaxies were formed. These 1st generation stars were mostly significantly larger than today's stars, about several hundred $M_{\odot}$. They lived only relatively briefly, several million years, and then exploded as supernovae, which enriched the interstellar space with heavier elements. All of this is probably correct in principle. However, the latest observations show that the earliest galaxies are somewhat "more advanced" than would be expected from their age. So perhaps we do not yet know the exact models of galaxy formation well. Small and medium-sized black holes are formed by the gravitational collapse of sufficiently massive stars.⁶³ There were a large number of these in early galaxies. By gradual merging of "stellar" black holes, black holes with masses of several thousand $M_{\odot}$ can be formed. Supermassive black holes of 10^6 - $10^9 M_{\odot}$ could grow to these masses in billions of years. However, they are also observed in much earlier galaxies.⁶⁴ Could they perhaps form in a non-stellar way, by direct gravitational collapse of large dense clouds of gas. But we do not know the exact mechanism.

Black holes are probably the most mysterious objects in the universe. Smaller black holes of stellar mass are formed at the end of the evolution of sufficiently massive stars, which, after consuming all their thermonuclear fuel, are no longer able to resist their gravity and succumb to complete gravitational collapse. In the center of galaxies, there are also giant black holes with more than a million times greater mass. A common feature of all black holes is that they are surrounded by an event horizon, from under which nothing, not even light, can escape. And in the center of a black hole, according to mathematical models of a black hole and that is the simplest is the Schwarzschild black hole. And there is a point where there is an infinite curvature of spacetime, infinite gradients of gravitational. According to mathematical models, all collapsing matter should end up in this singularity, even matter that was later absorbed by the black hole. This is certainly an unacceptable result according to the classical theory of black holes.⁶⁵ According to quantum physics, nothing

⁶⁰ Braibant, S.; Giacomelli, G.; Spurio, M. (2009). Particles and Fundamental Interactions: An Introduction to Particle Physics. Springer. pp. 313–314. ISBN 978-94-007-2463-1, accessed on 14 Mar 2026

⁶¹ Yukawa, Hideki (1935). "On the Interaction of Elementary Particles. I". *Proceedings of the Physico-Mathematical Society of Japan*. 3rd Series. 17: 48–57. doi:10.11429/ppmsj1919.17.0_48, accessed on 14 Mar 2026

⁶² Radvanyi, Pierre (January–February 2011). "Physics and Radioactivity after the Discovery of Polonium and Radium" (electronic). *Chemistry International*. 33 (1). online: International Union of Pure and Applied Chemistry. Archived from the original on 9 July 2023, accessed on 14 Mar 2026

⁶³ Carr, B., Kühnel, F. and Visinelli, L. (2021) Constraints on Stupendously Large Black Holes. *Monthly Notices of the Royal Astronomical Society*, 501, 2029–2043, accessed on 16 Mar 2026

⁶⁴ Mehrgan, K., Thomas, J., Saglia, R., Mazzalay, X., Erwin, P., Bender, R., et al. (2019) A 40-Billion Solar Mass Black Hole in the Extreme Core of Holm 15A, the Central Galaxy of Abell 85. *The Astrophysical Journal*, 887, Article No. 195, accessed on 16 Mar 2026

⁶⁵ Hawking, S.W. (1998) *A Brief History of Time: From the Big Bang to Black Holes*. Introduction by Carl Sagan; Illustrations by Ron Miller. Bantam Dell Publishing Group, New York.

so pathological as a singularity should happen. In the immediate vicinity of the center of a black hole, quantum fluctuations of the geometry of spacetime would strongly increase, up to fluctuations of topology, so that the spatial singularity would dissolve in the topological foam of quantum fluctuations. So, we don't actually know what's inside a black hole, at its center.

5. Formation of Dark Matter and Dark Energy

We observe that the gravitational effect in galaxies and galaxy clusters is stronger than would correspond to the usual glowing and non-glowing matter contained there. So, there must be some substance that exhibits gravity, but which we do not see astronomically. We call it dark because it does not glow and matter because it interacts gravitationally in the same way as matter. But we do not know what it is. It was thought that it could be hard-to-see objects made of dust, brown dwarfs, or black holes in the halo of galaxies; this has not yet been confirmed. Physically, it seems that dark matter could be made of weakly interacting massive particles WIMPs, which gravitate due to their mass, but apart from gravity, exhibit only weak interactions. Their detection by nuclear and radiation physics methods is therefore very difficult; despite intensive efforts over many decades, it has not yet been possible. When astronomically measuring the rate of retreat of very distant type Ia supernovae, we surprisingly observe that the universe is expanding at an accelerated rate, instead of its expansion being slowed down by the attractive gravitational effect of matter. Therefore, in addition to gravity, there must be something in the universe that acts in the opposite direction, against gravity. It is astronomically invisible, so we call it dark and energy, because it supplies the energy needed for acceleration. However, we do not know what it is. It may be an inherent property of space-time (such as the cosmological constant), or some kind of "quintessence" (dark energy and the accelerated expansion of the universe).⁶⁶

Dark matter and dark energy are distinct, unseen components that formed in the early universe, making up roughly 95% of the total mass-energy content, with dark matter acting as the cosmic scaffolding that clumped together and dark energy acting as the uniform repulsive force causing accelerated expansion. Dark matter likely formed fractions of a second after the Big Bang, similar to ordinary matter, while dark energy is believed to be the energy of vacuum space that came to dominate the universe's expansion roughly 5 billion years ago. Dark matter is an invisible, non-baryonic form of matter that exerts gravitational pull but does not interact with light. Scientists believe dark matter formed in the first fractions of a second after the Big Bang around the same time as ordinary matter. It

clumped together, forming a "cosmic web" or halo around galaxies, providing the gravitational scaffolding needed for gas to gather and form stars.⁶⁷ Dark energy is a mysterious force, uniformly distributed across space, that drives the accelerated expansion of the universe. Dark energy has likely existed from the beginning, but its influence was negligible compared to the attractive gravity of matter and radiation in the early universe. Einstein proposed that, this is the energy of empty space. As space expands, more space is created, meaning the total amount of dark energy increases, pushing galaxies apart faster. A dynamic energy field that fills space, potentially changing in strength over time, rather than remaining constant like the cosmological constant.⁶⁸ It pushes galaxies apart, dominating the current 68% of the universe's mass-energy content.

6. The Evaluation of Time

End of Time. All fundamental physical laws are time invariant; no equations in physics contain a time direction. We can apply them in one direction or the other and there is nothing to show which direction is correct. A fundamental exception is the 2nd law of thermodynamics, which as a statistical principle shows that natural processes spontaneously proceed in the direction of increasing entropy, as a measure of the disorder of the system. Physical statistics explains this by saying that the number of disordered states of a system of particles is always significantly higher than the number of ordered states. Biochemical processes of life seemingly go against this current of increasing entropy. New aspects regarding the passage of time were brought by the special and general theories of relativity. Actually, we don't really know what time is? How did primordial life arise at the molecular and cellular level? Biologists have well researched the evolution of the amazing diversity of life; chemists have well researched the complex biochemical processes at the molecular-cellular level. Although much remains to be explored here, the essence of life is already well understood. However, we do not know how primordial life arose at the molecular chemical pre-cellular level, including the establishment of reproduction and inheritance RNA, DNA? And we do not know also whether and how life could develop outside Earth, on other planets in the universe? And how to search for it?

From the point of view of the general theory of relativity, initial singularity was not only the beginning of the universe, but also the beginning of time. What about the passage of time and causal relationships in the final stages of the evolution of the universe? In the case of a closed universe, the situation is to some extent inversely analogous to the beginning of the universe. All causal relationships end in the vicinity of the final

⁶⁶ Netchitailo, V. (2019) Dark Matter Cosmology and Astrophysics. *Journal of High Energy Physics, Gravitation and Cosmology*, 5, 999-1050, accessed on 16 Mar 2026

⁶⁷ Bird, Simeon; Albert, Andrea; Dawson, Will; Ali-Haïmoud, Yacine; Coogan, Adam; Drlica-Wagner, Alex; Feng, Qi; Inman, Derek; Inomata, Keisuke; Kovetz, Ely; Kusenko, Alexander; Lehmann, Benjamin V.; Muñoz, Julian B.; Singh, Rajeev; Takhistov, Volodymyr; Tsai, Yu-Dai (1 August 2023). "Primordial black hole dark matter". *Physics of the Dark Universe*. 41 101231, doi:10.1016/j.dark.2023.101231, accessed on 16 Mar 2026

⁶⁸ <https://www.wtamu.edu/~cbaird/sq/2014/07/25/is-there-any-difference-between-antimatter-dark-matter-dark-energy-and-degenerate-matter/#>,
<https://www.wtamu.edu/~cbaird/sq/2014/07/25/is-there-any-difference-between-antimatter-dark-matter-dark-energy-and-degenerate-matter/#:~:text=Dark%20energy%20is%20weak%20and%20mostly%20operates,thinly%20but%20evenly%20throughout%20the%20entire%20universe.>

singularity (they cannot be extended analytically beyond this world point) - the great collapse also represents the end of time. In the case of the open universe, from a mathematical point of view, the coordinate time continues undisturbed to infinity. However, from the real point of view of the operationalist conception of time in the final stages of open space, where there will be no more phenomena and events ("thermal death"), we do not have time how and with what to measure and in fact is not "what" to measure. In this sense, even in the open universe, the end of time effectively occurs.

The Arrow of Time. What actually distinguishes between the past and the future? what determines the direction of time? This asymmetry of time - the "arrows" that point from the past to the future is plays a crucial role in our daily experience. All basic laws of physics have the property of time reversibility. If these laws allow a certain causal sequence of events, then they also allow a sequence of time-reversed events. The laws of mechanics allow the reversal of every movement of a body. Similarly, the laws of electrodynamics do not distinguish between the future and the past. So, the laws of physics are at their deepest level symmetric in time. If we remain purely at the level of mathematically formulated laws of physics, we will find no difference between the past and the future. Yet, we observe a strong causal direction in all the actual events in nature. Natural events always take place in one particular direction, while in the opposite direction never as the glass Bootle can roll spontaneously from the table and break, but the broken shards will never spontaneously combine in the original glass. The observed mechanisms of this temporal direction of natural phenomena can be divided into four categories:

1. The radiation arrow of time. It also called the electromagnetic arrow. It is given by the fact that the island system of accelerating moving charges emits electromagnetic waves, which carry energy from the source at the speed of light, while these waves will be manifest on distant bodies in the future. The energy of the radiating system also decreases in the future. In addition to these "retarded" waves, the laws of electrodynamics formally allow for "advancing" waves. As waves coming from infinity that the source absorbs; these waves can also be understood as waves radiated into the past. In fact, with each spontaneous emission of the source, we observe only the retarded emission of waves. The same applies to the emission of gravitational waves.

2. The thermodynamic arrow of time. According to the 2nd law of thermodynamics, is determined by the monotonic increase of the entropy of an isolated system near thermodynamic equilibrium. Time flows in the direction in which things age, hot objects cool, systems decompose, their disorder increases spontaneously. From this regularity also derives the biological arrow of time, indicating the direction of biological evolution and the individual course of life of man and all living beings, accompanied by ageing. The very laws of motion of the system's individual parts also allow movements that decrease entropy. Still, their probability is significantly lower than that of movements

that, according to statistical physics, increase disorder (entropy). This is because in practice, the number of disordered states is incomparably greater than the number of ordered states. The second thermodynamic theorem is thus a statistical consequence of the fact that there are many more disordered states than ordered states. And this situation is basically given by the initial conditions. States with high entropy significantly exceed those with low entropy. Therefore, almost every change in the system will most likely lead to a state with higher entropy. The time arrow of entropy growth is simply a statistical tendency of systems to evolve toward more common and frequent states. Although violation of the 2nd law of thermodynamics takes place locally, it only occurs on small spatial and temporal scales, or a molecule with a certain velocity (corresponding to the average thermal energy in a gas) with collisions with surrounding molecules can significantly accelerate (or slow down), but only for a very short time; then it returns to normal.

3. The cosmological arrow of time. It is determined by the observation that as time grows, so does the expansion of the universe.

4. The psychological arrow of time. It is based on the fact that our memory reflects the part of events which we call the past and which is clearly distinguished from the future in our psychic understanding. So we have a kind of "psychic feeling" for the passage of time, part "Space and time".

The question naturally arises as to whether all these manifestations of time are somehow connected to each other; or whether there is a "primary" or "universal" arrow of time, which is manifested by said "partial" arrows of time. So, let's look at the possibilities of merging or reducing at least some of them. The psychological and thermodynamic arrows of time seem to be essentially the same. The psychological arrow of time is a consequence of the thermodynamic arrow, because mental processes share an arrow of time determined by thermodynamics. If we imagine the brain as a physico-chemical system of neurons performing logical operations and recording sensory sensations in memory, all these operations are irreversible for thermodynamic reasons. It is necessary to expend energy to arrange the memory elements in the brain into a certain state, while a part of it is always dissipated in the form of heat and thus increases the disorder of the whole system. According to the laws of thermodynamics, this increase in disorder is always higher than the increase in order in memory. The direction of time in which our memory records data thus agrees with the direction in which disorder grows - with the direction of entropy growth. It can even be said that the disorder (entropy) increases with time, actually because we conceive and measure time in the direction of increasing entropy?

Finding a direct connection between the radiation (electrodynamic) and thermodynamic arrows of time is not easy. The electromagnetic arrow is in a way a manifestation of the principle (or requirement) of causality in the Minkowski spacetime of (locally) inertial systems, within which Maxwell's electrodynamics works. The thermodynamic (entropic) arrow of time is determined by the laws of statistical mechanics applied

to a situation where the initial conditions imply a significantly larger number of disordered than ordered states. The laws of mechanics itself reflect, among other things, causal relationships. The idea that "field equations also determine the regularities of the motion of their resources" can also help to find connections. Perhaps it will be ideologically possible to combine all of this comprehensively in future unitary field theory.

As for the cosmological arrow of time, which points in the same direction as thermodynamics, it is probably just a coincidence: we live by coincidence in a stage of expanding space, so the arrow of time is now identical with the expansion of the universe. If the universe is closed and the expansion is replaced by contraction in the future, nothing will change on the arrow of time in locally inertial systems (as well as on local laws of physics in general). Still, agreement with the arrow of universe evolution will turn into a contradiction including temporarily Stefen Hawking. Once thought that the cosmological arrow of time is the primary, and that as the evolution of the universe transitions from the stage of expansion to the state of contraction, the direction of the passage of time is also reversed. Now, however, they have mostly seen the error of this view and accepted the position of Zeldovich and Novikov on the irrelevance of the cosmological arrow of time. In the early days of quantum physics, antiparticles (such as the positron) were considered to be particles with "negative energy", or particles moving "backwards in time" (formal coordinate transformations in the Dirac equation allow this). At one time, these concepts played an important heuristic role in the development of particle physics. Now these misleading notions are abandoned, and both particles and antiparticles have an "equal" place in the standard model, in applications as well as in unitary schemes. They have nothing to do with the direction of time!

Now talk about the 'arrow of time and the anthropic principle'. The agreement of the thermodynamic, cosmological and psychological arrows of time can be put into a certain connection with the anthropic principle and the work "Anthropic principle or cosmic God".⁶⁹ We necessarily live in the "intermediate" stage of the expansion of space. In the late stages of the universe's evolution, the conditions for the existence of life and intelligent information processing will not be suitable. There will be no one to study the connection between the expansion or contraction of the universe and the time direction in which entropy increases. In accordance with the concept of inflationary expansion and the anthropic principle, the universe expands almost exactly at a critical speed, so that the shrinkage phase either does not occur at all or occurs only after a very long time. In the meantime, all the stars will go out, the galaxies will collapse, and no more free energy sources will be available. The universe will enter a state of almost maximum disorder, which will no longer increase locally - the thermodynamic arrow of time will

actually disappear. Thus, life and all orderly processing of information will disappear. It can therefore be concluded that the common essence of all "partial" arrows of time is the principle of causality for each locally inertial frame of reference. In analysing the various possibilities of the evolution of the universe, we are therefore entitled to proceed from the concept that there is a clear universal "arrow of time" determining the direction of evolution of physical systems in each locally inertial frame of reference. These local arrows of time are transmitted from one place to another by means of special and general relativistic transformational laws and create a branching causal structure in the spacetime of the entire universe.

7. The Future Development of the Universe (Hidden-Dark Matter)

What is the future development of the universe? It is very difficult to decide which of the two basic branches of evolution is realized in the real universe. The accuracy of measuring the deceleration parameter q remains insufficient, and when determining the average density of matter in space, the problem of hidden matter (dark, non-radiant substances) arises. If we take only the "luminous" mass contained in galaxies and in clusters of galaxies, we would indicate an open space. However, it turns out that this "luminous" substance is far from representing all the matter in the universe. Hidden dark matter in galaxies and clusters of galaxies When monitoring the dynamics of the rotation of galaxies, it shows that the real (gravitational) mass of galaxies appears about one order larger than that from luminosity astronomically determined mass; according to today's observations, the galactic halo is much larger in size than previously thought and probably contains a larger portion of the total mass of galaxies. Even greater disproportion arises in galaxy clusters, where the relevant difference is almost two orders of magnitude, so that at the observed relative velocities of the individual galaxies, the system-cluster of galaxies can be stably gravitationally bound.

This is evidenced by the analysis of the motion of very sparse glowing gas around galaxies. If the mass of the galaxy were concentrated only in the visible region, the orbital velocity of the surrounding glowing gas would be inversely proportional to the square root of the distance from the center of the galaxy (according to Kepler's law). In a simplified spherically symmetric model, at a distance r from the center of the galaxy, the orbital velocity of a substance will be given by the relation $v^2 = G.M(r)/r$, where $M(r)$ is the mass contained in a sphere of radius r . For a constant density of matter, $\rho(r) = \rho$, then inside will be $v^2 = (4/3) \pi r^3 \rho G/r$ (orbital velocity will increase in direct proportion to the distance r). At the same time, outside the galaxy, the dependence $v^2 = G.M/r$ will apply, where M is the total mass of the galaxy. Outside the galaxy, according to Newton's laws, the orbital velocity of matter (gases) should decrease with the square root of the distance.

⁶⁹ <https://astronuclphysics.info/AntropPrincip.htm>, accessed on 16 Mar 2026

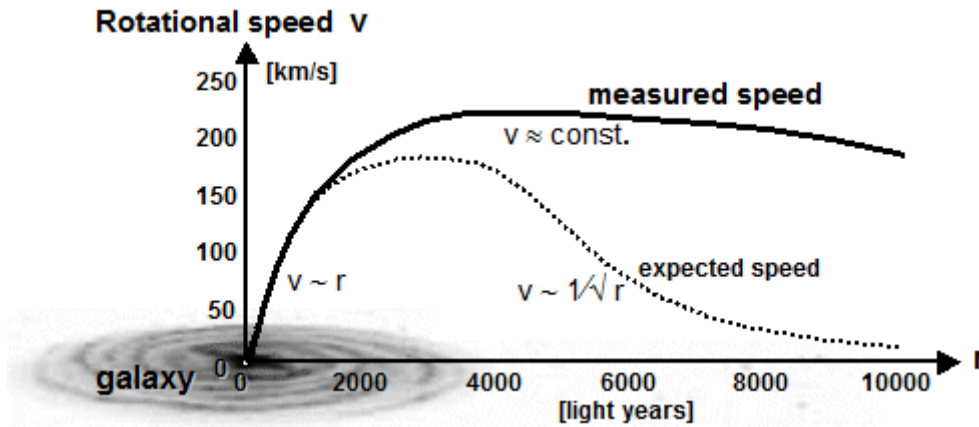


Figure 1: Typical rotation curve

In reality, it is observed that up to a distance of several radii of the visible part of the galaxy, the gas orbital velocity remains roughly constant (solid curve in Fig 1, which is flat), so that in this non-radiative region the mass density appears to be approximately the same as in the luminous areas of the galaxy. Typical rotation curve, which dependence of the orbital velocity of matter on the distance from the center of the galaxy has been shown in figure 1 above. It can be said that stars in galaxies and galaxies in galaxy clusters orbit, and overall, they move so fast that centrifugal force and inertia would have long ago had to scatter them into space, if they had not been held by the gravity of some unknown hidden mass. This fact was pointed out in 1934 by F. Zwicky, who at the observatories in Mt. Wilson and Mt. Palomar observed faster movement by spectroscopy of galaxies at the edge of a cluster of galaxies and stars in the peripheral parts of galaxies, than would correspond to the law of gravity at astronomically determined masses of luminous matter.

To explain this paradox, it is necessary to assume that in galaxies a much stronger gravitational field acts than corresponds to the classical mass of electrons, nucleons, atoms, ions that form stars (with planets) and interstellar gas. There must be a large amount of some hidden and non-radiant dark matter that has gravitational effects. The measured rotational curves of ordinary galaxies show a content of at least 70% of dark matter (up to 90% in dwarf galaxies). Measurements of motions in large systems of galaxy clusters show that hidden matter is not only contained in galaxies, but is distributed throughout the universe, with different local densities. The average density of dark matter in the entire observable universe is estimated at $2 \times 10^{-27} \text{ kg/m}^3$. However, due to gravity, it can cluster into much larger concentrations in the centers of galaxies. On the other hand, in large cosmic voids, the density of dark matter is estimated to be about 10-times lower.

This hidden mass should be composed of particles that are affected only by gravitational and possibly weak interaction (the effect of weak interaction would be negligible due to the low effective cross section and short-range). Still, they are not affected by strong and electromagnetic interactions (or electromagnetic interaction does not manifest observationally). Hidden matter would be affected - and would affect the surrounding universe - only gravitationally. In short,

galaxies rotate too fast to be held together by the gravity of the visible matter in stars and interstellar gas. So, there should be a kind of hidden gravitational "glue" that holds galaxies and clusters of galaxies together, so that the stars do not fly away from the rotating galaxies into the surrounding universe. Without this hidden matter, galaxies and galaxy systems would be unstable and would not hold together.

8. Dark Matter and Black Hole

Dark Matter. Dark matter is therefore a hypothetical form of matter that is spread over very large regions of the universe. It holds together the galaxies that orbit faster in the peripheral regions, than would correspond to the gravity of visible matter; the same is true in galaxy clusters. It is called "dark" because it does not emit, absorb or reflect any electromagnetic radiation, making it invisible to telescopes. However, its existence (and some basic properties, especially its distribution) can be derived from its gravitational effects on visible matter, radiation and on the large-scale structure of the universe. Below, we briefly discuss these effects and try to find possibilities for revealing the nature and composition of dark matter. The formation of galaxies and galaxy clusters in the era of matter was significantly influenced by the universe's matter composition. If this substance were composed only of protons, electrons and atoms of hydrogen and helium, intense radiation (from the not too long time of the radiation era) would hinder and prevent the formation of galactic structures for a long time - the universe would remain homogeneous, smooth, without large-scale structures. The presence of dark matter, which does not directly interact with radiation, soon allowed gravitational contractions to "win" over the destructive effects of radiation. The observed faster (earlier) formation of galactic structures requires additional (only gravitationally interacting) matter, dark matter, than would correspond to the dynamics of known matter during the expansion of the universe. This is perhaps the most important cosmological indicator for hidden matter - it enabled, among other things, the formation of our Galaxy, in which the solar system, planet Earth, the evolution of life and our existence.

Dark matter should be about 10 times more in galaxies and galaxy clusters than luminous (or radiation-absorbing) matter - it is dominant on a large spatial

scale. The name "dark matter" could lead to the misconception that this substance will absorb light much like the dark clouds of interstellar dust. Nothing like this is observed, "dark" or rather "hidden" matter is perfectly transparent to light and other electromagnetic radiation. It does not emit, absorb or reflect electromagnetic radiation, it shows only a universal gravitational interaction and probably also a weak interaction (see below). If this is the case, dark matter is not able to dissipate its internal energy, it cannot "settle" in large quantizes near the stars, its accretion is negligible. It can collect and gravitate only in huge formations of matter such as galaxies and clusters of galaxies. It can be said that dark matter can be a kind of "backbone" or "skeleton" on which ordinary luminous matter is "packed". For example, a massive star, if it is inside a cloud of dark matter, can in principle absorb a small amount of dark matter by spherical accretion (radiation and stellar wind do not prevent this). A gravitationally bound disk of rotating dark matter can form around massive compact objects such as black holes, but with virtually no accretion. Due to the absence of friction, the orbiting dark matter cannot get rid of excess angular momentum in any way and therefore cannot descend to progressively lower orbits to finally be absorbed by a black hole. It will continuously orbit around. This phenomenon can be expected especially for supermassive black holes in the center of galaxies, where a greater concentration of dark matter is assumed and the dark-matter rotating disk can be very massive. Although it does not directly contribute to accretion, it can greatly influence the structure and dynamics of the normal-mass accretion disk. In addition to its gravitational influence on the motion of glowing astronomical objects like stars, galaxies. Dark matter manifests itself in an attractive gravitational influence on the propagation of light - the effects of a gravitational lens.

For the curvature of electromagnetic rays, it does not matter whether the gravitational substance is glowing or dark. In this way of gravitational lensing, it would be possible to detect the distribution of dark matter even without a direct link to luminous matter even hypothetical dark galaxies? The question naturally arises, what is this hidden dark matter made of? In particular, they could be the usual forms of matter such as ionized intergalactic gas, molecular clouds, infrared or brown dwarfs similar to Jupiter (stars so light that they did not ignite thermonuclear reactions), burnt-out stars of the 1st generation, after which left black dwarfs, neutron stars and the like. They could also be numerous smaller black holes of stellar origin. As most of the degenerate matter hidden in these black holes has a baryon origin. This component is called baryon dark matter and is not fundamentally very different from the commonly known substance composed of atoms and that is more than 99.9% by weight here is made up of baryons- protons and neutrons in the nuclei of atoms.

Black Holes. Black holes of small and medium masses could generally be ideal candidates for dark matter, as they do not emit light and, due to their very small dimensions, practically do not absorb light from an astronomical point of view. Stellar black holes of mass $> \sim 3M_{\odot}$ (formed by the collapse of massive stars

at the end of their evolution) are too few. An interesting hypothesis, however, is the black holes of primordial origin, which could have formed in large numbers from the hot, extremely dense plasma that filled the universe immediately after the Big Bang. Microscopic quantum fluctuations they increase to a macroscopic scale during inflationary expansion- regions with significantly lower and higher densities of matter and energy have emerged, from which all structures in the universe later created. In the very early stages of the universe, soon after the inflation period, a large amount of significant condensation could be present, which could quickly collapse into black holes. This would create a large number of primordial black holes of various weights, especially low ones. These primordial black holes can be considered of non- baryonic origin. They formed before nucleosynthesis. Their detection is very difficult; it could perhaps be possible through gravitational microlenses.

If some compact object (with a mass of at least $10^{-9} M_{\odot}$) were to pass through the line of sight from a more distant star towards us during its movement, it could cause a transient achromatic brightening of the star. The mass of this transiting compact object could be estimated from the degree of this brightening. Such gravitational microlenses are very rarely observed; those few cases are not distinguishable from free-moving errant planets? If the hypothesis of primordial black holes were to be confirmed, it would be a very plausible origin of dark matter, as there would be no need to look for any unknown particles outside the standard model. Alternatively, primordial black holes may form at least part of the dark matter. Un-structuredness and spreading-out of dark matter. Now question is, what distribution and what structures can dark matter form? Interstellar gas composed of ordinary matter like hydrogen and helium can condense by gravity to form globules, protostars, and stars. At first glance, dark matter could do the same. However, contraction and collapse require the way in which the particles lose the kinetic energy generated by the adiabatic compression and slow down so that gravity prevails and the contraction can continue. In ordinary matter, this occurs loss of kinetic energy through electromagnetic interactions, radiation of electromagnetic waves. However, dark matter particles do not have an electromagnetic interaction and have no way to lose energy. From this point of view, dark matter probably cannot form more complex gravitationally compressed star-sized structures.

For similar reasons, dark matter cannot contribute significantly to accretion on compact objects. Ordinary matter trapped in the accretion disk loses kinetic energy and angular momentum due to friction caused by electromagnetic interactions. And it moves in a spiral until it is absorbed. Dark matter probably does not show friction. Its particles would orbit the compact object constantly in the disk. Only particles coming with a very small impact parameter can be captured - in the case of dark matter, only spherical accretion can occur, which is generally inefficient. According to current knowledge or hypotheses, dark matter does not form local structures; it is spread out in clouds comparable in size to galaxies. This is probably the case in the

current cold, rarefied universe. Now, what is the role of dark matter in the early universe?⁷⁰ It could be different in the early, dense universe, during the formation of the first stars and galaxies. Dark matter, in close contact with atomic-baryonic matter, could significantly participate in the gravitational contractions of dense, extensive clouds of this mixture. Clusters of dark matter could have initiated the formation of galaxies. Also, the early massive stars of the 1st generation could contain, in addition to the usual atomic-baryonic matter, a certain amount of dark matter, and that collapsed in the protostar phase together with molecular clouds of hydrogen and helium. Dark matter could also be involved in the early formation of giant black holes, present at the center of most galaxies.⁷⁰

The more complex dynamics of the expansion of the universe. Some new aspects in the issue of the distant future of the universe, in relation to the mean density of matter in the observed part of the universe, are now brought about by the presumed inflationary expansion of the early universe. As a result of this inflationary stage, the radius of the universe would probably be many times (by many orders of magnitude) larger than the horizon, than the observable region of the universe. The local density in the observed part of the universe may then differ somewhat from the global mean. That means that even very accurate determination of the average density of matter in the observed universe it cannot decide on its own between a closed and an open universe, especially if this measured density will be near to the critical density. After a sufficiently long time, the density of matter in the now observed part of the universe mixes with the density of matter in other parts of the universe, and the total density can move to the "opposite side" of the $r = r_{\text{crit}}$ limit than now. Let us recall that, according to current quantum cosmology of the inflationary model, a closed universe is expected, albeit very close to the planar one.

9. Accelerated Expansion of the Universe and Dark Energy

According to the standard cosmological model, the expansion of the universe is hampered by the attractive gravitational effects of matter. It must therefore slow down both in the closed universe (where it would eventually contract) and in the open universe (where the expansion will slow down, but it never stops completely). After all, to quantify the deceleration of the expansion of the universe, we introduced the so-called deceleration parameter q . Again, the gravity of dark matter in particular should make a decisive contribution to slowing down the expansion of the universe. The cosmological constant in Einstein's gravitational equations, according to previous ideas, perhaps may have played a decisive role in the inflationary expansion of the universe at the very beginning, but did not need to be considered for further evolution of the universe.⁷¹ However, the dynamics of expansion (or contraction) of the universe, and the time course of the scale factor or expansion function $a(t)$ and the expansion history of the universe, can be found out by determining the relationship between the cosmological

redshift Z in the spectrum of distant objects and their distances. These distances are derived from the ratio of the actual and observed (apparent) luminosity of suitable standard candles.

For large cosmological distances, type Ia supernovae are suitable "standard beacons", which astronomers are currently able to observe with the help of large telescopes up to distances of more than 6 billion light-years. Supernova Ia can be identified by the shape of the spectrum, their brightness is determined from the course of the light curve - the increase, peak and decrease of the brightness of the supernova. Photometric measurements of such different distant supernovae (with different Z 's) make it possible to determine how the universe expanded at different time periods. By performing multiple measurements at different distances, we can create a graph that maps the expansion of the universe as a function of its age. In 1998-99, two groups of American astronomers undertook the astronomical mapping of the dynamics of space expansion by photometric measurement of a large number of type Ia supernovae. The first group was led by A. Reiss and B. Schmidt (Space Telescope, Baltimore) within the project 'High-Z Supernova Search', which aimed to search for supernovae with large redshift Z . The second group (Supernova Cosmology Project) was led by S. Perlmutter in Lawrence Berkeley Laboratory. The original goal of these observations was to find out how big the slowdown in the expansion of the universe is.

These accurate photometric measurements of distances to supernovae of type Ia are very useful for very distant supernovae. Type Ia (high value Z) are less bright than would correspond to their cosmological redshift Z in universe, the expansion of which slows down due to the gravitational effects of the mass. For closer supernovae with a smaller Z , the relationship between distance and redshift corresponded to the standard scenario. However, the most distant galaxies seem to have driven "something" further than the usual Friedman expansion of the universe. Respectively (which is the same thing), these very distant galaxies, corresponding to the earlier periods of the universe, are moving away at a slower speed than would correspond to Friedman's dependence.

From such a measured relationship between the cosmological redshift and the distance of supernovae, it was surprisingly observed that the expansion of the universe is probably not slowing down at the moment, but is accelerating on the contrary! The expansion of the universe has normally slowed down only to about half the current age of the universe, to about 6-7 billion years, but then began to accelerate, which continues. A supernova of type Ia arises in a close binary star consisting of a giant star and a white dwarf, where matter is transferred from the giant to a white dwarf, whose mass gradually increases. It then crosses the Chandrasekhar limit ($1.4 M_{\odot}$) and the white dwarf explodes thermonuclearly, which manifests itself as a type Ia supernova explosion. All type Ia supernovae explode ac-

⁷⁰ <https://astronuclphysics.info/Gravitace4-8.htm#Kvasary-Mechanismus>, accessed on 16 Mar 2026

⁷¹ <https://astronuclphysics.info/Gravitace5-5.htm>, accessed on 16 Mar 2026

cording to the same mechanism and with the same initial mass and therefore the amount of energy released is practically the same every time.

It has been hypothesized that this accelerating expansion is caused by a kind of pervasive vacuum so-called dark energy or DE with a negative energy density so high, that its repulsive effects overcome the gravitational action of all matter in the universe. In the simplest case, it is assumed that dark energy and emerging repulsive action are distributed approximately homogenous in space. This mysterious hidden or dark energy is sometimes referred to as the fifth state or quintessence. The general theory of relativity, leading to a negative pressure that would induce antigravity repulsion at cosmological distances, acting opposite to the gravitational attraction of ordinary matter. That would be the simplest explanation of dark energy (various hypothetical possibilities to explain the origin of dark energy. So, if dark energy is the energy of (empty) space itself, then as the universe expands, more dark energy comes into the universe, which causes the expansion to accelerate, it is still faster. According to current cosmology, the primary cause of the universe's expansion is the energy-momentum left over from the Big Bang. And the repulsive force of dark energy, when it prevails over the attractive cosmic gravity, will further accelerate this expansion permanently. According to current knowledge, it seems that the universe will not only expand forever, but its expansion will continue to accelerate more and more.

If the dark energy density is constant over time or decreases more slowly than the density of ordinary matter. After the end of the initial inflation expansion and the onset of the Fridman expansion, a period of deceleration would take a long time, when the gravitational effects of total matter (shining + hidden) prevail over the repulsive forces of dark energy and the expansion slows down. After a proper reduction in the density of the mass, a reversal would occur. For a short time, the two forces would be balanced or indecisive universe, then dark energy would prevail and cosmic expansion would eventually go from the deceleration stage to acceleration and the constant acceleration of expansion, towards the thermal death of the universe. Unless a convincing alternative astrophysical explanation of the observed data for distant supernovae is found, the accelerated expansion of the universe and the existence of dark energy must be taken very seriously. It would be one of the most surprising and mysterious discoveries in the history of astronomy. The processing of some newer and larger sets of several hundred distant type Ia supernovae somewhat reduces the statistical significance of the data from the first observation, further measurements will specify. Evolution of cosmological models, where time course of radius a (scale factor) of the universe, depending on the value of cosmological constant L and mass distribution density r (r_{crit} is the value of critical mass density, a_E and L_E denote values of space radius and cosmological constant corresponding to Einstein's cosmological model). And that has been shown in figure 2 below.

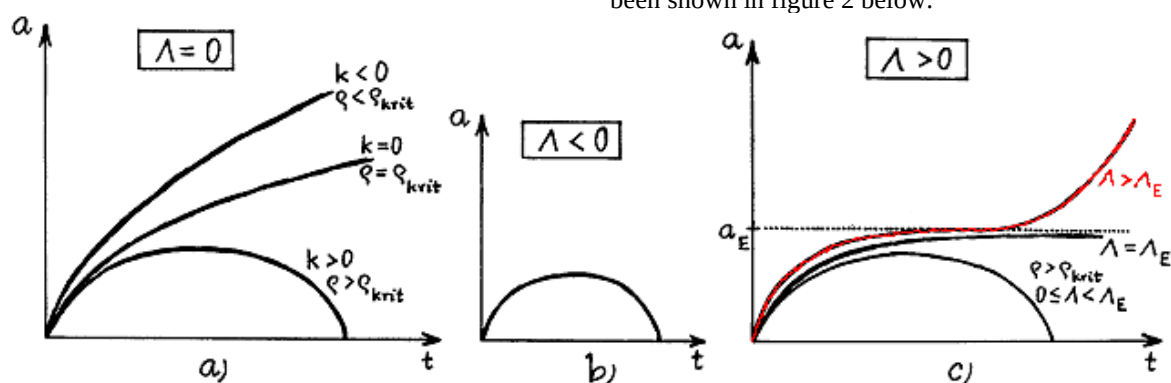


Figure 2: Evolution of cosmological models

Three Indications for Dark Energy. Now have three independent indications for the accelerated expansion of the universe. The measurement of supernovae Ia is the most important; it is a direct indication, and it has been discussed above. In addition, there are two other indirect, looser and model-dependent indications—inhomogeneities of relic radiation in correlation with the large-scale structure of the universe. The small anisotropies of relic radiation reflect inhomogeneities in the distribution of matter just after the end of the radiation era. One possible origin of these inhomogeneities may be the so-called acoustic horizon of density waves and oscillations in the hot plasma of the lepton and radiation era. It is believed that galaxies later formed from these initial inhomogeneities, stretched by the expansion of space over long distances of hundreds of millions of light-years. Their current distribution - clustering - depends on the dynamics of the expansion

of the universe. Detailed analysis of relic radiation inhomogeneities performed by COBE and WMAP satellites, and even more sensitive analysis of relic radiation is performed by the PLANCK satellite, and its correlations with astronomical mapping of the large-scale distribution of galaxies suggest that the observed clustering structure corresponds to the accelerated dynamics of space expansion. After all, even the comparisons of the density of galaxy clusters with low and high redshifts give a slight indication of accelerated expansion. Equation of state of dark energy can be modelled in a simple general form as an "ideal liquid" $p_{de} = w \cdot c^2 \cdot r_{de}$. Where p_{de} is the pressure, r_{de} is the dark energy density, and w is the state constant. If the universe were filled only with the dark energy "de", the acceleration $\ddot{a}$ of the scale function $a(t)$ with time is given by substituting p_{de} and r_{de} into 2.

Table 1:

The "functioning" of this contribution of dark energy in the dynamics of the expansion of the universe depends on the value of the coefficient w in the equation of state of dark energy $p_{de} = w \cdot c^2 \cdot \rho_{de}$

a)	$w > 0$	$\Rightarrow$	ordinary gravitational matter slowing down expansion (here, an irrelevant case)
b)	$w < -1/3$	$\Rightarrow$	general dark energy accelerating expansion; quintessence
c)	$w = -1$	$\Rightarrow$	cosmological constant L , generating vacuum dark energy
d)	$w < -1$	$\Rightarrow$	aggressive dark energy (quintessence) accelerating expansion exponentially above all limits- phantom energy

Measurement of the dynamics of the expansion of the universe using quasars. In addition to supernovae Ia, the dynamics of the expansion of the universe extend to even greater distances. So, earlier periods can be studied using quasars. Quasars are giant black holes in the center of galaxies that absorb a large amount of surrounding gas in a large accretion disk, part of which is ejected along the axis of rotation in massive jets. The absolute magnitude (actual radiant power) of quasars is different. Still, it turns out that this absolute magnitude is related to the spectrum of quasar radiation, especially to the ratio of ultraviolet and X-ray radiation. Quasars, with spectrometric analysis, can then, in principle, be used as "standard candles" for measuring the greatest cosmological distances. At present, these spectrometric measurements are performed on a large number of quasars of different distances.

10. The Influence of Dark Energy on the Evolution of the Universe

Dark energy is very dilute but ubiquitous, and its effect is cumulative. It is imperceptible on terrestrial scales and within the solar system, but it may be dominant on a cosmological scale throughout the universe. Current estimates indicate that approximately 4% of ordinary ("luminous" or absorbent) matter in the universe can be observed, compared to about 70% of dark energy and 25% of dark (hidden, non-radiant) matter. Therefore, if the presence of dark energy (or a non-zero cosmological constant) is truly established, it will alter

our conceptions of the dynamics of the universe's evolution, which now consists of three stages rather than the prior two.

➤ Fast expansion dynamics during the initial phase of the inflationary period.

➤ The cosmos expanded according to the standard Fridman model, first dominated by radiation and thereafter by matter. The gravitational pull of matter slows the universe's rate of expansion (visible and, above all, hidden). The density of stuff, both visible and dark, decreases as the cosmos grows.

➤ Dark energy takes over once the universe's matter has been sufficiently diluted. The universe's pace of expansion ceases slowing down and starts to increase instead. A repulsive cosmological member will eventually force the universe to behave as an almost empty de Sitter universe with exponential expansion. This is a sort of late "2nd inflation phase" that is incredibly sluggish compared to primordial inflation because the vacuum energy density, cosmological constant, and Hubble constant H are all several orders of magnitude smaller than they were at the beginning. However, during this late accelerated expansion stage, "heat death" and an open universe would occur. Studies of supernovae indicate that this "tipping point" between the acceleration and slowing of space expansion occurred approximately 5-7 billion years ago. At that time, antigravity forces caused a lethal "tipping of the weighing pans" due to dark energy.

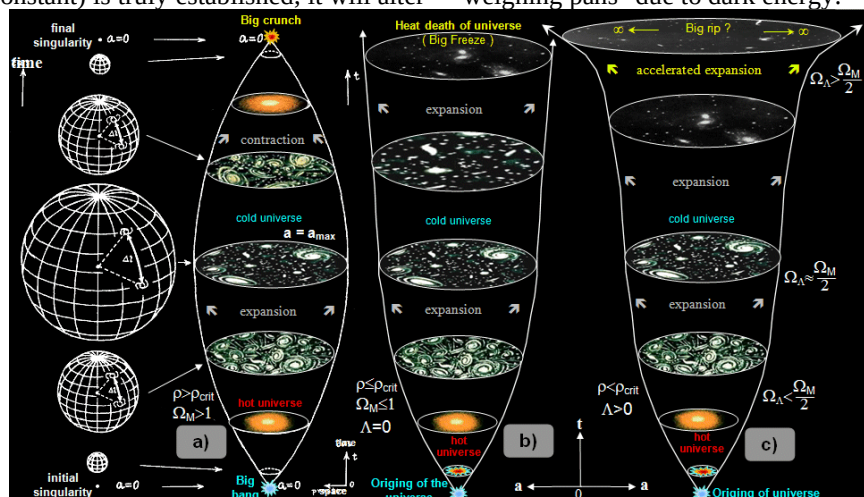


Figure 3: Different possibilities of the dynamics of the evolution of the universe. a) Closed space. b) Open space. c) Open universe with final accelerated expansion

In the universe, hidden (dark, non-radiant) matter and hidden (dark) energy fundamentally have opposing functions. The universe and its structures are held together by hidden matter, which also prevents or slows

down the universe's expansion. The distribution of hidden matter in the early universe was the primary driver of the formation of enormous structures, such as galaxies and galaxy clusters (at the beginning of the matter era). And the galaxies and galaxy clusters are still held

together by gravity through this dark matter. However, if hidden energy prevails, its repulsive effects prevent structures from forming and cause the cosmos to expand worldwide at an ever-increasing rate.

The new cosmological model, which incorporates hidden matter and energy, is frequently called Lambda Cold Dark Matter (LCDM), in which the acceleration of expansion is described by the cosmological constant Λ (L). With the exception of the inflationary stage, dark energy had no involvement in the early cosmos. However, in the far future, it might have a significant impact; it could even blow the universe apart and dissolve it in nothingness. The "duel" between dark matter and dark energy, between their attracting and repulsive gravitational effects, will therefore determine the final fate of the universe in the future if the idea of dark (hidden) matter and energy proves to be correct. The visible glowing material is passively transported away by dark matter and energy, which create the global structure of spacetime. Because of its modest representation, it only has a secondary function in the dynamics of the cosmos. On the other hand, luminous matter acts as a source of electromagnetic signal, an indicator that enables us to map the dynamics and distribution of motion of both luminous and hidden matter in far-off space. Dark energy is most likely a field attribute of spacetime rather than the typical material, substance, or particle nature. For the foreseeable future, it will only be possible to speculate about the nature of dark energy or alternative explanations for the accelerated expansion of the universe, even though recent astronomical observations may make it possible to specify the representation of dark energy and perhaps even estimate its equation of state and the relationship between pressure p and density ρ . Thus far, there are essentially four options or hypotheses.

1. Negative pressure and vacuum energy. Regarding the ideas of unitary field theories' phase transitions. This was thought to be a "false vacuum" energy density of the same type that led to a large accelerated inflation expansion at the beginning of the cosmos. According to this theory, even the current vacuum may be "somewhat false." Still, it only produces a "little" accelerated expansion of the universe because its energy density is several orders of magnitude lower than it was at the beginning. According to this theory, the vacuum energy density is constant throughout space and time, independent of the universe's expansion, and equivalent to the cosmological constant Λ in Einstein's gravitational equations. Immanently "woven" into the hypothetical "yarn" of the space-time structure, it would be an immutable fundamental form of energy (case c in table 1). There are theories regarding the potential modest change in certain scientific "constants," but they mostly assume the cosmological constant and the dark energy it produces are immutable.

2. a brand-new field. The fifth interaction, which fills the cosmos, is sometimes referred to as quintessence (case b in Table 1). Generally speaking, the field of this interaction will no longer be constant; instead, it will be dynamic, with varying strengths over time and in different regions of the cosmos. Quintessence can be repulsive (as it seems now) or even enticing, depending

on the ratio of its potential to kinetic energy at a particular moment. It varies as the universe expands; if it was initially set at a particular intensity, it should diminish with expansion, but at a rate different from the density of matter, radiation, or hidden matter. However, generally speaking, this unidentified field of the fifth interaction may be controlled and evolve according to its own dynamics, of which we do not yet know; we can think of three possibilities. As predicted by the closed universe model shown in Fig. 3a, its intensity may ultimately decline, causing the universe to stop expanding and eventually shrink. Dark energy would then become attractive, eventually collapsing in a "great crash" (which doesn't seem plausible anymore). Alternatively, it might stay roughly constant, resulting in a steady, slow acceleration in a situation like the cosmological constant's vacuum energy (Fig. 3b). As an alternative, we may envision the quintessence field becoming more intense over time, which would accelerate the universe's expansion indefinitely and possibly tear apart all of its structures, as depicted in Fig. 3c.

3. Variations from relativity's general theory. A somewhat different dynamics of the universe's evolution at extreme cosmic distances than that predicted by the "classical" general theory of relativity, which is well proven at shorter "astrophysical" distances, may be the reason for the accelerated expansion. It is necessary to create a new theory of gravity. The alteration of the current situation does not appear to be particularly likely. GTR shouldn't contradict other experiments and findings that have been satisfactorily explained.

4. There is no such thing as dark energy. Its fast expansion is only an optical delusion. Alternative theories regarding the existence or nonexistence of dark energy and accelerated expansion. It seems sensible to investigate the observable phenomenon of the universe's faster expansion using more easily comprehensible and credible reasons, given the enigmatic nature of the hypothesized dark energy. Our incomplete cosmological understanding of the universe's large-scale structure may be the source of what we perceive as dark energy. The Fridman model suggests that the universe's expansion may not be entirely homogeneous and isotropic. The universe is not entirely uniform and smooth. It is made up of several structures. Large cosmic voids are surrounded by a "cosmic network" comprising many galaxies. According to GTR, the geometry of spacetime, including the local expansion rate, is likewise impacted by the universe's inhomogeneous matter distribution. Large voids accelerate time relative to regions of the cosmos with higher matter densities (conventional and dark matter) or return the flow of time to normal. Radiation from the far-off universe frequently travels through these areas with varying gravities, and a small increase in its redshift can build up here. After all, the expansion may appear faster to us at other far-off places because we, as observers at the edge of our galaxy, may also be inside a sort of enormous "bubble" with a slightly lower Hubble expansion velocity. Therefore, it is possible that dark energy and accelerated expansion do not exist, and that the universe's matter inhomogeneity may trick us into simulating an expansion rate that differs from what is predicted.

This could appear to be a rather comprehensible and convincing explanation of the deceptive nature of the universe's accelerating expansion. But let's examine the universe's actual observed global inhomogeneities. The variations in matter density on the local cosmic scales of planets, stars, and galaxies are enormous—on the order of ~ 1030 . However, the cosmos is extremely uniform on large scales, with density variations of about 0.01 per cent (less than 1 particle in 10,000). On a large cosmological scale, the cosmos remains highly uniform even though its (very little) matter eventually clumped into galaxies and "cosmic webs" at birth. In contrast to the enormous voids, the amount of matter in the cosmos is comparatively very little (on average, about 1 proton per cubic meter of space). Therefore, the faster expansion cannot be explained by the astronomically reported inhomogeneities. Therefore, the cosmological constant Λ and accelerated expansion are still regarded as fixed components of modern cosmology. Nevertheless, the most challenging unresolved issue in astrophysics and cosmology at the moment is the nature of dark energy.

The Late Accelerated Expanding Universe.

Because of its fast expansion and normal gravitational attraction, the cosmos would look very different in the distant future than it does now. Two completely different things will happen globally in such a universe: 1) All of the expanding matter in the universe, including distant galaxies that are not gravitationally bound to one another, will rapidly recede until they are out of our line of sight beyond the event horizon, "disappear" both causally and visually, are "swept" from our cosmic horizon, and enter the "invisible." We can picture this as a new expanding space is created between distant galaxies so quickly that even light appears to be slow to keep up with the rate of expansion—it is insufficient to carry information between them. 2) On the other hand, when adjacent galaxies continue to be attracted to one another by gravity, they will unite into a single huge "super galaxy." In a few hundred billion years, the visible universe will consist of a single massive galaxy surrounded by a vast, insurmountable void. One option for the ultimate future of the observable universe is that parts of the galaxy may eventually collapse into a gigantic black hole in the far future (hundreds of trillions of years). Let's compare this bleak prediction with the previously given reflection.

Astrophysics and Cosmology in the Late Accelerated Universe. It is also worthwhile to consider the observational and epistemic aspects of this development. In a hypothetical science fiction scenario, let's imagine that life and eventually an intelligent civilization would emerge in hundreds of billions of years in the late accelerated expanding universe on a suitable planet around some star in this super galaxy. These "humans" would create cutting-edge science and technology, refining tools to enhance life and explore space and environment, even though they won't physically resemble us. At this point, both Earth and our civilization will vanish, along with all of our knowledge. From the start, they will have to develop their own understanding of the natural world and the cosmos. It is unlikely that transhumanism will become a reality anytime soon.

Compared to our present astronomers, these future astronomers might reach entirely different conclusions about the cosmos as a whole. In the vast void of space, even the biggest telescopes would be unable to detect any far-off galaxies whose spectral shift would indicate the universe's expansion. They would discover that there are no other galaxies in the cosmos and that they reside in a single, massive galaxy, likely elliptical and with minimal gas. Relic radiation, which is now microwave, is no longer observable due to its extreme dilution and elongation. What kind of cosmological theory these future observers would develop is difficult to predict. They most likely wouldn't even imagine a cosmos formed by the Big Bang. Accelerated expansion will "obliterate" any traces of the universe's early evolution and begin irreversibly.

They would observe a large number of stars of different generations and metallicities, and could build a robust framework for stellar nuclear astrophysics, well explaining the formation of heavier elements in the universe. By spectrometric analysis, they would determine the abundances of the light elements' hydrogen, deuterium, and helium in interstellar space. It's hard to say what kind of theory they would create for the origin of these elements. At the theoretical level of fundamental physics, they would be able to investigate elementary particles, atoms, and other structures through accelerator experiments. They would create what we now call special relativity and quantum physics. Of course, they would easily examine Newton's current law of gravitation. The question is, would they also build our general theory of relativity, or would they arrive at another relativistic physics of gravitation? By applying the model to the entire homogeneous and isotropic universe (even though its observable universe wouldn't be like that!), they could arrive at an analogy of Friedman's equations. One of their solutions - the universe expanding from a hypothetical singularity - they might find theoretically interesting, but so bizarre that they probably wouldn't relate it to the real universe, which would appear completely different at the time. Observational facts, followed by the application of physical laws, provide an astrophysical model of the universe. However, the ways we discovered these fundamental phenomena in the universe will not remain available permanently. Our ability to explore fundamental questions about the structure and evolution of the universe depends on when and where in cosmic history we happen to live. This also applies to any possible other civilizations that may arise in different stages of the universe's evolution. From the point of view of the current scenario of space evolution, we can welcome that we are fortunate to live at a suitable time when we have a good view of distant space. By analyzing astronomical observations (not only in optical and electromagnetic) we can get a realistic idea of universe evolution almost to period of its origin.

If the very intense (case d in Table 1) "phantom" dark energy continues to drive the expansion of the universe with increasing speed, in about a billion years, we will not even see our "fingertips", because everything around us will move away at super-light speed. The ex-

ponential course of expansion leads to an ever-accelerating expansion, which could theoretically approach infinite speed in the distant future. Conjecturing this scenario "to the end" may lead to the idea that ever-accelerating expansion will not only absolutely distance (beyond the horizon) all distant structures in space, as outlined above in the "Late Accelerated Expanding Universe" passage, but that dark energy will eventually overcome all interactions and binding forces. "Antigravity" will tear apart all bound structures - gradually galaxies, planetary systems, stars. In the final phase, according to some ideas, the atoms would rupture, and even the elementary particles themselves, and perhaps even the structure of space-time, would rupture. Such a scenario of cosmic evolution is sometimes referred to as the "big rip".

Mysteries of Nature. The existence of hidden or dark matter substance and even more hidden, darker and more mysterious dark energies in the universe is a great challenge not only for astrophysics and cosmology, but also for elementary particle physics, if we look for its source at the quantum level. The problem of explaining a non-zero but very small cosmological constant L represents a major challenge for unitary field theories. In current quantum field theories, including a large number of quantum fluctuations, the value of rL is found to be more than 120 orders of magnitude higher. To analyze this problem, one could perhaps say its own even the anthropic principle. Anthropic justification in co-production with the idea of a multiverse - a huge set of different universes with different properties of elementary particles, fundamental interactions and thus the amount of vacuum energy. And even different dimensions of space, could reflect, at least on a philosophical level, these hidden mysterious properties.

Origin and Evolution of the Universe. For better clarity, a large amount of knowledge and hypotheses about the origin and evolution of the universe are discussed in this article, and it will be expedient to briefly and simplified recapitulate within the framework of the current standard cosmological model in several points, capturing the basic processes:

1. Creation of the universe. It is assumed to have occurred approximately 13.8 billion years ago in an explosively hot so-called big bang. The hypothetical initial singularity was rather a "topological foam" of spacetime. In the beginning there was no causality or any laws of physics, all physical forces were connected. At the Planck time of 10^{-43} s, gravity began to operate; the strong, weak and electromagnetic interactions were still unified. Spacetime was created, followed by the rapid expansion of the universe.

2. Inflationary expansion of the universe. It occurred almost immediately after the Big Bang and after gravity became independent, at 10^{-35} seconds. It was very violent but short, after about 10^{-32} seconds it stopped, and the universe was already expanding according to Fridman's model. The inflationary expansion of the very early universe ensured that the universe became globally smooth and flat. The energy of inflationary expansion was transformed into elementary particles - leptons, quarks, gluons. The strong interaction is

separated from the electro-weak one. Quarks and gluons were initially free, forming the so-called quark-gluon plasma. It is assumed that as yet unknown particles of so-called dark matter may also be created here.

3. Hadron era. After the first microsecond, due to the strong interaction in the quark-gluon plasma, the free quarks combine into hadrons, mainly protons, neutrons and unstable mesons. Due to the so-called baryon asymmetry, slightly more matter than antimatter was created (in a ratio of $1:10^9$).

4. Lepton era. In a time of 10^{-4} s, the nucleons and antinucleons annihilated each other (into pions which decayed into muons, electrons and neutrinos), only a small excess of 10^{-9} nucleons remained. An equilibrium mixture of light particles - leptons - electrons, positrons, neutrinos, mixed with photons prevailed.

5. Primordial cosmological nucleosynthesis. In 10 s. - approx. 1000 s., the fusion of protons and the remaining free neutrons took place to form the nuclei of deuterium ^2H , tritium ^3H , helium ^4He and ^3He , in a small amount of beryllium, lithium, boron. The final result of this primordial nucleosynthesis was the representation of atomic nuclei: 75% hydrogen ^1H , 25% helium ^4He , a small amount of deuterium ^2H ($\sim 4 \times 10^{-2}\%$), helium ^3He ($\sim 2 \times 10^{-3}\%$) and a trace amount of Li, Be, B. Heavier elements could have formed much later, in stars.

6. Photon era of radiation. In all the above-mentioned early periods of the universe, there was a high temperature - great kinetic energy of particles and photons, the matter in the universe was in a plasmatic state. In the period $\sim 10 \text{ s.} \div 10^{13} \text{ s.}$, radiation-dominated photon plasma prevailed in space.

7. Formation of atoms and era of matter. In about 380,000 years, when the temperature dropped below 3000 °K, protons and helium nuclei combine with electrons to form neutral atoms of hydrogen and helium. The universe becomes transparent to light; its mass is made up of gaseous hydrogen and helium.

8. Formation of large-scale structures and creating of galaxies and stars. After the formation of atoms ("recombination"), the "dark age" occurred, because the radiation from the early hot universe had already died out and there were no stars yet. Cold matter, gaseous hydrogen and helium, begins to organize itself into large-scale structures through gravitational contraction, galaxies and clusters of galaxies are formed (the formation of large structures was also greatly assisted by the so-called dark matter). Gravitational contraction of denser gas clouds creates the first generation of stars, which end the "dark age" with their radiation. Massive stars thermonuclearly synthesize heavier elements from hydrogen and helium, explode as supernovae and enrich the surrounding matter with heavy elements. The stars of the next generations are then created from this substance, including our Sun. After their formation, stars are surrounded by clouds of residual gas ("protoplanetary disks"), in which planets orbiting the central star (such as the planets of the solar system, including Earth) gradually form.

9. Late evolution, the future of the universe. During all these processes, the expansion of the universe was still taking place, which was gradually slowed

down by the attractive gravitational action of all the matter of the universe, including dark matter. However, this deceleration of expansion lasted only about 7 billion years. After sufficient dilution of the gravitating matter, the so-called dark energy, which has anti-gravitational effects, began to prevail. The deceleration of the expansion gradually decreased until it turned into an acceleration of the expansion. This situation continues even now and the continued accelerated expansion of the universe is expected in the future. In the distant future

11. Possibilities of 'End of Universe'

Astrophysics and cosmology are concerned in particular with the study of the evolution of space objects and the cosmos as a whole. The current expansion of the universe, where individual possibilities are examined beforehand, is the fundamental knowledge of astronomy. The topic of where the universe's evolution is heading in the future is just as fascinating and fundamental as the question of the universe's origin and early phases. What happens to all of space's incredible structures and matter? According to the conventional cosmological model, the universe's future relies on whether the average density of cosmic mass ρ is less or larger than the critical density ρ_{crit} , excluding improbable scenarios like a stable or oscillating cosmos.

Closed universe. The universe is closed at supercritical density and will only expand to a certain point before gravity takes over, expansion stops, and shrinkage begins. The redshift turns the relic radiation blue, and its temperature initially rises slowly but eventually grows indefinitely. This process continues until the universe reaches a very dense, hot state (theoretically a singularity), and the universe undergoes gravitational collapse, sometimes known as a Big Crunch or a Big Collapse. Every construction will be demolished, along with the material that makes it up. Therefore, the last stages of a closed universe occur, roughly speaking, in reverse order to the early universe's birth and expansion; when the energy of the relic radiation increases, the atoms of interstellar and stellar matter will once more disintegrate into elementary particles. In contrast to the early universe, there will actually be a large number of compact objects in the final stage, such as neutron stars and black holes, which rapidly expand and eventually merge due to particle and radiation accretion. Recent astronomical measurements suggest that this closed-space scenario is unlikely.

Open Universe. According to the mainstream cosmological model, the universe will expand continuously beyond all bounds if the density of cosmic matter is below the critical density. Gravity will slow the expansion, but it will never stop. There will be "enough time" to implement extremely laborious astrophysical evolution scenarios for stars, galaxies, and the entire universe. According to the astrophysical scenario of stellar evolution, the Sun will gradually run out of hydrogen in 5–7 billion years and begin to expand into a red giant. The inner planets Mercury, Venus, and perhaps Earth and Mars will be gradually consumed by them. This red giant transforms into a white dwarf after a few million years. Meanwhile, the solar system's planets will likewise experience full manifestations of

gravitational instability, with some planets perhaps exiting the system entirely.

Galaxies' gas and dust will produce several additional generations of stars over the next 10 to 30 billion years, enriching the cosmic matter with heavier elements through nucleosynthesis. But hydrogen, which is the usual "fuel" for stars in galaxies, is rapidly running out. The star birthrate is decreasing in most galaxies. The majority of galaxies will burn out after 100 billion years. After that, there won't be any more material for the creation of new stars, and the cosmos will descend into an ever-deepening darkness that will only sporadically be briefly illuminated by supernova explosions, which are the dying stage of some of the last enormous stars. Only the compact bodies of the latest stages of stellar evolution—white dwarfs, black dwarfs, neutron stars, and black holes—remain after the last stars die out. They will orbit the supermassive black holes at the heart of the galaxies with the remaining diluted gas, and their material will progressively cool until it reaches the temperature of the surrounding cosmos. It will take a very long time. In roughly 10¹⁵ years, a white dwarf will cool to a black dwarf state.

Neutron star fusions, which originated as a component of binary or many systems, will be minor occurrences throughout this time. They will radiate the circulation's kinetic energy as gravitational waves as they orbit one another, progressively getting closer until they eventually merge. Along with the gravitational wave flash, a significant amount of neutron material is released during this event. This material then explosively nucleosynthesizes to form a hot, high-concentration mixture of heavy elements. The surrounding dark cosmos will be momentarily illuminated by these hot regions of matter before they quickly expand and vanish. Whether the proton decays into leptons as predicted by some grand-unification theories, albeit with a very long half-life >10³³ years; in an open universe, however, there is enough time or remains a stable particle as it appears from experience to date, will determine the future fate of these remaining structures. That is unknown at this time. These material configurations in the wide cosmos might not change indefinitely in the case of stable protons.

However, the quantum tunneling effect might happen on such unfathomably long-time scales: light atomic nuclei might be able to overcome the electric repulsive barrier between themselves, resulting in cold nuclear fusion and the spontaneous fusion of light nuclei into heavier ones. The tunnel effect in this case has almost no probability since cold nuclear fusion is not conceivable under normal conditions. But even this tiny likelihood could appear over a time horizon of about >>10¹⁰⁰ years? This hypothetical theory of cold nuclear fusion suggests that lighter atomic nuclei in compact cosmic objects, such as star remnants, could progressively combine into heavier ones up to iron, a process that could take more than 10¹⁰⁰⁰ years to achieve. They might then collapse into black holes or neutron stars. However, there will never be an experimental way to confirm this mechanism, therefore it will always stay theoretical. Protons in the nuclei of atoms in the atmosphere and inside compact bodies will gradually

decay in the second scenario, known as proton instability (except black holes). Their temperature will remain slightly below zero at a few tenths of a °K due to the energy lost during this decay. Leptons and radiation will be released into the surrounding space when the matter from black dwarfs, neutron stars, gasses, and the remaining planets gradually breaks down.

In the meantime, gravitational waves that take away rotational energy cause the majority of galaxies to collapse into enormous black holes. After roughly 1035 years, the majority of what's left in space are black holes, which are encircled by light particles and sparsely distributed radiation. Black holes will first expand due to accretion, but their quantum evaporation takes over once the temperature of relic radiation has sufficiently dropped. Hawking's quantum mechanism causes black holes to evaporate after a very long time (about 1060 years), leaving the cosmos mostly composed of extremely sparsely distributed particles and continuously cooling and diluting radiation. Only a bland, sparse collection of subatomic particles—electrons, positrons, photons, and neutrinos—will remain from the formerly magnificently structured universe. These particles will fly in the never-ending darkness of the perpetual freezing wasteland without interacting with one another. There will be no more events or phenomena, time seems to have stopped, and the universe will be essentially dead and empty. According to the principles of thermodynamics, all useable energy will be exhausted (degraded into waste heat and radiation); life could not exist in such a setting, and all chemical reactions would cease. The "great cold" or the "thermal death" of the universe are terms used to describe this unending freezing extinction of all structures and events. What does "the Future of the Universe" entail? There are two options for how this expansion might proceed: 1) That in the future the expansion will end and turn into contraction. Thus, a great crash is the collapse of the universe and will cause it to vanish. 2) The expansion will go on indefinitely, but the attracting gravity of stuff will essentially slow it down. Option 1 has already been dropped as of right now. Furthermore, recent astronomical measurements of type Ia supernovae that are extremely far away further demonstrate that the evidence.

The cosmos is continuously growing. For the first nine billion years or so, the expansion slowed down. However, after that, it started to pick up speed, and the universe is currently growing more quickly. We have no idea how or if it will all end. Different possibilities of "great cooling - heat death of the cosmos" or even "huge rip" because of the universe's exponentially rising pace of expansion are being proposed. This has to do with dark energy's as-yet-unknown characteristics. There will undoubtedly always be a number of unanswered questions because resolving one issue typically prompts more. This inherent restriction of our understanding should be freely acknowledged. Some experts have some issues with this because they are rather "scholastically" focused on teaching at universities. They attempt to be "extremely clever" and replace "axioms" that pupils have "to buffoon" with some inexplicable phenomena, issues, or qualities; it seems learned

and scholarly. There should be some space for independent thought and an attempt at an informal, illustrated comprehension of the true essence even when there is no other option. It may include a few fairly unconventional and speculative theories at the conclusion that it was unable to fully incorporate into the continuity of astrophysics and cosmology interpretation. Below is a description of those speculative theories.

Loss of Information in a Black Hole. The characteristics of black holes have been thoroughly covered above. With the exception of the total mass, charges, and rotating momentum, all information regarding the specific characteristics of the collapsing matter is lost to the outside world when a black hole is created through gravitational collapse. Both hair and microscopic structure are absent from black holes. The phrase "a black hole has no hair" is a metaphor for this, meaning that it just possesses mass, charge, and rotational angular momentum. This peculiar circumstance is referred to as the 'paradox of information loss'. Quantum evaporation: what is it? or matter coming back from a black hole. In the context of classical or non-quantum physics, black holes are attributed to the actual temperature (proportional to the surface gravity) and the actual entropy (proportional to the surface horizon) based on this analogy, creating a kind of 'thermodynamics of black holes'. There would be inconsistencies in these thermodynamics. Regardless of the strength of the surface gravity, a black hole's temperature must be absolute zero since, according to classical physics, it may absorb bodies and radiation but cannot release anything. Similarly, since a black hole might theoretically be created by the collapse of an arbitrarily large number of tiny particles, the entropy of a black hole should be infinite according to classical physics, independent of the size of the horizon surface. Therefore, in classical physics, the comparison between the rules of thermodynamics and black hole mechanics would have no deeper scientific significance and would merely be an outward and essentially random similarity.

Black hole features have only been studied in terms of the classical general theory of relativity; quantum phenomena have not been taken into consideration. Since there is yet no fully developed quantum theory of gravity, a fully consistent quantum method is not yet possible. Therefore, we have to settle with a sort of "semi-quantum" strategy: we will only quantize other physical fields, leaving gravity unquantized. To put it another way, we will use quantum physics to explain how matter moves and how non-gravitational fields behave in curved spacetime (against the background of unquantized geometry of spacetime - in the unquantized gravitational field). It can be anticipated that this semi-quantum approximation will accurately describe reality in almost every scenario, with the exception of phenomena in the immediate vicinity of singularities, since the effects of quantitation of spacetime itself can be applied significantly in microscales of the order of ~10-33 cm (see §B.3), while they are very small in the scales of ordinary physics (i.e., above 10-13 cm). Entropy is a measure of a system's disorder from the perspectives of statistical physics and information theory.

The black hole's entropy is then measured by this massive amount of lost information. The somewhat deceptive term "holographic principle" was later used to the proportionality between the horizon's surface and the entropy of the absorbed materials.

Holographic Principle. A 'holographic image' in optics is created in such a way that a beam of coherent light from a laser is split into two parts, one of which hits the photographic layer directly, and the other part after reflection from the imaged object. Both of these beams interfere and create a structure of thin interference stripes on the photographic emulsion, carrying information about the phase differences of the two beams. If we then irradiate this two-dimensional image with coherent light again from a laser. The reflected rays reconstruct the same phase differences that created the image - the impression of a three-dimensional image of the original object is created. The holographic image has the interesting property that even from a fragment of the hologram we can see the entire three-dimensional image, albeit with a lower resolution. The two-dimensional surface of the black hole's horizon carries all the information appropriately reduced "the black hole has no hair" about the three-dimensional configurational masses absorbed in the black hole, just as a two-dimensional hologram carries information about a three-dimensional object. However, the similarity with holography ends here, because specific detailed information about the absorbed matter except for the mass M , the momentum of the rotational moment J and possibly the electric charge Q is lost and cannot be reconstructed in any way.

However, some experts in the field of astrophysics and unitary field theories (started with G. 't Hooft and L. Susskind) liked the holographic idea and led them to believe that in a similar way all information about other systems, not only black holes, could be located on the surface area) of the area in which they are located. A thought experiment with a very large black hole could indirectly point to this, around whose horizon the usual laws of physics would apply as in a state of weightlessness, in a free-falling locally inertial system there would be only tiny tidal forces. Below the horizon, based on the holographic proportionality between the surface of the black hole's horizon and its entropy, we can imagine that all information about the matter inside is localized on the horizon, whose surface maintains information about the entire internal space. However, this interpretation is not very physically correct, because the theorem "a black hole has no hair" and the proportionality between the surface of the horizon and entropy applies to the outer, not the inner, space of the black hole.

The holographic principle was further generalized in connection with the construction of superstring theory: "Information degrees of freedom about a system inside a volume V can be localized encoded on the surface V of this volume, while the information density does not exceed one bit per Planck surface l_p^2 ". The holographic principle is generally the statement that information about an N -dimensional region (its interior) is encoded at the $N-1$ dimensional boundary of that region. Within the general theory of relativity, it is theoretically supported only at the horizons of black

holes. In other cases, it is only an extrapolation and analogy and which is an unsubstantiated hypothesis. So, the universe is apparently not holographic. However, holographic concepts are sometimes used in different variants of superstring theory. However, Superstring theory is a theoretical framework in physics proposing that the fundamental constituents of the universe are not point-like particles, but tiny, vibrating one-dimensional "strings". It aims to unify quantum mechanics and general relativity, incorporating "supersymmetry" to include both bosons and fermions, potentially serving as a "Theory of Everything". Question is holographic universe possible? An adequate skeptical answer is 'Probably not'

Universe may inside a Gigantic Black Hole. The development of black hole astrophysics in the 1960s - 1980s and the attractiveness of these exotic objects led to yet another bizarre hypothesis: That our entire universe with all the galaxies, nebulae, stars, planets and other structures that can be seen through telescopes or inferred from detection of electromagnetic or corpuscular radiation and possibly gravitational waves could be located inside a gigantic black hole. And existing inside an even larger whole or the multiverse. However, there is no direct connection with the multiverse hypothesis like 'Anthropic principle and the existence of multiple universes.' The origin of this universe could then be explained by an equally bizarre idea: that the Big Bang was a kind of Big Bounce, where the gravitational collapse in the previous universe created a "wormhole." The outlet of which opened into a new expanding universe? So, all unverified assumptions, furthermore, from an astrophysical point of view, it would not be consistent with the cosmological principle of global homogeneity and isotropy of the universe. In the outward direction, towards the horizon of the black hole, a sparser distribution of galaxies would be observed than towards the center, towards the singularity. No edge of the universe at the horizon, nor condensation in the direction towards the center and possibly fall into the singularity, is not observed. Some astrophysicists like the idea of the universe inside a black hole, but mainly popularizers and those interested in the fields of philosophy, culture and social sciences. They find it exciting and mysterious. However, it does not correspond to the real universe that we observe and live in which.

Universe may be a Giant Quantum Computer. Successful analyzes and computer simulations of many processes in the universe using powerful computers with sophisticated software have given some authors the impression that this is not just a random success of erudite astrophysicists and computer experts, but because the universe itself is a kind of gigantic software system, that we are just trying to find out. And from the point of view of evolution, the Universe is a kind of autodidactic system...? Surely most experts do not mean this completely unfounded science fiction hypothesis literally, but rather metaphorically! "We could be living in the digital world depicted in the Matrix without knowing it?" Probably not! The literal hypothetical that "the universe is a computer" is definitely not true. Instead, a more plausible claim should be: "A number

of processes in the universe can be software algorithmized" and analyzed on large computers possibly quantum computers in the future, allowing them to better understand, simulate, and extrapolate into the future. Philosophically, this suggests that the universe is knowable in terms of the idea of the material unity of the world.

Cosmic Consciousness. The universe may be a living thing that is aware of itself. This sci-fi idea is too subjective and anthropomorphic to discuss in detail in our Astro-physics thesis. Astrophysics and cosmology view the universe as a barren and inhospitable place consisting almost entirely of empty space and inanimate matter. Life is extremely precious. On Earth, matter organized itself to a high level of complexity by special mechanisms and gradually created living beings like Stars, planets, life in the universe. We don't yet know if this has happened in other places in the universe. Some philosophers, alternative naturalists and environmentalists, in the spirit of anthropomorphism, would like to see the universe not completely dead, but the Universe as a living, evolving and learning system with which we humans would live in harmony with each other, because a better and sustainable life on Earth, without crises and devastation of the natural environment. This is certainly a positive motivation. However, somewhat deceptive here can be the uncompromising motivation against materialism, which wrongly equates objective enlightened scientific materialism, which helps to protect nature by better knowledge of reality, with vulgar human materialism, leading to selfishness, consumer society and the devastation of nature. However, here is no objective confirmation of this idea.

12. The Ultimate Fate or Death of Universe

Theoretically, phantom dark energy is a very unstable type of dark energy whose density rises as the universe expands, possibly causing a Big Rip. It is referred described as "phantom" due to its peculiar characteristics, which imply repulsive pressure greater than the energy density itself. It is a hypothetical extension beyond standard dark energy, which has a constant density. Gravity now appears to be stronger at the scales of galaxies and galaxy clusters than would be expected for "luminous" or absorbing matter made up of protons, neutrons, and electrons as measured by astronomers. Thus, dark-hidden gravitational matter is introduced. Conversely, gravity looks less on the larger cosmological scales, where the universe expands, than would be expected given the total attraction of ordinary and dark matter particles. As a result, dark energy is a weak antigravity that acts against gravity and apart from matter—is introduced. Dark energy is needed in current models of the universe to account for the acceleration of space expansion that has been detected based on

measurements of supernova distances in far-off galaxies (which appear to be more distant than they should be if the expansion of the universe did not accelerate). But new observations are being assessed, alternative possibilities are being investigated, and the problems of dark matter and dark energy are still being debated.

The question now is, how will the universe end? Or what is the universe's final destiny? Everything that has originated, existing, and is evolving must eventually come to an end or extinction and that based on all of our observations of nature and life. We also believe that the entire cosmos possesses this quality. This article has examined several astrophysical processes that could eventually lead to the extinction or death of the universe as we know it in the far future. The evolution and extinction of the universe is a cosmological framework tracing the universe from its origin in the Big Bang through its expansion to its eventual, inevitable end. The universe is currently experiencing an accelerating expansion driven by dark energy, making the most likely ultimate fate a Big Freeze or Heat Death, although other scenarios like the Big Rip or Big Crunch remain possibilities. For the sake of clarity, let's list the main ways that our universe can go extinct, be destroyed, or die based on current astrophysics and cosmology:

1. Thermal/Heat Death, often known as the Big Freeze, is the universe's infinite expansion. The adiabatic expansion will continue indefinitely if the gravity of matter in space is unable to slow down and stop cosmological expansion. This will result in an infinite dilution of the average density of matter and a drop in temperature to almost zero. The expanding universe depletes all energy, all processes in the universe cease, and Big Freeze or Thermal Death occurs, as discussed in Open Universe above.⁷² This mechanism, therefore, remains theoretical. In the second scenario, known as proton instability excluding black holes, protons within atomic nuclei in the atmosphere and inside compact objects will slowly decay. Their temperature will stay just below zero, at a few tenths of a Kelvin, due to energy loss during decay. As matter from black dwarfs, neutron stars, gases, and remaining planets gradually decomposes, leptons and radiation will be emitted into space. Meanwhile, gravitational waves that remove rotational energy continue to propagate.⁷³ In actuality, this is a situation where the cosmos asymptotically approaches absolute zero temperature due to continuing expansion.⁷⁴

According to this theory, the world eventually approaches a state of maximum entropy, where everything is distributed uniformly and there are no energy gradients, which are necessary to support information processing, including life. In this scenario, stars are pre-

⁷² Tegmark, Max (May 2003). "Parallel Universes". *Scientific American*. 288 (5): 40–51, accessed on 16 Mar 2026 [doi:10.1038/scientificamerican0503-40](https://doi.org/10.1038/scientificamerican0503-40), accessed on 16 Mar 2026

⁷³ Werlang, T.; Ribeiro, G. A. P.; Rigolin, Gustavo (2013). "Interplay Between Quantum Phase Transitions and the Behavior of Quantum Correlations at Finite Temperatures". *International Journal of Modern Physics B*. 27:

1345032, [doi:10.1142/S021797921345032X](https://doi.org/10.1142/S021797921345032X), accessed on 16 Mar 2026

⁷⁴ Glanz, James (1998). "Breakthrough of the year 1998. Astronomy: Cosmic Motion Revealed". *Science*. 282 (5397): 2156–2157, [doi:10.1126/science.282.5397.2156a](https://doi.org/10.1126/science.282.5397.2156a), accessed on 16 Mar 2026

dicted to form properly for 1012 to 1014 (1–100 trillion) years, but eventually the gas supply required for star formation would run out. This scenario has gained momentum as the most likely outcome. The universe will gradually and unavoidably become darker when current stars run out of fuel and stop shining. Black holes will eventually rule the cosmos, yet as they emit light, they will eventually fade away. Radiation from Hawking.⁷⁵ The Poincare recurrence theorem, thermal fluctuations, and the fluctuation theorem could all lead to a spontaneous entropy drop over infinite time.⁷⁶ Any of the three spatial models can accommodate the heat death scenario, but it necessitates that the universe eventually reach a minimum temperature. It could only happen in a flat or hyperbolic geometry in the absence of dark energy. It might also happen in a closed universe with a positive cosmological constant.

2. The Big Crunch is the universe's collapse. The expansion of the universe will cease if the density of matter in the universe is high enough for its gravitational pull to overcome the cosmological expansion caused by the Big Bang. This will be followed by a contraction that will progressively accelerate and the universe will end in gravitational collapse, which is the final, extremely hot and dense end of the universe or the theoretically collapses with singularities and that is known as the Big Crunch. It is occasionally believed that the Big Bang and the creation of a new universe might happen again following this universe's collapse, although this is merely an unproven theory.⁷⁷ A symmetric theory regarding the universe's ultimate destiny is the Big Crunch hypothesis. Similar to how the Big Bang theory began as a cosmic expansion, this theory postulates that the universe's average density will be sufficient to halt its expansion and cause it to start contracting. The outcome is unclear; at large scales, unknown quantum processes must be taken into account. A straightforward estimate would have all of the universe's matter and spacetime collapse into a dimensionless singularity back into how the cosmos began with the Big Bang.

The universe's temperature would be so high in the final moments of the Big Crunch that atoms and atomic nuclei would disintegrate and be drawn into already-

forming black holes. Similar to the Big Bang, all of the universe's substance would be compressed into an endlessly hot, infinitely dense singularity at the Big Crunch.⁷⁸ A new universe might be created if a second Big Bang occurs after the Big Crunch. However, some physicists have suggested that a dark energy fluctuation may lead to a Big Crunch-style event. Since measurements have only been available for a brief period of time and could reverse in the future, recent information indicates that this scenario is unlikely but has not been ruled out. It was predicted in the 1960s and 1970s that the cosmos will collapse in roughly 100 billion years.⁷⁹ Recent astronomical studies indicate that the cosmos is most likely open and that this closed space hypothesis is not very feasible.

3. The Big Rip is the universe's infinite, accelerating expansion. This theory supports the earlier theory of endless expansion: the accelerated expansion of the universe could progressively accelerate exponentially indefinitely if the density of dark energy were high enough and the expansion of the universe would potentially rise. This would separate the planets from the stars by first dispersing galaxy clusters, then individual galaxies.⁸⁰ Stars, planets, molecules, atoms, atomic nuclei, elementary particles, and ultimately the structure of space-time would all be broken down by the internal pressure of rapidly expanding space. The current Hubble constant describes a rate of acceleration of the cosmos that is great enough to increase the distance between local objects like galaxies, which are held together by gravity, but not large enough to destroy them.⁸¹

All material objects in the universe, beginning with galaxies, would eventually (in a finite amount of time) disintegrate into unbound elementary particles, radiation, and beyond if the Hubble constant were to steadily climb to infinity. The universe ends as what is essentially a singularity as the energy density, scale factor, and expansion rate become infinite.⁸² A more abrupt huge rip might happen in the unique scenario of phantom dark energy, which is thought to have negative kinetic energy and would cause a faster rate of acceleration than other cosmological constants predict.⁸³ Thus, a cyclic model of the cosmos that reverses its

⁷⁵ Adams, Fred C.; Laughlin, Gregory (1997). "A dying universe: the long-term fate and evolution of astrophysical objects". *Reviews of Modern Physics*. 69 (2): 337–372, doi:10.1103/RevModPhys.69.337, accessed on 16 Mar 2026

⁷⁶ Linde, Andrei (2007). "Sinks in the landscape, Boltzmann brains and the cosmological constant problem". *Journal of Cosmology and Astroparticle Physics*. 2007 (1): 022. arXiv:hep-th/0611043, accessed on 16 Mar 2026 doi:10.1088/1475-7516/2007/01/022, accessed on 16 Mar 2026

⁷⁷ Perlmutter, Saul (April 2003). "Supernovas, Dark Energy, and the Accelerating Universe". *Physics Today*. 56 (4): 53–60, doi:10.1063/1.1580050, accessed on 15 Mar 2026

⁷⁸ Davies, Paul (1997). *The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe*. Basic Books. ISBN 978-0-465-03851-0, accessed on 15 Mar 2026

⁷⁹ Adams, Douglas (1995). *The restaurant at the end of the Universe* (1st ed.). New York: Ballantine Books. ISBN 978-0-345-39181-0, accessed on 15 Mar 2026

⁸⁰ Harrison, E. (1992). "The redshift-distance and velocity-distance laws". *The Astrophysical Journal*. 403: 28–31, doi:10.1086/172179, accessed on 15 Mar 2026

⁸¹ Croton, Darren J. (14 October 2013). "Damn You, Little h! (Or, Real-World Applications of the Hubble Constant Using Observed and Simulated Data)". *Publications of the Astronomical Society of Australia*. 30 e052, doi:10.1017/pasa.2013.31, accessed on 16 Mar 2026

⁸² Braibant, S.; Giacomelli, G.; Spurio, M. (2009). *Particles and Fundamental Interactions: An Introduction to Particle Physics*. Springer. pp. 313–314. ISBN 978-94-007-2463-1, from the original on 15 April 2021, accessed on 16 Mar 2026

⁸³ Ludwick, Kevin J. (2017-09-14). "The viability of phantom dark energy: A review". *Modern Physics Letters A*. 32 (28): 1730025, doi:10.1142/S0217732317300257, accessed on 16 Mar 2026

growth very soon before the impending Big Rip was one use of phantom dark energy in 2007. If the mass-energy of every point in the universe is dense enough to collapse into black hole core material that will bounce after reaching a maximum threshold of compression, generating the next big bang, this cyclic model may get more complex. The quantity and dynamics of the behavior of the enigmatic and ghostly dark energy, about which we now know very little, will determine whether and when such an event could occur. Only wildly speculative estimations for 100–200 billion years have been found thus far.

4. The Big Bounce is the collapse of an earlier cosmos. One cosmological theory regarding the beginning of the known universe is the Big Bounce hypothesis.⁸⁴ A scientific theory about the origin of the known universe is called the Big Bounce. It comes from the Big Bang's oscillatory universe or cyclic repetition theory, which holds that the first cosmic event was caused by the collapse of an earlier universe.⁸⁵ After inflation theory surfaced as a solution to the horizon problem, which had arisen from advancements in observations exposing the large-scale structure of the cosmos, it lost significant attention in the early 1980s.⁸⁶ According to this idea, the universe will repeatedly experience a Big Bang followed by a Big Crunch.⁸⁷

One variation of the Big Bang theory of cosmology holds that the cosmos was initially infinitely dense. Such a description appears to contradict other more widely accepted theories, particularly the uncertainty principle of quantum physics.⁸⁸ Consequently, a different interpretation of the Big Bang idea has emerged as a result of quantum mechanics, namely that the universe tunneled into existence and had a finite density consistent with quantum mechanics before growing in a way controlled by classical physics.⁸⁹ Additionally, if the universe is closed, this theory predicts that if a universal singularity is attained or a repulsive quantum force induces re-expansion, the collapsing universe will give rise to another universe in a Big Bang-like event.⁹⁰

It was discovered that inflation was unavoidably eternal, producing an infinite number of distinct universes with generally distinct characteristics, implying that the characteristics of the observable universe are purely coincidental.⁹¹ As a predicted and falsifiable potential solution to the horizon problem, a different idea was developed that featured a Big Bounce.⁹² Investigation continued as of 2022.⁹³

5. False vacuum quantum transition is known as vacuum instability. The quantum cosmology of the very early cosmos, which makes the assumption of inflation expansion, served as the inspiration for this quite strange scenario. A phase transition from a false highly stimulated vacuum to a real vacuum with a reduced energy density coincides with (and causes) the universe's very rapid exponential expansion. Although our current vacuum in the cosmos may not be the real lowest, it is also somewhat fake and has a propensity to transition to a genuine vacuum with even lower energy. In this scenario, a tiny bubble of a true low-energy vacuum may form somewhere in the cosmos. This bubble has the potential to grow exponentially at super-light speeds, and it will ultimately give way to the entire universe. Theoretically, this disastrous vacuum breakdown process might happen at any time. However, the very fact of the peaceful existence of our universe for more than 13 billion years suggests that the probability is very small, it is estimated that in the next perhaps 10^{100} years there will be no such catastrophe. Moreover, according to some other hypotheses, this process would did not destroy our universe, but could lead to the creation of a parallel other universe in a topologically different space.

Analytical Result. A study that was published in Physical Review Letters in May 2023 states that the Big Bounce should have left marks in the cosmic microwave background (CMB), or primordial light. However, when comparing Planck satellite observations with the simulated CMB in the scenario that the universe bounced on itself only once, that specific bounce

⁸⁴ Abelev, B.; Adam, J.; Adamová, D.; Aggarwal, M. M.; Aglieri Rinella, G.; Agnello, M.; Agostinelli, A.; Agrawal, N.; Ahammed, Z.; Ahmad, N.; Ahmed, I.; Ahn, S. U.; Ahn, S. A.; Aimo, I.; Aiola, S. (2014-11-10). "Beauty production in pp collisions at $\sqrt{s}=2.76$ TeV measured via semi-electronic decays" (PDF). *Physics Letters B*. 738: 97–108, doi:10.1016/j.physletb.2014.09.026, accessed on 16 Mar 2026

⁸⁵ Novello, M.; Bergliaffa, S. E. Perez (2008-07-01). "Bouncing cosmologies". *Physics Reports*. 463 (4): 127–213, doi:10.1016/j.physrep.2008.04.006, accessed on 16 Mar 2026

⁸⁶ Finelli, Fabio; Brandenberger, Robert (2002-05-15). "Generation of a scale-invariant spectrum of adiabatic fluctuations in cosmological models with a contracting phase". *Physical Review D*. 65 (10): 103522, doi:10.1103/PhysRevD.65.103522, accessed on 16 Mar 2026

⁸⁷ Ashtekar, Abhay; Pawłowski, Tomasz; Singh, Parampreet (2 October 2006). "Quantum nature of the big bang: Improved dynamics". *Physical Review D*. 74 (8): 084003, doi:10.1103/PhysRevD.74.084003, accessed on 16 Mar 2026

⁸⁸ Brandenberger, Robert; Peter, Patrick (2017). "Bouncing Cosmologies: Progress and Problems". *Foundations of Physics*. 47 (6): 797–850, doi:10.1007/s10701-016-0057-0. ISSN 0015-9018, accessed on 17 Mar 2026

⁸⁹ Halliwell, J. J. (1991). "Quantum cosmology and the creation of the universe". *Scientific American*. 265 (6): 76, 85, doi:10.1038/scientificamerican1291-76, accessed on 17 Mar 2026

⁹⁰ Lehnert, Jean-Luc; Steinhardt, Paul J. (2013). "Planck 2013 results support the cyclic universe". *Physical Review D*. 87 (12): 123533, doi:10.1103/PhysRevD.87.123533. ISSN 1550-7998,

⁹¹ McKee, Maggie (25 September 2014). "Ingenious: Paul J. Steinhardt – The Princeton physicist on what's wrong with inflation theory and his view of the Big Bang". *Nautilus*. No. 17. NautilusThink Inc. Archived from the original on 23 January 2017, accessed on 17 Mar 2026

⁹² Steinhardt, Paul J.; Turok, Neil (2005). "The cyclic model simplified". *New Astronomy Reviews*. 49 (2–6): 43–57, doi:10.1016/j.newar.2005.01.003. ISSN 1387-6473, accessed on 17 Mar 2026

⁹³ Ijjas, Anna; Steinhardt, Paul J. (January 10, 2022). "Entropy, black holes, and the new cyclic universe". *Physics Letters B*. 824: 136823, doi:10.1016/j.physletb.2021.136823, accessed on 17 Mar 2026

signature was not discovered.⁹⁴ It is less likely that a second Big Bang, which would create a new universe, would occur after the Big Crunch, where gravity reverses expansion. .⁹⁵ Although not completely ruled out, other hypothesized scenarios, such as the Big Rip (where expansion tears apart atoms), are likewise thought to be less likely based on available observational data.⁹⁶ Variant/option No. 1 seems to be the most likely manner to terminate the cosmos based on existing astrophysical knowledge. (Heat/Thermal Death or the Universe's Great Freeze). This is the most widely accepted model, according to astrophysicist Katie Mack, because measurements of dark energy indicate that it behaves like a cosmological constant, and that causing an accelerated expansion that results in dilution rather than a cataclysmic collapse or tear.⁹⁷ The vast astrophysical uncertainties we have regarding the universe's global structure, the dynamics of its evolution, and the nature and equations of state of dark matter and dark energy must be emphasized. We may only have a limited understanding of the metagalaxy's current properties, which could drastically alter in the far future. As a result, none of the potential end-of-the-universe scenarios are assured.

Revision of Accelerated Expansion of Universe.

The accelerated expansion of the universe was inferred in 1998-99 from measurements of about 60 type Ia supernovae and was widely accepted in the following years as discussed above. However, more recent frequency shift measurements and analyzes of 740 Type Ia supernovae scattered in various directions across the sky, likely show a smaller rate of accelerated expansion, than was inferred from the first measurements. Moreover, it has been shown here that this acceleration is not exactly the same in all directions, that it may be a relatively local effect (it is directed along our apparent motion relative to the cosmic microwave radiation) and cannot be unambiguously attributed to dark energy, which would cause the same acceleration in all directions. This could indicate that the acceleration is an observational artefact of our cosmological location, and perhaps even lead to the abandonment of the concept of accelerated expansion and dark energy.

However, doubts about the accelerated expansion of the universe and dark energy also arise from more precise astrophysical properties of the objects from which this hypothesis arose - white dwarfs and their explosions - type Ia supernovae. More recent, more detailed analyses of a large number of supernovae (e.g. in the DESI project) have shown that the brightnesses of type Ia supernovae are in fact significantly influenced by the age of the white dwarfs, from which they are formed. Younger white dwarfs were formed from stars of the 2nd and 3rd generations, already enriched

with higher metallicity. Supernovae from younger white dwarfs are therefore generally more intense, while supernovae from older white dwarfs, composed only of hydrogen and helium, are weaker. These changes in the brightness of supernovae affect the resulting observational data in essentially the same way as dark energy. The fading of distant supernovae can therefore arise not only as a result of cosmological effects, but also as a result of details of stellar astrophysics. This may lead to an observational overestimation of the distance of high-redshift supernovae. Definitive decisions about the expansion history of our universe will emerge only from spectrometric measurements of a much larger number of supernovae and other very distant one's objects, using large telescopic systems. However, accelerated expansion is still considered a fixed part of current cosmology.

Basic Composition of Universe. Physical cosmology's fundamental goal is to explain the universe's global structure and evolution as well as what mass or matter, fields, and particles and that is composed of. It has been discovered that during the universe's evolution, the makeup of the matter that fills it underwent substantial changes. From fluctuating fields and quanta in the early universe right after the Big Bang to quarks and baryons (protons, neutrons), photons, electrons, muons, neutrinos, light atomic nuclei of hydrogen and helium following initial nucleosynthesis, and ultimately all heavier atoms created during nucleosynthesis in stars and during the supernova explosion. The Elements-Abundance graph shows that the universe's composition has settled down to roughly 75% hydrogen, 25% helium, and a small number of heavier elements,⁹⁸ All this is ordinary matter made up of baryons, electrons, photons.

But the idea of dark matter and dark energy is drastically different; they are complementary to our previous understanding of the universe's makeup. Figure 4 below depicts the matter-energy mix of the current cosmos based on existing knowledge. There is a significant gnoseological component to this global composition as well. Up until recently, we believed that we would gradually learn everything there is to know about the universe through astronomical observation of glowing objects and absorbing clouds of gas and dust in optical, infrared, radio, X, or gamma electromagnetic radiation. All we needed were larger and more sophisticated telescopes and other instruments. As it turns out, humans can only see around 4% of the universe's stuff in this way. About 25% of dark matter and 70% of dark energy are still unknown to humans. Therefore, stars, nebulae, or galaxies are not necessary for the universe's overall characteristics or its evolution. This brilliant or otherwise astronomically detectable matter in space is only

⁹⁴ Van Tent, Bartjan; Delgado, Paola C. M.; Durrer, Ruth (2023-05-09). "Constraining the Bispectrum from Bouncing Cosmologies with Planck". *Physical Review Letters*. 130 (19) 191002, doi:10.1103/PhysRevLett.130.191002. ISSN 0031-9007, accessed on 17 Mar 2026

⁹⁵ Sutter, Paul (March 2023). "Dark energy could lead to a second (and third, and fourth) Big Bang, new research suggests". Space.com, accessed on 17 Mar 2026

⁹⁶ <https://www.space.com/astronomy/how-will-the-universe-end>, accessed on 17 Mar 2026

⁹⁷ <https://www.cbc.ca/radio/quirks/sep-26-tailings-pond-de-toxification-baboon-friendship-and-longevity-ancient-dna-in-dirt-and-more-1.5736876/>, accessed on 17 Mar 2026

⁹⁸ <https://astronuclphysics.info/Prvky-zastoupeni.gif>, accessed on 17 Mar 2026

the "tip of the iceberg"; we are unable to see the main mass. The majority of the cosmos is composed of unknown and invisible things. The fact that we know so little about the universe is a disheartening discovery. Basic composition of universe has shown in figure 4

below and these values were obtained by a detailed analysis of the correlation of the LCDM model with extensive astronomical observations and sensitive measurements of intensity, spectrum and subtle fluctuations of relic microwave radiation

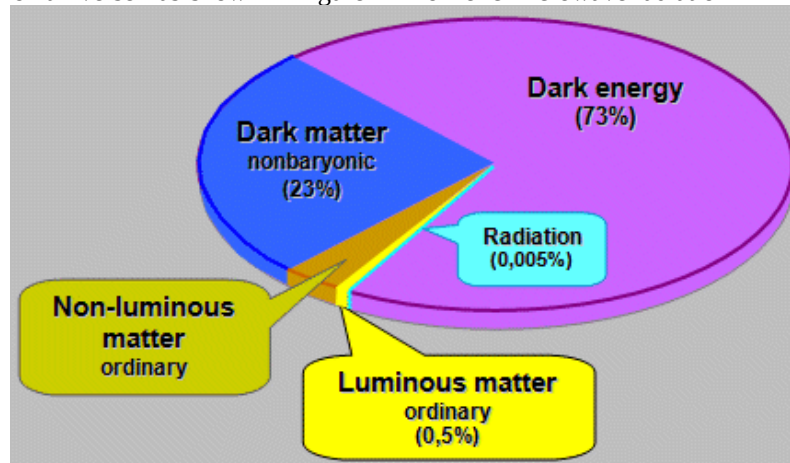


Figure 4: Basic composition of universe

13. Astrophysics and Cosmology: Hope for Human Society and Global Civilization

The latest and best evidence available on the space density of matter and the expansion rate of the universe suggest that we are on a one-way trip: the collective gravity of everything in the universe is insufficient to halt and reverse the cosmic expansion. Currently, the most successful description of the universe and its origin combine the big bang with our modern understanding of gravity, derived from Einstein's general theory of relativity. The early universe was a trillion-degree maelstrom of matter mixed with energy, affectionately known as the primordial soup. During the fourteen-billion-year expansion that followed, the background temperature of the universe has dropped to a mere 3° on the absolute (kelvin) temperature scale. As the universe continues to expand, this temperature will continue to approach zero. Such a low background temperature does not directly affect us on Earth because our Sun grants us a cozy life. But as each generation of stars is born from the interstellar gas clouds of the galaxy, less and less gas remains to compose the next generation of stars. Eventually the gas supply will run out, as it already has in nearly half the galaxies in the universe. The small fraction of stars with the highest mass collapse completely, never to be seen again. Some stars end their lives by blowing their guts across the galaxy in a supernova explosion.⁹⁹ This returned gas can then be tapped for the next generation.

But the majority of stars including Sun is ultimately exhaust the fuel at their cores and, after the bulbous giant phase, collapse to form a compact orb of matter that radiates its feeble leftover-heat to the frigid universe. So, if sun or other stars burn out and no new ones are formed to replace them, then the universe will eventually contain no living stars. What about Earth? We rely on the Sun for a daily infusion of energy to sustain life. If the Sun and the energy from all other stars were

cut off from us then mechanical and chemical processes, where life included on and within Earth would wind down. Eventually, the energy of all motion gets lost to friction and the system reaches a single uniform temperature. This would really be bad. The starless Earth will lie naked in the presence of the frozen background of the expanding universe. The temperature on Earth will drop the way a freshly baked pie cools on a window sill. Yet Earth is not alone in this fate. Trillions of years into the future, when all stars are gone, and every process in every nook and cranny of the expanding universe has wound down, all parts of the cosmos will cool to the same temperature as the ever-cooling background. At that time, space travel will no longer provide refuge. Even Hell will have frozen over. We may then declare that the universe has died. And that is not with an explosion, but with a cry.

A sense of despondency regarding the ultimate viewpoint and the meaning of our existence will inevitably be suggested in us if we mix the knowledge of modern astrophysics and cosmology about the evolution of the cosmos with other risks from a human perspective. The threat to humanity and the length of human civilization are multifaceted. We put ourselves in the greatest risk. Hatred and deadly wars are fostered by greed, selfishness, and pride, particularly among celebrities and the wealthy and powerful of this world who pretend to control and manipulate others often with religious causes, greed to wealth along with regional and global conflict. Potential worldwide conflicts involving existing WMDs could endanger human civilization as a whole. Natural raw materials are wasted, garbage is contaminated, and the environment is completely destroyed due to consumer society. Particularly in Africa, Asia, and some troublesome minority in Western nations, there is an overpopulation of people, particularly unproductive individuals, who will parasitize nature and civilization. This population

⁹⁹ <https://neildegrassetyson.com/essays/1996-06-ends-of-the-world/>, accessed on 17 Mar 2026

growth could result in violent conflicts and the destruction of the natural world, endangering human civilization as a whole, unless widespread enlightenment and efficient birth control are implemented. Unjust social institutions founded on human inequity must also be eliminated. Some of the ignorant and careless individual have been brainwashed with wrong religious ideologies that allow them to harm their neighbors. Only when humanity works together harmoniously will it be able to pull on a single rope and, maybe, avert some horrible threats in the future.

Earth's atmosphere. Earth's present atmosphere is a 78% nitrogen and 21% oxygen mixture, vital for life and climate regulation through greenhouse gases, but it is currently being rapidly modified by anthropogenic emissions. Future atmospheric changes include increased greenhouse gases and warming by 2050, followed by long-term, inevitable deoxygenation over millions of years due to a brightening sun. Rapid changes are driven by human activity like pollution, fossil fuel use, etc. Long-term changes are driven by the natural evolution of the Sun and Earth's geological cycles.¹⁰⁰ The proper environment like temperature, humidity, pressure for many kinds of life, including humans, is greatly influenced by the Earth's atmosphere. Increasing the quantity of so-called greenhouse gases, particularly CO₂, might cause our biosphere's temperature to rise unfavorably in severe circumstances, with the exception of levels that are unsuitable for life. By evaporating into the surrounding universe, the Earth steadily loses its atmosphere and may someday become a dead planet with no atmosphere at all. A gradual, inevitable reduction of oxygen to levels incapable of supporting complex life is expected as the Sun grows hotter and brighter. The atmosphere will eventually shift to a lower-oxygen, methane-rich state.¹⁰¹ The oxygenated atmosphere, which allows for complex life, has a total estimated lifespan of about 1 billion years.

Planet Earth. The future of Planet Earth is a complex interplay between immediate human-driven environmental shifts and long-term natural, cosmic, and geological evolution. While the planet faces significant risks within this century, its ultimate fate is tied to the aging Sun, which will render it uninhabitable in roughly 1 billion years and destroy it in about 7.5 billion years. Continued global warming is expected, with temperatures projected to reach or exceed 1.5°C above pre-industrial levels within decades. Key threats include the melting of glaciers and sea ice, accelerated sea-level rise, increased frequency of extreme heat waves, droughts, and intensified tropical cyclones. Widespread species loss, known as the Holocene extinction, is ongoing due to human habitat destruction, pollution, and climate change. Our Mother Earth poses a grave threat to us as well. A hellish fire of molten rocks rages beneath the tiny layer of the earth's crust

that we live on, which is divided into a number of lithospheric plates. Where lithospheric plates converge, earthquakes and volcanic activity take place. Massive streams of hot molten rocks rise by thermal convection in the earth's mantle beneath the thin layer of the crust, resembling a time bomb. Lava gushes violently under extreme pressure, resembling a devastating super volcano, if it melts to the surface. In addition to destroying hundreds of kilometers of land, such a super volcano can produce thousands of kilometers of volcanic gas and dust, which can obstruct sunlight and result in a catastrophic ecological disaster with drastic climate change. One of the region's most at risk from a catastrophic super volcano is Yellowstone National Park in North America.

The Sun's luminosity will increase by about 10% over the next billion years, leading to a moist greenhouse effect that will cause the runaway evaporation of the oceans. This will lead to the extinction of most life on the surface. As the Sun enters its red giant phase, it will expand significantly, likely engulfing and vaporizing Earth.¹⁰² The Earth's magnetic field, which shields it from a torrent of charged particles from the Sun, may deteriorate in the far future, posing another concern. The whirling semi-fluid outer region of the nucleus functions as a magnetohydrodynamic dynamo that produces the Earth's magnetic field. This nucleus cools and hardens throughout the planet's later phases of evolution, diminishing the magnetic field and ultimately vanishing. Because the possibility of life on a planet's surface has two negative outcomes. Increased levels of harsh ionizing radiation that are detrimental to living things start to penetrate the biosphere from space. Additionally, a star's solar wind is a powerful stream of charged particles that can spray into the surrounding universe and destroy the atmosphere. Water evaporates more quickly as a result of the atmosphere's disappearance, and the stellar wind also carries this steam into space. Life on Earth could not continue if the atmosphere and water were to disappear and the stellar wind also carries this steam into space. Life on our planet could not continue if the atmosphere and water were lost.

Near Space (like Asteroids). Not only do well-known planets like Earth orbit the Sun, but there are also many smaller bodies in the solar system that range in size from tens or hundreds of kilometers—small planets or asteroids—to fractions of millimeters, several centimeters, and meters (meteorites). Those name asteroid, which means star-like arose from the fact that the sun illuminated by nearby bodies of ground-based telescopes look like tiny points of light, like distant stars, unlike the stars but move across the sky like planets. Some of these objects can travel across the planets' orbits, collide with them, be drawn in by their gravitational pull, and strike their surface at speeds of tens of

¹⁰⁰ <https://astrobiology.com/2025/08/as-earths-atmosphere-changes-so-will-its-response-to-geomagnetic-storms.html>, accessed on 22 Mar 2026

¹⁰¹ <https://www.facebook.com/techtimespage/posts/a-new-nasa-supported-study-has-modeled-what-our-planets-distant-future-might-look-like/835616455940761/>, accessed on 17 Mar 2026

¹⁰² [https://science.nasa.gov/climate-change/effects/#:~:text=](https://science.nasa.gov/climate-change/effects/#:~:text=,), accessed on 17 Mar 2026

kilometers per second. Impact craters from these bodies' impacts are widely scattered throughout all terrestrial planets. The orbit of the Earth is also crossed by thousands of the aforementioned bodies. Similar to meteors, small bodies burn in the atmosphere; the amount of fallout from such a meteor is thought to be millions of tons annually. The Earth's atmosphere efficiently shields us from tiny space missiles because tiny meteor bodies burn there rather than falling to the ground. Because friction in the atmosphere causes them to lose nearly all of their kinetic energy, even larger meteorites that strike the earth's surface do not constitute a greater threat and most of their mass evaporates.

Unfortunately, the Earth's orbit is also intersected by the orbits of asteroids and larger bodies; thankfully, this usually happens when the Earth is not at the specific location. Astronomers claim that 'we live in a space shooting range' because there is a chance that an asteroid will strike Earth and that Earth will strike an asteroid. Larger bodies that weigh more than 1000 tons and have a diameter of tens of meters pose a serious threat and it would cause only a local catastrophe. A planet several kilometers in length and weighing more than 10¹² kg would abruptly release energy larger than 10²² J, which is equivalent to the detonation of more than a million thermonuclear bombs. Massive volumes of rocks, gas, and dust would be ejected into the atmosphere in addition to instantly destroying a region spanning thousands of kilometers. A significant portion of the earth's surface could be burned by a fiery meteor shower caused by molten rocks falling to the surface. The sun's radiation would be considerably reduced for a longer amount of time if large amounts of expelled dust remained in the atmosphere for numerous years. This would result in drastic climate change and a worldwide environmental disaster. Most likely, humanity would not endure! An asteroid collision of this kind is believed to have happened 65 million years ago, at which point dinosaurs and the majority of other species of plants and animals went extinct. We do not yet have the chance to stop such a cosmic catastrophe. The Earth has collided with asteroid-sized cosmic bodies on multiple occasions in the past, and it is likely to do so in the future, with deadly repercussions for the continuation of human civilization. Finding dangerous asteroids and anticipating a potential cosmic collision are becoming increasingly feasible thanks to current astronomy technologies. There are essentially two fundamental approaches to preventing an imminent disaster:

1. We could prevent an oncoming collision by altering the trajectory of such a potentially hazardous cosmic body, either by diverting it or altering its speed so that it crosses the Earth's orbit when the Earth is not there, if we knew its future orbit well in advance many years. The application of a force, ideally perpendicular to the instantaneous direction of movement, could have an impact on such a path deflection. The usage of nuclear charge is proposed; if it were to explode, the energy would create a rocket effect and mostly by ejecting molten material from the crater, which would cause the asteroid's orbit to be deflected. or using powerful laser beams for shelling. It is also being considered to launch

a spacecraft into orbit close to an asteroid, which would cause the asteroid's orbit to be deflected by gravity.

2. Another option would be to shatter the explosion's body, but several pieces would fall to Earth in their original orbits. A worldwide disaster might not be brought on by the individual pieces. However, it is a debatable and less-than-ideal method that is only appropriate for tiny asteroids (fragments of which would mostly burn in the atmosphere). But we don't now have enough missile capability to carry out any of these interventions and that perhaps in 50 years! As long as humanity doesn't squander its resources on pointless wars, armaments, and political and religious conflicts. The asteroid "falling on our head" while we do nothing except watch.

Distant Universe (like supernovae, gamma-ray bursts). Large amounts of radiant energy, particularly hard ionizing radiation, would likely strike Earth if some of the closer or nearby stars within a distance of roughly 30 light-years across exploded as supernovae. This could potentially cause a catastrophic natural disaster that could endanger life as we know it! Even from an even more distant universe, hundreds or thousands of light-years, narrowly collimated gamma-ray bursts emitted by collapsing objects - massive stars, neutron star collisions, accretion disks around black holes - can be potentially dangerous to us, if their rotational axis is turned toward us. The entire solar system would be impacted, not just Earth. These high-energy occurrences are important for humans from an astrophysics perspective. Another major concern for planetary life is the possibility of cosmic radiation from catastrophic processes in space.

Sun and It's Future. Our life-giving star Sun will destroy humanity even if we are able to prevent catastrophic wars, asteroid collisions, mega volcanoes, and other natural disasters, as well as shield the planet from a large flash of cosmic rays from a nearby supernova explosion or neutron star fusion. The Sun's present radiant power will rise by roughly 40% during the next three billion years. The oceans will evaporate, the Earth's temperature will rise by tens of degrees, and all life will perish. The Sun will reach the end of its evolution and run out of thermonuclear fuel, particularly hydrogen, in roughly 5 billion years. After then, the Sun inflates and, like a red giant, consumes and evaporates all of the inner planets, including Earth, becoming a planetary nebula before turning into a white dwarf. Additionally, if Mercury, Venus, Earth, and Mars orbit at the same distance as they do now, the Sun in the red giant stage will be big enough to swallow them all. However, the ensuing consequence may allow Earth and Mars to escape this fate. The Sun will produce much more solar wind in the latter stages due to its increased radiative strength, which will transport a sizable portion of its material into space outside the solar system. As a result, the Sun's overall mass will decrease, increasing the orbits' radii. The Earth can orbit at a safe distance that the Sun's swollen surface cannot reach if the Sun's mass is substantially decreased in this way. Nevertheless, the Earth would be a barren planet with a scorching, dry surface where life could no longer thrive even if this advantageous evolution occurred.

The only option to keep Earth habitable over time in the face of the Sun's increasing radiant output is to progressively expand Earth's orbit around the Sun. It would be enough very slowly, on the order of millimeters each year. We don't currently have the technical means to do so, hence it's sci-fi. However, our descendants will probably have far more energy resources in the far future. Furthermore, it is theoretically possible to employ asteroid energy and gravity to raise Earth's orbit. The asteroid could be carefully directed into a tight coronary orbit with Earth, where it would gravitationally transfer kinetic energy to the Earth in the direction of orbit. In this fashion, life may theoretically maintain Earth's habitability for roughly 5 billion years. However, because the Sun's radiation varies somewhat quickly, this would already be an issue in the last phases of its evolution. High-energy gas streams from an expanding envelope would strike the ground. Then it would be helpful if the Sun's (the white dwarf's) brilliance drastically decreased and the harsh ultraviolet component dominated the radiation. The earth would need to be swiftly transferred to a closer orbit since it would freeze in a far orbit¹⁰³. Intense UV radiation would wipe out life and the atmosphere if we brought the Earth to a very close orbit to preserve the temperature as in the science fiction scenario. However, if human society survives at all at that point, it will undoubtedly change into something entirely new.

Global Evolution and Extinction of Universe.

Until the solar system ends, humanity could be able to leave Earth and the Solar system and settle on others suitable spacecraft. So far, it seems less believable. However, we probably wouldn't have any hope if the cosmos were closed and imploded into a massive collision or blazing fire. We wouldn't pose a serious threat if the universe were open, at least not for the foreseeable future. Finding regions of local entropy fluctuation, where energy supplies are still accessible for the advancement and upkeep of civilization, would become more challenging in an expanding and constantly cooling cosmos. In the end, the 'destruction of human civilization' would result from the 'heat death of the cosmos'. When food, an ordered type of energy, is given to living things, the majority of it gets transformed into heat. And that is an energy form that is disorganized. Even if civilization changes in the far future and intelligent information from living things' surroundings is processed into electronic forms, like as anthropic principle or cosmic God. In theory, the fundamental thermodynamic process would remain unchanged. However, information processing would become much more energy-efficient. According to the laws of thermodynamics, this increase in disorder is always greater

than the increase in order in memory. Even the arrangement of electronic memory elements in a particular state requires energy, and a portion of it is always dissipated in the form of heat, increasing the clutter of the entire system. This idea would simply postpone civilization's demise due to heat death.

What is more terrifying is that our entire universe is also a small experiment done by a high-dimensional big boss. The idea of the multiverse, which is an endless number universe, could be represented by some, but only hypothetical, prospect of perpetual existence. A theoretical cosmological theory known as the multiverse postulates that there are other, potentially infinite, separate worlds in addition to our own.¹⁰⁴ Together, these universes are often called parallel or bubble universes—comprise everything in existence, including all space, time, matter, energy, and physical laws. However, multiverse is still primarily a theoretical concept, the multiverse provides a framework to address fundamental questions about the nature of space, time, and existence.¹⁰⁵ While a single universe may die due to collapse or heat death, the multiverse as a whole will endure forever, and fresh life may emerge in individual worlds. But we have no hope in this. In any event, we can say that the theories and knowledge of modern cosmology and astrophysics sadly do not provide us with a true understanding of the eternal existence and advancement of human civilization.¹⁰⁶ However, we may reassure ourselves that the knowledge we now possess is undoubtedly incomplete. Many things may go undetected; we may not even know what they are. And we might be able to draw some hope from this human ignorance.

14. Conclusion

Simply described, quantum cosmology is the application of quantum concepts to the entire cosmos. Despite this extremely lofty mission description, present physics can already do this task, at least in part. There are two primary useful simplifications in practice. First, it is predicated on the finding that the early cosmos was relatively simple in that it was homogeneous and highly isotropic in space. This proposes an approximation approach in which perturbations are added as a tiny correction once geometries and matter configurations are precisely isotropic and homogeneous on spatial slices. Second, the semi-classical approximation is commonly used, which involves working to leading or first sub-leading order while taking into account an expansion in Planck's constant $\hbar$ in the dimensionless inverse Planck mass. Therefore, at the conclusion of the computations, it is necessary to verify if the approximations were appropriate. However, using these assumptions, it is possible to uncover quantum processes in the early cosmos

¹⁰³ Abelev, B.; Adam, J.; Adamová, D.; Aggarwal, M. M.; Aglieri Rinella, G.; Agnello, M.; Agostinelli, A.; Agrawal, N.; Ahammed, Z.; Ahmad, N.; Ahmed, I.; Ahn, S. U.; Ahn, S. A.; Aimo, I.; Aiola, S. (2014-11-10). "Beauty production in pp collisions at $\sqrt{s}=2.76$ TeV measured via semi-electronic decays" (PDF). *Physics Letters B*. 738: 97–108, doi: 10.1016/j.physletb.2014.09.026, accessed on 16 Mar 2026

¹⁰⁴ Romeo, Jess (7 January 2022). "The Real Science of the Multiverse". *JSTOR Daily*. *JSTOR*, accessed on 17 Mar 2026

¹⁰⁵ Swain, Frank (2017). *The Universe Next Door: A Journey Through 55 Alternative Realities, Parallel Worlds and Possible Futures*. London: New Scientist. p. 12. ISBN 978-1-4736-5867-7, accessed on 22 Mar 2026

¹⁰⁶ Ijjas, Anna; Steinhardt, Paul J. (January 10, 2022). "Entropy, black holes, and the new cyclic universe" *Physics Letters B*. 824 136823, doi: 10.1016/j.physletb.2021.136823, accessed on 17 Mar 2026

rather well. In order to comprehend quantum gravity (or holography), entanglement and other fundamentally quantum events give rise to classical spacetime and Einstein's equations. Using this method, it has been discussed in cosmic physics, which deals with expanding universes with a big bang. However, because the holographic gravity theories contain a negative cosmological constant, their generic cosmological solutions feature time-dependent scalar fields that can result in realistic cosmic evolution with accelerated expansion in late time. This makes the theories simply impractical. Observationally, the presence of decreasing dark energy sets these models apart from the Lambda-CDM model.

In the microworld, quarks, leptons, and bosons are examples of structureless or elementary particles. Once more, fundamental particles might be thought of as excitations or ripples in an underlying quantum field that penetrates all of space-time, since Internal Structure as Quantum Fields lacks physical elements. A ripple in the electron field is an electron. On the other hand, a photon is an electromagnetic field ripple. These particles are not merely empty spots; a cloud of virtual particles, which are transient variations in these fields, surrounds them. Conversely, protons and neutrons were once believed to be fundamental particles, but it is now understood that they are composite particles like hadrons. Protons are now made up of one down quark and two up quarks. One up quark and two down quarks make form a neutron. Gluons, which continuously exchange color charges to bond these quarks together, act as glue. Some theoretical models, like string theory, imply that particles might not be zero-dimensional points but rather small vibrating strings of energy, despite the fact that measurements have revealed no interior structure down to 10⁻¹⁹ meters. There is currently no experimental evidence to corroborate the preon idea put out by others, which postulates that quarks and leptons are made up of smaller particles. The end of the universe is extinction, so the purpose of evolution is to delay the process of extinction. This is like the end of life is death, and the purpose of living is to try to delay the

process of death and leave a trace in the world after death.

The most plausible future is one in which expansion never stops. The universe will turn into a cold, dark emptiness with maximum entropy when the stars run out of fuel. The Big Freeze or Heat Death, in which expansion continues and the universe becomes cold, dark, and empty, is the most likely long-term outcome. Dark energy may someday triumph over gravity and tear apart stars, galaxies, and perhaps even atoms if it becomes more powerful. Gravity might reverse the expansion and cause the universe to collapse back into a high-density, high-temperature singularity if the density of the universe is high enough or closed universe. a cyclical scenario in which the expansion and contraction cycle may be repeated when a Big Crunch sets off a new Big Bang. The final result is largely dependent on the universe's density and how dark energy, which propels the accelerated expansion, behaves. According to observations, the universe is flat and will keep expanding forever. All of the aforementioned possibilities, however, are predicated on a basic version of the dark energy equation of state. The Heat Death, also known as the Big Freeze, is the most likely way the universe will end, according to current astrophysical understanding and cosmological consensus. This is the anticipated outcome of the dark energy-driven acceleration of the universe's expansion. But as the name suggests, not much is currently understood about the physics of dark energy. If the hypothesis of inflation is genuine, the universe went through an episode dominated by a different kind of dark energy in the earliest moments of the Big Bang, but inflation terminated, indicating an equation of state more complex than those assumed for present-day dark energy. The dark energy equation of state might alter once more, which would have unpredictable and difficult-to-parameterize effects. The possibilities surrounding dark energy and dark matter's involvement in the cosmos are unclear since their nature is still mysterious, if not speculative.

CONSTRUCTION OF KINETIC CURVES OF CONTACT FORMATION BY CRUSHING MICROASPERITIES IN CONTACT BETWEEN DISSIMILAR MATERIALS UNDER THERMOFORMING IMPACT USING ARTIFICIAL INTELLIGENCE METHODS

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Abstract

An analysis of the formation of true contact (which, under certain temperature and pressure conditions, transitions into physical contact) between dissimilar crystalline materials with markedly different physico-mechanical properties has been carried out using the copper–corundum contact pair as an example. The applicability of artificial intelligence methods for modeling the kinetics of true contact formation and microasperity deformation is examined. An algorithm for constructing kinetic curves of contact formation between dissimilar materials using artificial intelligence methods over a wide range of temperatures and pressures has been developed. In the future, this algorithm may serve as the basis for an automated system for controlling the technological process of producing precision detachable and non-detachable joints and high-purity metallic surfaces with controllable and adjustable mechanical properties, free of foreign particles on the surface and in the near-contact volume.

Keywords: kinetic dependencies, true contact, physical contact, precision detachable and non-detachable joints, artificial intelligence, copper, corundum, thermoforming impact, microasperity.

At the current stage of development of engineering and technology, many design and technological solutions are based on solid-phase contact interaction under various types of thermoforming impact. A special place among these is occupied by technological processes based on plastic deformation of contact surfaces (pressure welding with heating, pressing and sintering of high-dispersion powders, production of metal nanoparticles from decomposition of metal–organic crystalline salts followed by welding of compact materials, all types of blade and diamond machining of metallic surfaces with adjustable mechanical properties, production of high-purity metallic surfaces with adjustable and controllable mechanical properties on the surface and in the near-contact volume free of foreign inclusions, etc.) with subsequent relaxation processes. In this case, maximum preservation of the complex of initial material properties of the assembly components is ensured, together with effective process control and regulation of the degree of contact precision.

According to modern concepts, the contact interaction of materials under thermoforming impact belongs to the class of solid-phase topochemical reactions [1–3] and proceeds in three main stages: (1) formation of physical contact; (2) activation of atoms at the contact surfaces and formation of strong chemical (metallic) bonds; (3) relaxation stage (diffusion processes, recrystallization, formation of common grains, etc.). Physical contact is understood as the approach of atoms of the contacting surfaces to a distance at which exchange processes of electron interaction become possible, i.e., to a distance of the crystal lattice parameter. This means that between the contacting surfaces during

the formation of a non-detachable joint (seizure), there must be no inclusions (contaminants), not even a complex of physical and chemical adsorption. For the production of a detachable precision joint (producing high-purity metallic surfaces), this condition is not mandatory.

Since the formation of physical contact is preceded by the formation of true contact through plastic deformation of the machining micro-irregularities (microasperities) of the contacting surfaces, as well as activation of the contact surfaces and seizure, the relevance of this study is self-evident.

At present, one of the most pressing tasks is the production of high-purity precision metallic surfaces used in high-technology industries such as mechanical engineering, electronics, etc., as well as the production of reliable welded joints in metallic structures.

On kinetic curves of contact formation, three stages characteristic of a creep kinetic curve can be identified: the period of active deformation (loading period), during which intensive growth of the contact area occurs; the period of non-steady-state creep — a transitional zone characterized by a gradual change (decrease) in the deformation rate and contact area, and redistribution of contact zones; and the period of steady-state creep, when the process reaches a stable state (constant rate) [4–6].

Experimental studies of the effect of the thermoforming impact level on the kinetics of crushing and deformation of microasperities of the contacting surfaces were carried out on a copper MB–corundum pair over a wide range of temperatures and pressures; the

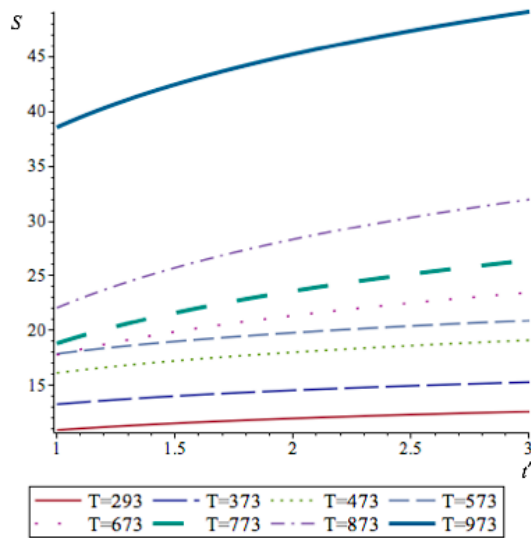
copper contact surface was prepared by planing with $R_z = 40\text{--}80\text{ }\mu\text{m}$ according to the method in [4].

Based on available experimental data on contact area S , % versus time t , s at various levels of thermoforming impact, dependencies of contact area formation on time were obtained for the active deformation stage and the steady-state creep stage in the contact of dissimilar materials with markedly different resistance to plastic deformation (using the copper–copper pair as an example).

The obtained dependencies obey the following law:

$$S = a + b \ln(t'), \quad (1)$$

where $t' = t / 10$; where 10 s corresponds to the onset time of true contact formation.



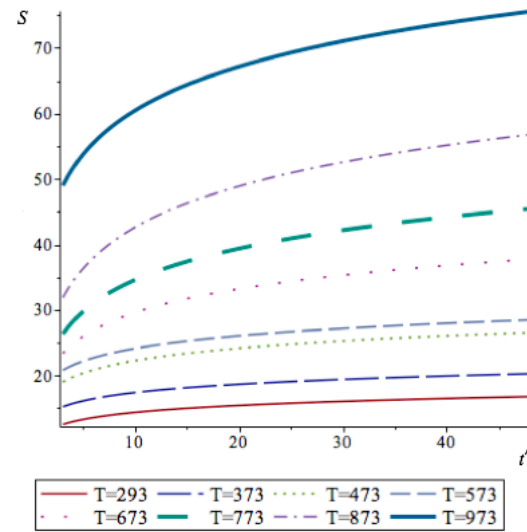
a — active deformation period, $t = 10\text{--}30\text{ s}$

The coefficients a and b in equation (1) were determined according to the formulae:

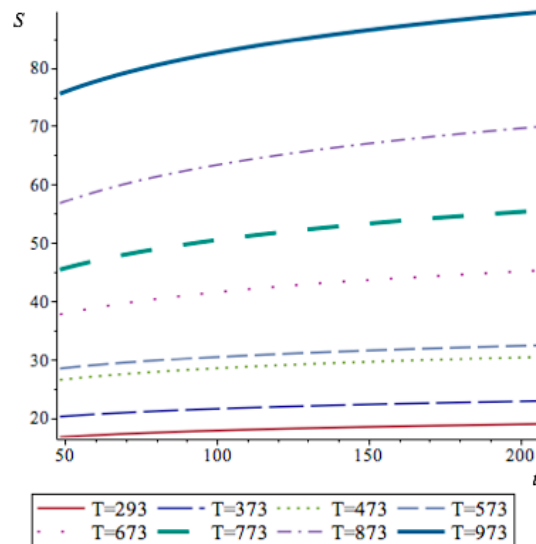
$$a = \bar{S} - b\bar{X}, \quad b = \frac{\overline{SX} - \bar{S} \cdot \bar{X}}{\overline{X^2} - (\bar{X})^2}, \quad (2)$$

where $X = \ln(t')$. Overbars in formulae (2) denote mean values of the corresponding quantities.

For nominal pressure $\sigma_H = 30\text{ MPa}$ and temperatures $T = 293\text{ K}, 373\text{ K}, 473\text{ K}, 573\text{ K}, 673\text{ K}, 773\text{ K}, 873\text{ K}, 973\text{ K}$, the resulting dependencies $S(t')$ are presented in Fig. 1 (a, b, c).



b — non-steady-state creep period, $t = 30\text{--}480\text{ s}$



c — steady-state creep period, $t = 480\text{--}2070\text{ s}$

Fig.1. Kinetics of contact formation at $\sigma_H = 30\text{ MPa}$:
a — active deformation period ($t = 10\text{--}30\text{ s}$); b — non-steady-state creep period ($t = 30\text{--}480\text{ s}$);
c — steady-state creep period ($t = 480\text{--}2070\text{ s}$).

Studies on microhardness changes are presented in Figure 2.

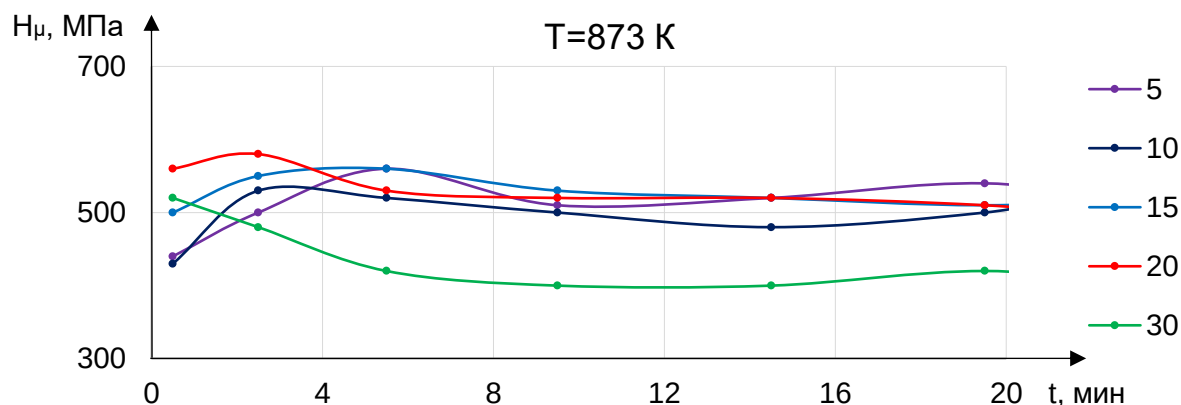


Fig. 2. Change in microhardness at the surface of microasperity contact pads under nominal pressure ($\sigma_H = 5 \dots 30$ MPa) and temperature $T = 873$ K.

These curves fully confirm the progression of the kinetic curves of true (physical) contact formation at the stages of active deformation, non-steady-state creep, and steady-state creep.

To determine the kinetic dependencies over a wide range of temperatures, pressures, and microasperity heights, artificial intelligence methods may be applied. To this end, augmentation of the available experimental data should be carried out using Python libraries to implement the computational algorithm.

For processing and analyzing experimental data, the NumPy and pandas libraries may be used to form arrays $S(t')$ and to structure samples by temperature and pressure parameters.

For building regression and neural network models, the scikit-learn library is used; if more refined description of the already established dependencies of contact area on temperature, pressure, and microasperity height over time is required, the PyTorch or TensorFlow/Keras libraries may be applied, enabling neural networks of various architectures and improving the accuracy of kinetic dependency approximation.

Construction of new kinetic curves outside the ranges covered by the experimental data is carried out using the SciPy package.

For visualization of results and construction of the final kinetic curves $S(t')$ over the entire time range, the Matplotlib library is used.

The algorithm for constructing kinetic curves of true contact formation may include the following steps:

1. Data preparation. Arrays of experimental values $S(t')$ are formed for the active deformation zone (10–30 s), non-steady-state creep (30–480 s), and steady-state creep (480–2070 s).

2. Data augmentation. Interpolation and generation of additional points are performed with account of physical constraints — monotonic growth and continuity of the function.

3. Model construction and training. Based on known experimental dependencies of contact area on temperature, pressure, and microasperity height over time, a regression or neural network model is constructed that provides the dependency $S=f(t, T, \sigma_H, R_z)$.

For moderate nonlinearity, regression approximation is used (linear, polynomial, or gradient boosting); for pronounced nonlinearity — a feedforward neural network (PyTorch or TensorFlow/Keras).

4. Using optimization methods (scipy.optimize module), the minimum discrepancy between the model dependency (constructed by artificial intelligence methods) and the experimental dependency derived from experimental data is determined.

5. Construction of the resultant curve. Based on the trained model, the kinetic dependency $S(t')$ is formed over the considered range of temperatures and pressures.

The presented algorithm may in the future serve as the basis for developing an automated system capable of performing numerical simulation of the stages of microasperity crushing, its staged nature, and forecasting the development of true (physical) contact between dissimilar materials at various levels of thermoforming impact. Implementation of this approach will allow optimization of the technological processes for producing precision detachable and non-detachable joints with controllable and adjustable mechanical properties on the surface and in the near-contact volume. A separate publication will be dedicated to solving this problem.

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THE ROLE OF MACHINE LEARNING IN COMBATING CLIMATE CHANGE: SMART GRIDS AND BIG DATA

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Abstract

This article explores the transformative role of Machine Learning (ML) and Big Data analytics in combating climate change, with a specific focus on the optimization of smart grids and renewable energy systems. Traditional climate modeling and energy management methods often struggle to capture the complex, nonlinear dynamics of environmental systems. In contrast, advanced ML architectures—such as deep reinforcement learning and time-series forecasting—excel at processing massive datasets from IoT devices and smart sensors. These technologies are crucial for forecasting energy demand, predicting weather patterns, and optimizing the integration of variable renewable sources like solar and wind power. Through a comprehensive review of current applications, this study highlights how AI-driven approaches significantly improve energy efficiency, support predictive maintenance, and enable dynamic load balancing within modern smart grids. Furthermore, the article critically addresses the challenges associated with ML deployment, including data privacy, model transparency, the digital divide, and the computational carbon footprint of AI systems themselves. Ultimately, the successful integration of ML into climate action necessitates interdisciplinary collaboration and equitable policy frameworks to ensure resilient and sustainable global energy infrastructures.

This article examines the utilization of machine learning and big data in addressing climate change, specifically focusing on smart grid optimization and renewable energy integration. The study highlights how predictive analytics enhances energy efficiency and supports climate adaptation, while also addressing challenges like data privacy and the environmental footprint of AI systems. The primary aim is to demonstrate the necessity of interdisciplinary collaboration for building resilient and sustainable global energy infrastructures.

Keywords: machine learning, big data, smart grids, climate change, renewable energy, predictive analytics.

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), global emissions must be drastically reduced within this decade to limit global warming to the critical 1.5°C threshold [1, p. 1]. Addressing a crisis of this magnitude requires moving beyond conventional approaches and adopting highly advanced, predictive technological frameworks.

Climate change is universally acknowledged as one of the most pressing challenges of the modern era, demanding innovative, multi-faceted strategies for long-term prediction, mitigation, and sustainable development [2, p. 3]. As global temperatures rise and extreme weather events become more frequent, the need for effective interventions to reduce greenhouse gas (GHG) emissions and enhance ecological resilience is increasingly urgent. Historically, environmental monitoring and climate prediction have relied on traditional modeling methods based on complex mathematical equations [1]. While these traditional frameworks have been effective to a certain degree, they require immense computational power and frequently struggle to accurately capture the highly dynamic and nonlinear complexities inherent in natural environmental systems. In contrast, Artificial Intelligence (AI) and its subset, Machine Learning (ML), offer transformative, data-driven alternatives. Unlike conventional programming, which requires explicit human-coded instructions, ML systems are designed to autonomously learn from data exposures, continuously parsing complex datasets to identify subtle patterns and improve their predictive accuracy over time.

To fully understand the structural role of these technologies, it is essential to define their hierarchical integration within climate sciences. Artificial intelligence broadly encompasses computational systems capable of executing tasks that typically require human cognition, such as adaptive scenario planning and autonomous network operations. Machine learning functions within this sphere by directly addressing data-intensive challenges, optimizing distribution, and forecasting environmental fluctuations. Deep learning (DL), a specialized subfield of ML, leverages multi-layer neural networks to model exceptionally complex, nonlinear relationships, such as high-resolution weather tracking or satellite image interpretation. Predictive analytics represents the functional application of these statistical and ML techniques to forecast future events. Together, these digital tools form the backbone of "next-generation climate adaptation," a paradigm that actively moves away from purely reactive infrastructure reinforcement. Instead, next-generation strategies utilize emerging digital capabilities to implement real-time decision-making, forecast-based renewable energy integration, and dynamic system optimizations [2, pp. 2–4].

The critical operational challenge of the modern energy transition lies in seamlessly integrating variable renewable resources, such as wind and solar power, into grids originally designed for steady-state fossil fuel operations. The inherent intermittency of these green energy sources threatens grid stability, necessitating advanced forecasting tools to balance supply and de-

mand seamlessly [3, pp. 3–5]]. By applying ML predictive models, system operators can anticipate transient weather anomalies and adjust electrical dispatch autonomously, directly reducing reliance on fossil fuel-based backup reserves. Furthermore, the deployment of these next-generation strategies is particularly crucial for developing regions, notably Least Developed Countries (LDCs) and Small Island Developing States (SIDS). These areas often face the most acute impacts of shifting climate patterns, yet they historically lack the robust infrastructural capacity to manage large-scale environmental risks. Consequently, leveraging ML for early disaster warning, agricultural optimization, and decentralized smart microgrids provides a vital, technologically equitable pathway for global climate resilience [1, pp. 6–8]].

Methodology

Data Acquisition and Analytical Framework

The analytical framework of this study relies on examining the deployment and operational mechanisms of diverse machine learning architectures within climate mitigation and energy transmission networks. The primary objective is to investigate how predictive algorithms process vast, continuous streams of heterogeneous data to optimize resource distribution and accurately forecast complex environmental trends.

The data sources feeding these next-generation ML algorithms are massive in scale and multimodal in nature. Data acquisition relies on an integrated network of localized ground sensors, global satellite imagery, meteorological stations, and interconnected IoT smart devices [1][4]. For example, in the realm of greenhouse gas tracking, platforms like Climate TRACE synthesize data from over 300 independent satellites and more than 11,000 physical sensors globally to monitor and quantify emissions with unparalleled precision. In disaster risk assessment, particularly for Small Island Developing States (SIDS), continuous high-resolution aerial imagery is collected to map urban footprints and structural vulnerabilities [1, pp. 8–10]. This continuous monitoring of spatial and temporal variations allows algorithms to detect transient ecological anomalies and diagnose structural inefficiencies long before they escalate into systemic failures.

Big Data and Predictive Analytics in Climate Modeling

Accurate climate modeling requires precise analysis of multifaceted datasets involving variables such as atmospheric carbon dioxide levels, ocean temperatures, and deforestation rates. Traditional models often fall short, but ML dramatically improves forecasting by parsing these complex datasets to identify nonlinear patterns that human researchers might miss.

To translate this big data into functional mitigation strategies, specific algorithmic models are tailored to distinct environmental challenges. In the tracking of land use and deforestation, Convolutional Neural Networks (CNNs) and spatial-temporal deep learning architectures are deployed to divide complex satellite images into distinct, analyzable segments. Advanced computer vision models, such as the Segment Anything Model (SAM), automate the extraction of geographic

data maps, significantly reducing the necessity for manual domain-specific analysis. Furthermore, for land resource management and urban expansion forecasting, Artificial Neural Network (ANN)-based cellular automaton models integrate physical variables like altitude, slope, and soil types to mathematically simulate land cover changes decades into the future. By leveraging Advanced Natural Language Processing (NLP) and Time-Series Forecasting models (such as LSTMs and Transformers), researchers can scan unstructured text and global satellite data to generate real-time adaptive insights, forecasting extreme weather events, hurricanes, and droughts to facilitate early warning systems for vulnerable populations [2, pp. 4–6].

AI-Driven Smart Grids and Energy Management

One of the most profound applications of ML is in the energy sector, specifically within the operation of smart grids and the integration of renewable energy resources. A critical barrier to widespread renewable energy adoption is the inherent intermittency of resources like wind and solar power. ML addresses this by optimizing both supply forecasting and grid management.

In energy optimization, Deep Reinforcement Learning (DRL) and sophisticated time-series analyses are utilized to forecast load distributions and predict the optimal charge and discharge cycles of battery storage networks [3, pp. 7–10]. Through these predictive algorithms, ML anticipates energy production based on local weather patterns, allowing grid operators to balance supply and demand seamlessly. DeepMind, an AI platform owned by Google, successfully demonstrated this by predicting wind patterns up to 36 hours in advance, effectively optimizing wind farm output and increasing the economic viability of wind power [4].

In distribution networks, ML autonomously adjusts energy flows, manages electrical loads, and responds dynamically to fluctuations in supply. Smart dispatch systems, such as those utilized by the National Grid of China, leverage ML to balance electricity loads in real time, directly minimizing the reliance on fossil fuel-based backup plants [1, pp. 11–13]. Furthermore, ML enhances smart grid reliability by facilitating predictive maintenance via Supervised Learning algorithms, which reduce transmission losses and swiftly identify fault lines. On a facility scale, Google applied ML techniques to reduce the cooling energy consumption of its data centers by an impressive 40%, demonstrating substantial potential for large-scale energy optimization [4].

Algorithmic Formulation of Deep Reinforcement Learning for Load Balancing

To move beyond theoretical energy management, it is crucial to understand the underlying computational architecture of AI-driven smart grids. The dynamic optimization of energy dispatch can be mathematically formulated as a Markov Decision Process (MDP) solved via Deep Reinforcement Learning (DRL).

In this framework, the AI agent (the grid controller) interacts with the smart grid environment to minimize operational costs and carbon emissions while fulfilling energy demand.

1. Mathematical Formulation:

At any given time step t , the system state S_t is defined by the energy demand D_t , renewable generation output G_t^{ren} , and the battery state of charge B_t :

$$S_t = \{D_t, G_t^{ren}, B_t\}$$

The agent takes an action A_t representing the energy dispatch strategy, such as charging or discharging

$$Q^*(s, a) = \mathbb{E} \left[R_{t+1} + \gamma \max_{a'} Q^*(S_{t+1}, a') \mid S_t = s, A_t = a \right]$$

Where $\gamma \in [0, 1]$

is the discount factor, and R_t is the immediate reward inversely proportional to the fossil fuel consumption.

2. Algorithmic Implementation (Pseudo-code):

To approximate the optimal Q -values in a continuous and highly dimensional environment like a national grid, a Deep Q-Network (DQN) is employed. Below is the operational pseudo-code representing the autonomous dispatch algorithm:

Algorithm 1: Deep Q-Learning for Smart Grid Energy Dispatch

1: Initialize replay memory capacity D
2: Initialize action-value network Q with random weights θ 3: FOR episode = 1 to M DO:

the storage system, or purchasing power from the main utility grid. The objective is to maximize the cumulative reward, which in this context means minimizing the loss function (cost and emissions). The Bellman equation for the optimal action-value function $Q^*(s, a)$ is expressed as:

4: Initialize starting state $S_1 = \{\text{Demand, Renewable Output, Battery SOC}\}$ 5: FOR time step $t = 1$ to T DO:

6: With probability ϵ select a random dispatch action A_t

7: Otherwise select $A_t = \arg\max_a Q(S_t, a; \theta)$

8: Execute action A_t (Charge Battery / Discharge / Grid Import)

9: Observe immediate reward R_t and the next state S_{t+1}

10: Store transition (S_t, A_t, R_t, S_{t+1}) in replay memory D

11: Sample random minibatch of transitions from D

12: Perform gradient descent step on the loss function to update θ

13: END FOR

14: END FOR

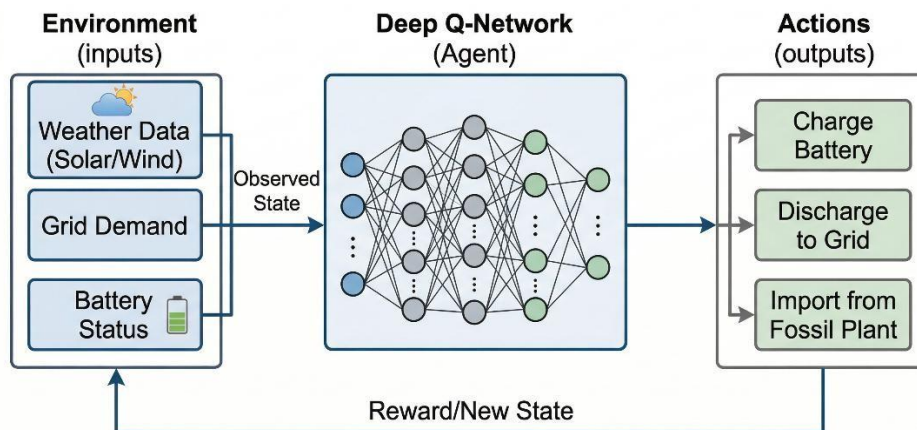


Figure 1: Deep Reinforcement Learning Architecture in Smart Grids

The AI agent (Deep Q-Network) continuously observes environment variables, including atmospheric conditions, current grid load, and local battery availability. It processes this non-linear input data to output optimal operational decisions (actions) for energy balancing.

Preliminary Simulation and Results To validate the theoretical framework of the proposed Deep Q-Network (DQN) architecture, a preliminary simulation was conducted using a PyTorchbased Python environment. The smart grid state was initialized with normalized real-time parameters: high grid demand (0.8), low renewable energy output (0.2), and a near-maximum battery state of charge (0.9).

When passed through the multi-layer neural network, the AI agent successfully evaluated the environmental constraints and autonomously outputted the optimal policy: "**Discharge Battery**". By prioritizing the stored renewable energy over purchasing power from the main grid, the algorithm practically demonstrated its capability to minimize reliance on carbon-intensive backup generation during peak load hours. This micro-simulation underscores the functional viability of integrating RL models into real-world energy dispatch systems.

```

import torch
import torch.nn as nn
import torch.optim as optim
import random

# 1. DQN (Deep Q-Network) Architecture for Smart Grid
class SmartGridDQN(nn.Module):
    def __init__(self, state_size, action_size):
        super(SmartGridDQN, self).__init__()
        # 3-layer Neural Network
        self.fc1 = nn.Linear(state_size, 64)
        self.fc2 = nn.Linear(64, 64)
        self.fc3 = nn.Linear(64, action_size)

    def forward(self, x):
        x = torch.relu(self.fc1(x))
        x = torch.relu(self.fc2(x))
        return self.fc3(x) # Output: Q-values (Action values)

# 2. Define Parameters
state_size = 3 # Inputs: [Demand, Renewable_Output, Battery_SOC]
action_size = 3 # Outputs: [0: Charge, 1: Discharge, 2: Import_from_Grid]

# Create the model
model = SmartGridDQN(state_size, action_size)
optimizer = optim.Adam(model.parameters(), lr=0.001)

# 3. Simple test simulation of the model
print("AI Model Loaded!\n")

# Imagine real-time data coming from the grid (Simulation with normalized values)
# [Demand is high, Solar energy is low, Battery is full]
current_state = torch.tensor([0.8, 0.2, 0.9], dtype=torch.float32)

# The model finds the best decision (Action) for this state
q_values = model(current_state)
best_action = torch.argmax(q_values).item()

actions = ["Charge Battery", "Discharge Battery", "Import Energy from Grid"]

print(f"Current State: Demand={current_state[0]:.2f}, Renewable Energy={current_state[1]:.2f}, Battery={current_state[2]:.2f}")
print(f"AI Decision: {actions[best_action]}")

```

AI Model Loaded!

Current State: Demand=0.80, Renewable Energy=0.20, Battery=0.90

AI Decision: Import Energy from Grid

Broader Applications, Challenges, and Ethical Considerations

Beyond energy grids, ML and big data are critical for reducing systemic inefficiencies across a wide array of sectors. In the transportation industry, ML optimizes traffic flows and logistics, substantially diminishing the sector's carbon footprint. Agriculture utilizes ML for precision farming; algorithms process fused datasets consisting of weather station outputs, drone imagery, and soil moisture readings to forecast crop yields, optimize irrigation, and minimize fertilizer use. Additionally, ML streamlines Carbon Capture and Storage (CCS) by modeling the most efficient methods for sequestering emissions and preventing underground leaks.

However, the deployment of ML in climate initiatives faces several critical barriers [1, pp. 14–17]. First, the dependency on massive, high-quality datasets introduces concerns regarding data silos, privacy, and security; sensitive national infrastructure data becomes vulnerable to cyberattacks. Second, the "black box" nature of many deep learning models limits transparency, hindering the trust necessary for managing critical infrastructure like power grids—a challenge that requires the accelerated adoption of Explainable AI (XAI) frameworks.

There is also a profound "digital divide" ensuring unequal access to these technologies. AI development is largely concentrated in wealthy nations, potentially exacerbating socio-economic inequalities and neglecting developing regions where climate solutions are most urgently needed. Algorithmic bias may further marginalize certain communities if models are trained on unrepresentative datasets. Lastly, a paradox exists within AI's environmental footprint: deep learning models and data centers are highly energy and water-intensive. The computational demands of training large-scale models must be carefully managed and powered by renewable energy to prevent AI from becoming a detriment to the very climate goals it seeks to achieve [1, pp. 18–20].

Conclusion

The integration of machine learning and big data into the energy sector and climate informatics has yielded substantial, quantifiable operational improvements. As demonstrated throughout this study, ML enables the highly accurate forecasting of renewable energy production and the dynamic optimization of smart grids. Beyond large-scale utility implementations, the deployment of AI-driven microgrids in highly vulnerable island environments—such as Barbados, Mauritius,

and the Seychelles—highlights the technology's profound capacity to accelerate decentralized clean energy independence. Furthermore, predictive analytics have revolutionized disaster risk management and biodiversity conservation. Initiatives like the UN's Early Warnings for All (EW4ALL) in Ethiopia, high-resolution drone mapping for structural vulnerability in the Caribbean, and multimodal deep learning for tracking deforestation in Colombia's Amazon unequivocally prove that ML can successfully transition raw, unstructured environmental data into proactive, life-saving interventions.

However, the realization of these technological benefits is fundamentally constrained by severe socioeconomic limitations and an intrinsic environmental paradox. The global "digital divide" remains a critical barrier; AI development is heavily concentrated in wealthy nations, often leaving Least Developed Countries (LDCs) without the requisite infrastructure, data continuity, or technical expertise. Furthermore, the immense computational demands of training complex deep learning architectures and Large Language Models (LLMs) carry a massive ecological footprint. With the OECD estimating that AI data centers could consume an astronomical 6.6 billion cubic meters of water globally by 2027, the unchecked exponential growth of computational demand must be strictly coupled with renewable energy sources to prevent AI from becoming a detriment to climate goals. Additionally, the dual-use nature of AI—where sophisticated algorithms can be exploited to optimize fossil fuel extraction or amplify climate disinformation—underscores the urgent need for rigorous, interdisciplinary governance.

Ultimately, machine learning and big data offer paradigm-shifting capabilities for global climate change mitigation and adaptation. By enhancing the predictive accuracy of climate models, optimizing smart grids, and facilitating the seamless integration of renewable energy, ML establishes a robust framework for resilient, low-carbon infrastructure. Nevertheless, algorithms cannot solve the climate crisis in isolation. The realization of AI's full potential relies heavily on robust data governance, explainable architectures (XAI), equitable policy frameworks, and unprecedented collaboration among technologists, climate scientists, and policymakers. Overcoming these overarching technological and ethical hurdles will ensure that machine learning serves as a technologically equitable and central element in achieving a sustainable global future.

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SECURITY ARCHITECTURE AND DATA MANAGEMENT IN A MICROSERVICE-BASED CAREER GUIDANCE PLATFORM

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Abstract

This paper presents the security architecture and data management approach implemented in Career Bridge, a microservice-based platform designed to match university graduates with relevant employment opportunities. The study addresses two interconnected aspects of the system: the multi-layered information security model and the structured relational data storage strategy. The security implementation is based on the CIA triad, JSON Web Token authentication, role-based access control, and OWASP API Security Top 10 guidelines. The data layer employs a database-per-service isolation pattern using cloud-hosted PostgreSQL via the Neon DBaaS platform, with Spring Data JPA and Hibernate managing object-relational mapping. The paper describes the rationale behind each design decision, the identified threats relevant to the platform, and the mechanisms applied to mitigate them. The proposed architecture demonstrates how security and data integrity can be effectively embedded into a distributed system from the design stage.

Keywords: information security, JWT authentication, OWASP, microservice architecture, PostgreSQL, DBaaS, Spring Security, role-based access control.

Introduction

The increasing adoption of distributed software platforms for career guidance and recruitment introduces significant challenges in the areas of data protection and system integrity. Platforms that process personal information about students — including educational background, technical skills, and career preferences — must ensure that this data is protected from unauthorized access, modification, and disclosure. At the same time, the distributed nature of microservice architectures requires a carefully designed data management strategy to maintain consistency, isolation, and performance across independent service boundaries.

Career Bridge is a microservice-based platform developed to address the employment gap faced by university graduates and junior developers by automating the matching of student competency profiles with employer vacancy requirements. The platform consists of five independent microservices responsible for profile management, vacancy storage, skill matching, notification delivery, and external vacancy integration. Given that the system processes sensitive personal data and operates across multiple independently deployed components, security and data management constitute foundational architectural concerns rather than supplementary features.

This paper focuses specifically on these two aspects of the Career Bridge platform. The security section describes the threat model, the adopted authentication and authorization mechanisms, and their alignment with established standards. The data management section describes the storage architecture, the schema isolation strategy, and the tools employed to ensure efficient and reliable data access. Together, these elements form the technical backbone of a platform designed to

operate securely and consistently in a cloud-hosted environment.

1. Information Security Architecture**1.1. Threat Model and Theoretical Foundation**

The security design of Career Bridge is grounded in the CIA triad — a foundational framework in information security that defines three core properties any secure system must preserve. Confidentiality ensures that personal data is accessible only to authorized parties. Integrity guarantees that data cannot be altered without authorization. Availability ensures that the platform remains accessible to legitimate users at all times [1, p. 38].

In the context of Career Bridge, confidentiality is enforced through JWT-based authentication and HTTPS transport encryption, ensuring that student profile data is protected both in transit and at the application layer. Integrity is maintained through input validation via Spring Validation and the use of parameterized JPA queries, which prevent injection-based data manipulation. Availability is supported through Docker containerization and cloud deployment on Render.com, which provides automatic service restart capabilities and infrastructure resilience [2, p. 14].

The principle of security by design, described by Ransome and Misra, was adopted as a guiding methodology [3, p. 62]. Rather than treating security as a post-development concern, all protective mechanisms were integrated into the system architecture during the initial design phase. This approach ensures that security boundaries align with service boundaries, reducing the attack surface of each individual component.

1.2. Authentication Mechanism: JSON Web Token

Authentication in Career Bridge is implemented using JSON Web Token, a stateless token-based mechanism that allows each microservice to independently verify the identity of a requesting party without maintaining a shared session store. When a user authenticates via the login endpoint, the server generates a signed JWT containing the user identifier and assigned role. This token is returned to the client and must be included in the Authorization header of all subsequent requests.

Each microservice validates the incoming token by verifying its cryptographic signature using a shared secret key. This eliminates the need for a centralized session management component and reduces inter-service dependency. A systematic literature review by de Almeida et al., covering more than fifty primary studies on authentication patterns in microservice architectures, identified the JWT combined with an Identity Provider as the most widely adopted and practically effective approach for distributed systems [4, p. 7]. This finding directly informed the authentication design of Career Bridge.

The token contains three components: a header specifying the signing algorithm, a payload encoding the user identity and role claims, and a cryptographic signature. The HS256 algorithm is used for signing. Tokens are configured with a fixed expiration period, after which re-authentication is required. This limits the validity window of any compromised credential.

1.3. Authorization and Role-Based Access Control

Career Bridge implements role-based access control with two defined roles: STUDENT and ADMIN. The role is embedded in the JWT payload and is evaluated at the service layer using Spring Security's method-level authorization annotations. Public endpoints — specifically the registration and login routes — are accessible without authentication. All other endpoints require a valid token.

The most critical authorization concern in the platform is the prevention of Broken Object Level Authorization, identified as the top-ranked vulnerability in the OWASP API Security Top 10 2023 report [5]. This vulnerability occurs when a user can access resources belonging to other users by manipulating object identifiers in API requests. In Career Bridge, this is mitigated by extracting the authenticated user's identifier from the security context and comparing it against the resource identifier in each request. A student user requesting the profile of another student receives a 403 Forbidden response regardless of whether the target resource exists.

Administrative operations — including user enumeration and deletion — are restricted to the ADMIN role. This separation ensures that student-facing endpoints cannot be used to enumerate or manipulate other users' data, even if a valid token is present.

1.4. Infrastructure Security

All communication between clients and the platform is encrypted via HTTPS, enforced by the Render.com deployment environment. Database connec-

tions to Neon PostgreSQL require SSL with the `channel_binding` parameter set to require, ensuring that no unencrypted connection can be established between the application layer and the data layer.

Application secrets — including the JWT signing key, database credentials, and service configuration — are stored exclusively as environment variables on the deployment platform and are never present in the source code or version control history. This practice aligns with the Twelve-Factor App methodology for configuration management and eliminates a common source of credential exposure in cloud-hosted applications.

Mamidi identifies these practices — HTTPS enforcement, secret management through environment variables, and input validation at every API boundary — as the essential baseline for securing REST APIs built on Spring Boot [6, p. 4]. All three elements are present in the Career Bridge implementation.

2. Data Management Architecture

2.1. Database Isolation Strategy

Career Bridge adopts the database-per-service pattern, in which each microservice maintains its own isolated schema within the cloud-hosted PostgreSQL instance. This pattern, described by Richardson as a fundamental requirement for genuine service independence, ensures that no service can directly access or modify the data of another service [7, p. 103]. All cross-service data access occurs exclusively through defined API contracts.

The platform maintains five isolated schemas: `student_schema` for user profiles and skill records, `vacancy_schema` for vacancy data and required competencies, `matching_schema` for computed matching results and scores, `notif_schema` for notification records, and `parser_schema` for imported vacancy data awaiting processing. This isolation reduces coupling between services and ensures that a failure or schema change in one service does not propagate to others.

The underlying database infrastructure is provided by Neon, a serverless PostgreSQL platform that eliminates the operational overhead of database server administration. Backup, monitoring, and scaling operations are managed by the provider, allowing the development team to focus on application logic. Kleppmann notes that the choice of data storage technology in distributed applications has direct implications for scalability, reliability, and consistency guarantees [8, p. 89]. The Neon DBaaS model was selected in recognition of these implications, as it provides a managed PostgreSQL environment with built-in high availability and SSL-enforced connections.

2.2. Object-Relational Mapping and Query Optimization

Data access across all services is implemented using Spring Data JPA with Hibernate as the underlying ORM provider. This combination enables declarative repository definitions, reducing the volume of boilerplate data access code and allowing the development team to express queries at the domain object level rather than the SQL level.

A significant performance consideration in the vacancy service is the management of the skill association

between vacancy records and their required competencies. Each competency is stored as an individual record in a related table rather than as a delimited string field, enabling the matching service to perform accurate set-based comparisons. However, this design introduces the risk of the N+1 query problem, in which loading a collection of vacancies triggers an individual database query for each associated skill set. Mihalcea identifies this as the most prevalent performance issue in Hibernate-based applications [9, p. 215]. The platform addresses this through the use of JOIN FETCH clauses and batch loading strategies, consolidating related data retrieval into a single query where possible.

The Specification API provided by Spring Data JPA is employed in the vacancy service to support dynamic multi-criteria filtering. This allows queries to be constructed programmatically based on the parameters present in a given request, without requiring a separate repository method for each possible filter combination. The result is a flexible and maintainable query layer that can accommodate evolving search requirements without structural refactoring.

2.3. Connection Management and Data Integrity

Database connections are managed through HikariCP, the default connection pool implementation provided by Spring Boot. A configured pool of persistent connections is maintained and reused across requests, avoiding the overhead of establishing new connections for each database interaction. Pool parameters are tuned to balance resource utilization with connection availability under expected load conditions.

All mutating operations in the platform are executed within transactional boundaries managed by Spring's declarative transaction framework. The `@Transactional` annotation is applied to service-layer methods to ensure that related operations either complete atomically or are rolled back in their entirety. Read-only transactions are explicitly marked to enable database-level optimizations. PostgreSQL's MVCC concurrency model ensures that concurrent read and write operations do not interfere with each other, supporting the simultaneous use of the platform by multiple users without locking conflicts.

Schema normalization is applied throughout the data model to eliminate redundancy and ensure data integrity. The first, second, and third normal forms are observed: skill associations are stored in dedicated relational tables rather than denormalized into parent records, foreign key relationships enforce referential integrity, and no transitive dependencies exist within any table structure. Delaney emphasizes that correct normalization is a prerequisite for both query performance and long-term data consistency in relational systems [10, p. 178].

Conclusion

This paper has described the security architecture and data management design of the Career Bridge platform. The security model integrates JWT-based stateless authentication, role-based access control, BOLA

mitigation through ownership verification, HTTPS enforcement, and environment-based secret management. Each of these mechanisms directly addresses specific threat categories identified in the OWASP API Security Top 10 standard and is grounded in established principles from the information security literature.

The data management architecture employs the database-per-service isolation pattern, cloud-hosted PostgreSQL via Neon DBaaS, Spring Data JPA with Hibernate for object-relational mapping, and HikariCP for connection pool management. The design addresses known performance challenges including the N+1 query problem and supports flexible multi-criteria querying through the Specification API. Normalization principles are consistently applied to maintain data integrity and minimize redundancy.

Together, these architectural choices demonstrate that security and data integrity can be effectively embedded into a distributed microservice platform from the earliest stages of design. Future work will focus on extending the security model to include OAuth2 integration, API rate limiting, and automated security scanning within the CI/CD pipeline, as well as evaluating the introduction of read replicas and caching layers to further improve data access performance under increased load.

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