



NJD-iScience

№155

The Norwegian Journal of Development of
the International Science





№155/2025

Norwegian Journal of development of the International Science

ISSN 3453-9875

It was established in November 2016 with support from the Norwegian Academy of Science.

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AGRICULTURAL SCIENCES

EFFECTS OF THE ACOUSTIC RADIATIONS ON THE INTENSIFICATION OF PLANTS GROWTH

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Abstract

The results of investigations of influence of acoustic radiation in the frequency range of 20 Hz and 50 kHz of some physical and chemical properties of irrigation water are represented. It is shown that range of ultrasonic radiation in a range close to 20 kHz is more effective for productive drip irrigation experienced plants which leads to increasing the concentration of dissolved trace metals in the irrigation water and also affects the change of pH suitable irrigation water. Two fixed frequencies in the studies were chosen to more clearly establish the fact of the occurrence of ultrasonic cavitation in irrigation water and were determined by the capabilities of the created device. The frequency of 20 kHz was chosen as the preferred one for fixing the increase in tomato yield by periodically weighing it and comparing it with the control irrigation line. Tomatoes were chosen as the most common greenhouse crop and a product often used in the diet.

Keywords: ultrasound, acoustic emission, cavitation, mass spectrometric analysis.

Introduction

A range of technical applications of hydrodynamic and ultrasonic cavitation rapidly increases in the world being directly used in medicine, naval applications, pharmaceuticals, chemical technologies, cosmetics and cosmetology, etc. The energy of the collapse of microbubbles, at which the temperature reaches 6000°C, and the pressure of hydraulic microjets to 40 MPa causes ionization of water and aqueous solutions and is accompanied by many poorly studied processes.

Studies of the influence of hydrodynamic cavitation on the change in the physicochemical properties of aqueous solutions are devoted to the works (Loraine G. 2012, Mandar B. 2013) and purification of water, both from bacteria and other contaminants, and disinfection of water are shown in works (Al-Mahrouki A. 2012, Kuwabara M. 2005). Ultrasonic cavitation can also lead to a change in cellular structures, as shown in the work (Mojca and et al. 2014) and be used in cancer therapy. The phenomenon of hydrodynamic cavitation was also used to purify water from pharmaceutical contamination (Chuang YH and et al. 2010).

In addition, there are even studies confirming the effect of sound on plant growth, for example to positive effects on plant growth and resilience, sound alerts plants of potential danger and aids in defense. Sound guides plants towards essential resources, like water, through phonotropic root growth (Marie Liesbeth Demey and et al. 2023).

There is evidence that sonication using low frequencies of sound (as little as a few dozen Hz) to as high as ultrasound (several dozen kHz) may increase organogenesis (Jaime A. Teixeira da Silva and et al. 2014).

The fact of influence on growth and development of cellular structures and transport of various substances into cells under the influence of acoustic frequencies and cavitation of various spectrum is known (Riesz P. 1985, Hernández-García D. 2008). For example, the effects of ultrasonic acoustic emission were studied in works (Villanueva 2015, Pan Li 2015) and accompanied by cavitation on various structural characteristics of water, including some aspects of physical chemistry, and microbiological composition.

The publication (Heidi Appel, Reginald Cocroft 2023) states that progress in understanding the ecology and evolution of plant acoustic sensing requires testing how plants respond to acoustic features of their natural environments, using methods that precisely measure and reproduce the stimulus experienced by the plant.

The article (Andrea Nardini and et al. 2024) has obviously aroused new interest in the phenomenon of ultrasonic sound production by plants exposed to stress, especially drought.

This article presents new data on the effect of fixed ultrasound frequencies on the properties of irrigated water when watering one of the most common crops like tomatoes among many greenhouse plants. For the first time, the effect of ultrasound at 20 and 50 kHz on the physical and chemical properties of irrigated water and the intensity of tomato growth was studied. In some fragmentary Russian information on the effect of hydrodynamic cavitation on irrigation water, energy-intensive pumping equipment was used for irrigation in the open ground. And the authors decided to use ultrasonic exposure to irrigation water as more compact and relatively inexpensive.

Obviously, the use of hydrodynamic and ultrasonic cavitation is an example of nanotechnology and many aspects of such impact have been little studied.

The questions were extensively studied and the results of the influence of the infrasonic spectrum of oscillations on the growth of some cereal species are used.

The issues of water structurization under the influence of cavitation continue to be studied and are of interest in various fields, including crop production and agro technology.

We set the task to investigate the influence of a wide range of acoustic effects on irrigation water and, accordingly, the associated effects of intensification of the growth of vegetables and ornamental plants. The main purpose of this work was showing the results of our research and to show that there is a real possibility to obtain fertilizer chelate by ultrasonic action on irrigation water.

Materials and Methods

Two experimental plants for the generation of infrasound and ultrasound with subsequent transfer of momentum to the piezoelectric transducers were created (radiators) for this purpose. Generating unit consists of a pulse generator and a specially shaped frequency amplifying unit signal power and the control panel.

The direct impact on the water is carried in the radiation unit via piezoelectric transducers (Dyussenov K. 2012) (Fig. 1 - the device for generating infrasound and ultrasound). The frequency spectrum of emission before and after the experiments on the influence of irrigation with acoustic oscillations was recorded using a broadband oscilloscope brand VALLEMAN PC SGU250 and made adjustment range from 20 - 50 Hz on the first unit and 20 - 50 kHz per second.

The experiments were carried out from the beginning of spring to the end of October previous year on the basis of experimental greenhouses with polycarbonate cover for the cultivation of tomato (*Lycopersicon esculentum* Mill) size 6x3x12 m, located in the suburb of Pavlodar (Kazakhstan).

Water was supplied by the system of drip irrigation GARDENA (Germany): drip irrigation of 100 plants was carried through a hose branch from local wells, and the second, with the same water, after passing through the intermediate container with piezoelectric transducers and the last 100 plants were watered from a watering can or hose, i.e. without the use of drip irrigation. Both hybrids of tomato (*Lycopersicon esculentum* Mill) F1 resistant to diseases TMV Va Fol (Master, Rosemary) and varieties that are affected Phytophthora, Fusarium and TMV (Bon appetite, raspberry cream, Budyonovka and Gold dome) were used in the experiment. The construction of the container with two piezoelectric transducers immersed in it, treated with sealant, to avoid corrosion, represented a channel of specially designed forms for organizing the flow turbulence to obtain the best effect of mixing the flow of water.

During experiments once every 5 - 6 days, water samples were taken for measurement of pH and mass spectrometric analysis. pH - metry was performed on a laboratory basis of the Eurasian National University

named after L. Gumilyov with overlapping pH measurements based on central laboratory of JSC "Kazakhstan Aluminum" combined with mass spectrometric analysis on the equipment of the company MALVERN (United Kingdom), allowing measurement of 28 chemical elements. Laboratory equipment has local and international metrological certification. As a result of investigations the following facts were established.

Results and Discussion

The frequency spectrum of the radiation in the range 20-50 Hz virtually did not affect the pH of irrigation water. The most characteristic effects on the structure of irrigation water at 20 Hz manifested in increasing cadmium concentration by almost 92% zinc and almost 7 times. As seen from the integrating spectrograms where abscissa mg dm^{-3} drawn on generalized results of analyzes of samples (Fig. 2, 3) with a sharp increase in the concentration of cadmium Cd (about 4 times), and tin Sn (by 11 times) the remaining group trace metals have remained virtually unchanged.

At the same time, the content is within the MPC as the EU countries and the United States, Russia and the MAC recommended by WHO. For example, MPC WHO compared with the data obtained are shown in Table (Table. 1).

Irrigation water treated with 20 Hz resulted in a strong inhibition of plants, after 6-7 irrigations to disease TMV plants (tobacco mosaic virus), but after changing the frequency of the acoustic oscillations at 50 Hz growth and development of plants recovered after 5 irrigations. The highest efficiency of irrigation water gave exposed to ultrasound in a range close to 20 kHz, the second pilot unit. Results of averaged spectrograms in mg/dm^3 (Fig. 4 - 5) show that a pronounced positive effect on the growth of tomato at a frequency range of 20 kHz the radiation had growth of concentration iron of 22%, copper Cu in 1,6 times and manganese Mn by 8 times.

It is possible that the increase in yield recorded when weighing tomatoes for experimental (that is, when watering water exposed to ultrasound) and control (when providing irrigation with ordinary water) is caused, as one of the reasons, by the activation of trace elements and the appearance of heteroauxins that activate the development of the root system of tomatoes. The cluster structure of irrigation water is also important, changing its structure, which requires further research.

After irrigation with irrigated water under the influence of ultrasonic radiation of 50 kHz, there was no increase in yield relative to the frequency of exposure of 20 kHz.

Thus, minor, an average of 1.14 - 2.01% grew acidity (pH) of the treated water for irrigation at 20 kHz and at a frequency of 50 kHz pH values increased to 3.28%. Analysis of the spectrograms and measurement of irrigation water pH after ultrasonic treatment led to the conclusion that the water gets new properties related to its partial ionization leading to changes in its molecular structure.

By collecting fruit, tomatoes (*Lycopersicon esculentum* Mill) treated with structured water, ahead of the growth rates of tomato bushes, which are watered with plain water. 285 kg of tomatoes were obtained from the

experimental plants and only 243 kg from controlled ones for the whole period of the experimental irrigation. At the same time 6-7 irrigations produced at a frequency of 20 kHz is allowed to increase the yield by 58-62%. Plants watered with structured water in October had a new brush, bloom, i.e. did not feel the onset of fall, and the control plants the leaves turned yellow, most of them died.

In the Fig. 6 a portion of the results of experiments is shown.

It can be seen that a number of tomato (*Lycopersicon esculentum* Mill) on the left, watered with plain water has ceased to exist and the right lane, when watering with water treated by ultrasound continues its rapid growth and fruiting.

In the Botanical garden of Odessa University the effect of ultrasound on the possibility of accelerating the rooting and increase the yield of rooted cuttings of roses (*Rosa* L.) were studied. Cuttings are cut from the middle of the annual semi lignified shoots. Related bunched cuttings were placed in a bath, the bottom of which served as a radiating plate, after which the tub was filled with water. Experimental cuttings were sounded 15, 30, 45 seconds, 1, 3, 5, 12 and 20 minutes at an intensity of 1 W cm^{-2} , and an oscillation frequency of 22 kHz, the controlled ones were kept in an aqueous environment. For rooting, a mixture of leaf soil, humus and river sand were used in the ratio 2:2:1. The test results showed that all varieties of treatment for three minutes increases the rooting and accelerates root formation. Rooting time in the experiment was 15 days, 28 days in the control.

In the greenhouse, the authors also made an experience in fixing the rate of rooting roses (*Rosa* L.), and the period was chosen when any plants rooted very badly - a period of late summer. Cuttings were rooted in the calcined garden ground. In the experiment - planting the soil was watered with structured water, then, at an angle of 45 degrees, cuttings with three buds were planted (03.08.2018). Control ones were cut into the soil, watered with plain water. The result exceeded all expectations - the root system of the prototype in the past month has formed well, control plants only the beginnings of roots formed during this period.

Land escape of a rose (*Rosa* L.), watered with structured water has a length of 4 cm, the roses (*Rosa* L.) with a simple watering 2 -2.5 cm. It is safe to conclude that water passed sonication in a range close to 20 kHz is accelerator plant growth and development. At the same time, the specified frequency range of ultrasonic treatment prevents premature aging plants and increases their resistance to disease and the impact of other external adverse factors.

A number of works are known, among them (Amira Mohamed Abd El-Sattar and et al. 2022), the effect of ultrasonic exposure period on germination and early seedling behaviors of fenugreek seeds under salt stress was investigated in a laboratory experiment.

Ultrasonication may alter plant growth and development (Anita Kiraly and et al. 2025), and an increasing number of studies are being carried out to investigate its effects on both in vitro plant culture and greenhouse or field plant production, as well as on the biochemical and molecular functions of plants.

It is quite obvious that ultrasonic and hydrodynamic cavitation has a rather complex mechanism of affecting water and aqueous solutions and is manifested in many physical and chemical aspects. Mass spectrometric analysis of irrigation water allowed to illustrate that partial ionization of irrigation water occurs with activation of metal ions dissolved in it.

Research on the effects of sound on plant growth has been studied (Ratnesh Chandra Mishra & Hanhong Bae, 2019) and it has been found that plants' sensitivity towards sound has started gaining attention only recently. The influence of sound vibrations on biology was discussed in a paper (Alexis M. Kollasch and et al. 2020) where various effects were identified.

It is possible that this factor as one of many can cause activation of plant growth, accelerates and enhances cellular metabolism.

In all probability, the activated metal ions, the concentration of some of which increased several times in the form that ultrasonic cavitation caused, greatly improve and intensify plant growth and appear as one of the factors contributing to this.

Conclusion

It is possible to conclude with high confidence that the different spectra using ultrasonic radiation can be in one way or another affect the physicochemical properties of water. This is confirmed by the experiments. Against the background of the primary results of the spectra of acoustic vibrations produced by irrigation water to 20 kHz (increasing the total yield of 15% after 7-8 drip irrigation, about 13-18 days) is likely to predict the intensification of the growth of terrestrial vegetables and obviously increase their productivity (fixed increase fruit size by 50-95%).

It is possible to draw a conclusion about the existing mechanism of interrelation of microbiological and physicochemical processes caused by the effect of cavitation on irrigated water for greenhouse growing tomatoes and cuttings of roses with a fixed effect on irrigation water of ultrasonic frequency spectrum from 16 to 24 kHz. Comparative testing and testing of both stems and leaves, and the root system of tomatoes revealed an increase in the green mass and increased development of plant roots. Thus, a direct link was established between the direct effects of increasing the concentration of trace elements of various metals, provoking to some extent the activation of plant growth without the introduction of special fertilizers.

Declaration

The authors would like to add that we completely exclude any conflict of interest. The research was carried out entirely on the initiative and at the authors' own expense as a great interest in the object of research.

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Table 1.
The comparative characteristics of the content of trace minerals

MAC (WHO) mg/dm ³	After influence 20 kHz mg/dm ³	After influence 50 kHz mg/dm ³
Cu 0.20	0.14	0.136
Zn 0.30	0.231	0.148
Cd 0.003	0.00039	0.00011



Fig. 1. The device for generating infrasound and ultrasound

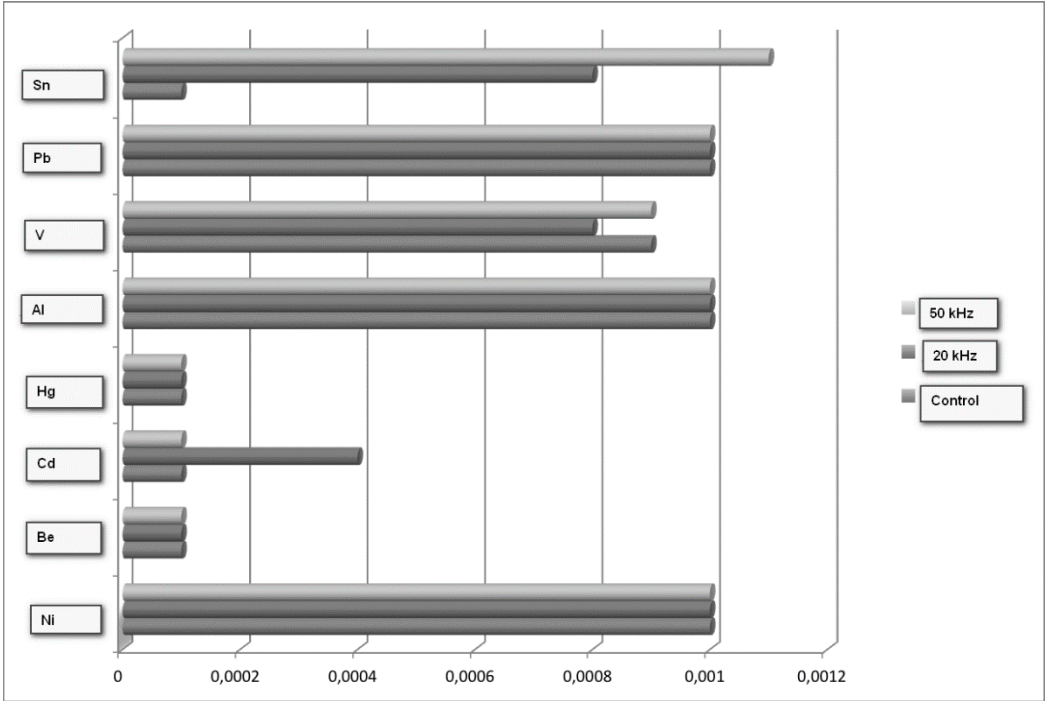


Fig. 2. The increasing of Sn and Cd concentration in water after ultrasound influence

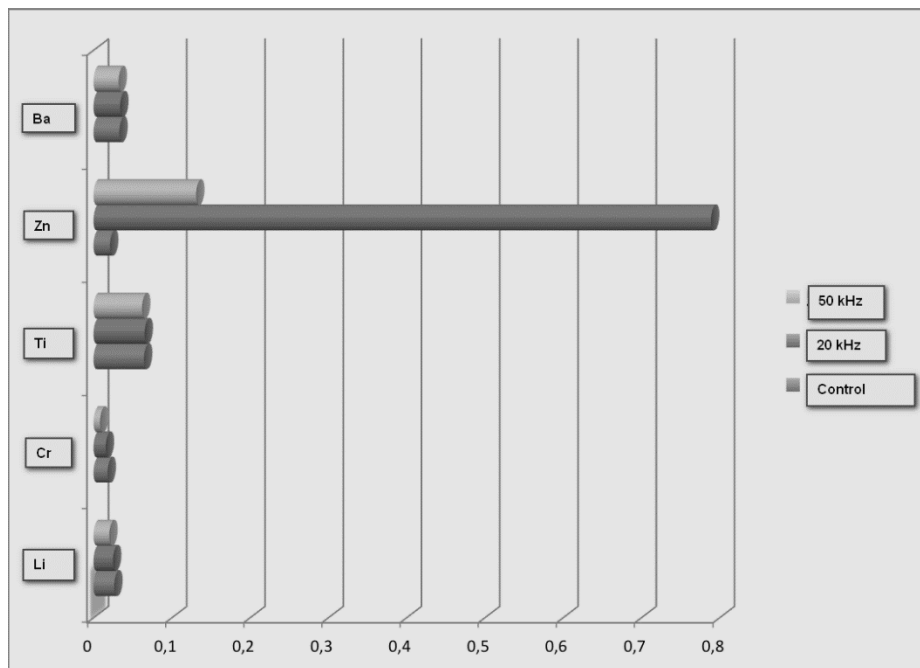


Fig. 3. The increasing of Zn concentration in water after ultrasound influence

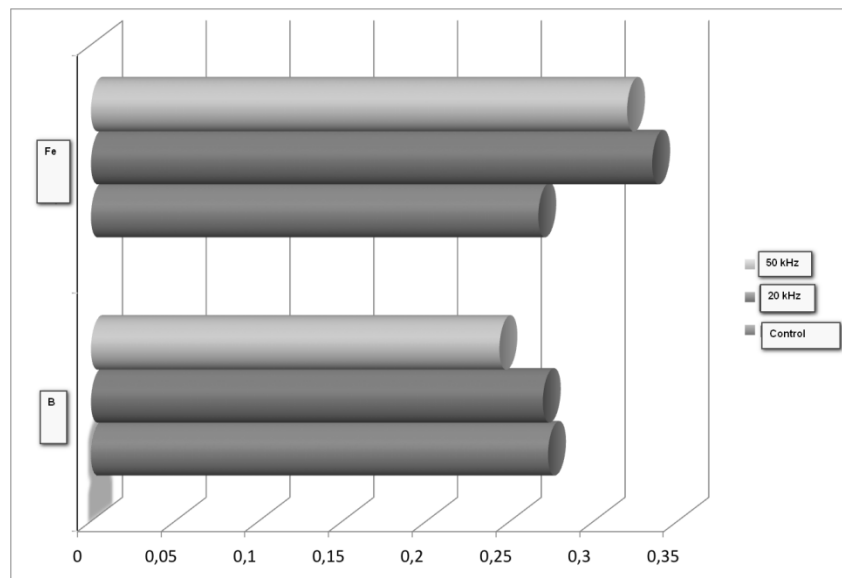


Fig. 4. The increasing of Fe concentration in water after ultrasound influence

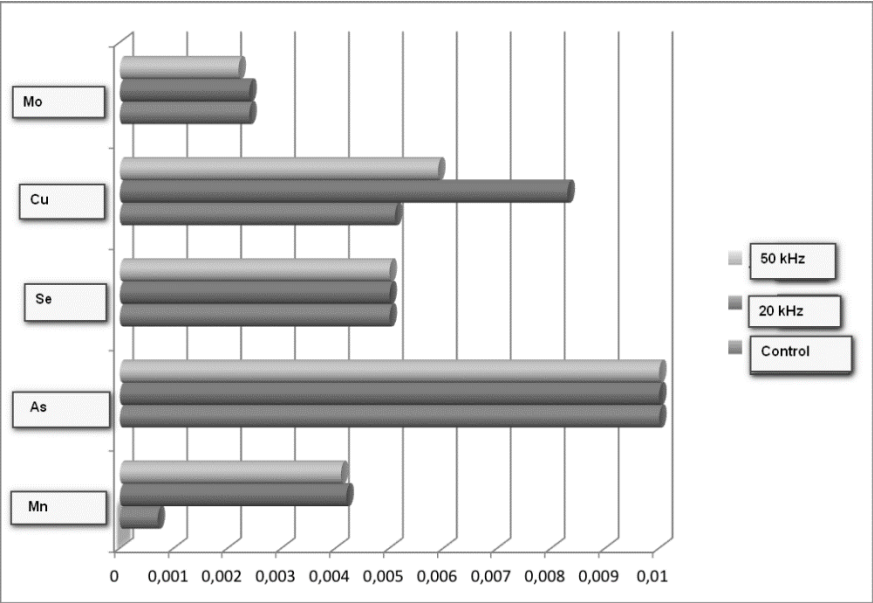


Fig. 5. The increasing of Cu and Mn concentration in water after ultrasound influence



Fig. 6. The comparison of the intensity of tomato growth with the action of ultrasound on water and without it

ASSESSMENT OF DURUM WHEAT (*T. DURUM DESF*) HYBRIDS RESISTANCE TO DROUGHT AND SALINITY UNDER LABORATORY AND FIELD CONDITIONS

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ОЦЕНКА УСТОЙЧИВОСТИ ГИБРИДОВ ТВЕРДОЙ ПШЕНИЦЫ (*T. DURUM DESF*) К ЗАСУХЕ И СОЛЕВОМУ СТРЕССУ В ЛАБОРАТОРНЫХ И ПОЛЕВЫХ УСЛОВИЯХ

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Abstract

The aim of this study was to assess the resistance of durum wheat (*T. durum Desf*) hybrids to drought and salinity under laboratory and field conditions. For this purpose, samples of durum wheat (*T. durum Desf*) collected at the Absheron Scientific Research were used. The samples were obtained from the Genbank of Institute of Genetic Resources. In 2023, direct and reciprocal crosses were carried out between the following durum wheat samples k-11 v. *hordeiforme*, 11272 AG-3118, k-59 v. *leucomelan*, k-43 v. *murciense*, black-awned wheat 2, v. *apulicum*, Sort Barakatli 95, k-194 v. *courulenssens*, k-11 v. *hordeiforme*, k-44 v. *murciense*, k-20 v. *leucomelan*, k-48 (8) v. *melanopus*, k-183 v. *albuprovinsale* and k-42 v. *affine*. In 2024 the F₁ generation seeds of durum wheat (*T. durum Desf*) obtained as a result of the hybridization were sown on the experimental plot of the Absheron Scientific Research Base of the Azerbaijan Republic.

In the course of the study, work was carried out with 21 combinations of durum wheat (paternal, maternal forms and hybrids) and changes in chlorophyll and carotenoid content under the influence of abiotic stresses (drought, salinity) at the heading stage were examined. In addition the productivity of these samples plant height, spike length, number of spikelet's per spike, number of grains per spike, grain weight per spike, and weight of 1000 grains. From the 21 durum wheat combinations, 9 samples were selected that were resistance to both drought and salinity. Maternal form AG-3118, Gomur, hybrid AG-3118 × Gomur hybrid Gomur × AG-3118, Maternal form ♀ k-42 *affine*, paternal form ♂ Gomur, hybrid Gomur × k-42 *affine*, hybrid k-42 *affine* × hybrid Gomur, k-42 *Affine* ♂.

The experiments conducted made it possible to identify genotypes with a high degree of tolerance to these types of stress. The results obtained may be used in the selection and introduction of new varieties of durum wheat

Аннотация

Целью настоящего исследования явилась оценка устойчивости гибридов твёрдой пшеницы (*T. durum Desf.*) к засухе и засолению в лабораторных и полевых условиях. В этих целях были взяты образцы твердой пшеницы (*T. durum Desf.*), высажены на Апшеронской, научно-исследовательской базе полученные из Генбанка, действующего при Институте Генетических Ресурсов. В 2023 году были проведены прямое и реципрокное скрещивание между образцами: k-11 v. *hordeiforme*, 11272 AG-3118, k-59 v. *leucomelan*, k-43 v. *murciense*, черноостый 2, v. *apulicum*, сорт Баракатлы 95, k-194 v. *courulenssens*, k-11 v. *hordeiforme*, k-44 v. *murciense*, k-20 v. *leucomelan*, k-48 (8) v. *melanopus*, k-183 v. *albuprovinsale* и k-42 v. *affine*. В 2024 году полученные семена поколения F₁ твердой пшеницы (*T. durum Desf*), были посажены на опытном участке Апшеронской научно-исследовательской базы Азербайджанской Республики.

В ходе исследования проведены работы с 21 комбинацией твердой пшеницы (отцовские♂, материнские♀ формы и гибриды), изучены изменения содержания хлорофилла и каротиноидов под воздействием абиотических стрессов (засуха, засоление) в фазе колошения. Кроме того, продуктивность данных образцов (отцовские♂, материнские♀ формы и гибриды) изучалась по шести параметрам: Высота растения, длина колоса, количество колосков в колосе, число зерен в колосе, масса зерен в колосе, масса 1000 зерен. Из 21 комбинации твердой пшеницы были отобраны 9 образцов, устойчивых как к засухе, так и к засолению: Материнская форма ♀ AG-3118, Отцовская форма ♂ Гомур, гибрид AG-3118 × Гомур, гибрид Гомур × AG-3118, Материнская форма ♀ k-42 *affine*, Отцовская форма ♂ Гомур, гибрид Гомур × k-42 *affine*, гибрид k-42 *affine* × гибрид Гомур, k-42 *affine* ♂. Проведённые опыты позволили выявить генотипы, обладающие высокой степенью толерантности к данным видам стресса и полученные результаты могут быть использованы при селекции и интродукции устойчивых сортов твёрдой пшеницы.

Keywords: drought resistance, salinity resistance, chlorophyll, plant height, grain weight per spike

Ключевые слова: засухоустойчивость, солеустойчивость, хлорофилл, высота растений, масса зерен в колосе.

Введение: Современное растениеводство сталкивается с возрастающими вызовами, связанными с глобальными климатическими изменениями и деградацией почв. Одними из наиболее опасных абиотических стрессов являются засуха и засоление, ограничивающие продуктивность сельскохозяйственных культур. В этих условиях особую актуальность приобретает селекция сортов и гибридов, обладающих высокой адаптивной способностью [5, с.343].

Анализ комплекса факторов засухоустойчивости говорит об их многообразии, сложности и динамичности этого явления в целом. Поэтому направленное выведение новых устойчивых форм может быть успешным лишь при условии ясного представления об особенностях различия исходных сортов, изменений в обмене веществ, вызванных засухой, и природе адаптаций к ее действию. Проблема засухоустойчивости продолжает оставаться одной из актуальных проблем физиологии растений.

Твёрдая пшеница (*T. durum Desf*) важная продовольственная культура, особенно в странах с засушливым климатом. Повышение её устойчивости к неблагоприятным условиям среды представляет собой приоритетное направление в селекции. Настоящее исследование направлено на комплексную оценку устойчивости гибридных форм (*T. durum Desf*) к водному и солевому стрессу [1, с.164].

Цель исследования: – Были использованы гибридные линии твёрдой пшеницы (*T. durum Desf*), полученных в результате скрещивания различных селекционных форм, определение изменения в листьях количественного содержания хлорофилла *a* и *b* у различных сортов твердой пшеницы (*T.durum Desf.*) под действием стресса (засухи, засоления). Также изучение структурного анализа по шести (высота растения, длина колоса, количество колосков в колосе, число зерен в колосе, масса зерен в колосе, масса 1000 зерен.). параметрам.

Материалы и методика. Исследования были выполнены в 2023-2024 году в лаборатории физиологии растений. Исследования устойчивости растений к засухе проводили по степени стресс - депрессии фотосинтетического пигментного комплекса (содержание общей суммы хлорофилла) в растворе осмотика (сахарозы 20 атм, соли 14 атм). Оценка устойчивости растений к засухе, солевому стрессу, по величине снижения концентрации пигментов проводили, используя высушенные листья, помещенные в пробирки с раствором осмотика (сахарозы), с раствором осмотика (соли) и водой (контроль), после чего для экстракции пигментов материал помещали в пробирки с 10 мл 96% этанола. С помощью современного спектрофотометра (UV - 3100PC, Япония) устанавливалась величина оптической плотности (*D*) хлорофилла *a* и *b* в общей смеси пигментов при двух длинах волны (*D*_{665,649}), соответствующих максимумам поглощения пигментов в

данном растворе. По полученным данным было рассчитано отношение (в процентах) концентрации пигментов в высушенных листьях на растворах осмотика (опыт) к концентрации их в воде (контроль). Это отношение и является мерой для определения относительной засухоустойчивости сравниваемых объектов [3, с.151-161].

Следующим методом является изучение засухоустойчивости в полевых условиях. Посев проводился по стандартной методике. Для изучения устойчивости, сорта пшеницы были посеяны на территории Института Генетических Ресурсов. Посев отвечал требованиям международного дескриптора, т.е. расстояние между растениями равнялось 5 см, а расстояние между рядами – 20 см. Учет производился по фенологическим фазам развития урожайности, (рост растения, масса зерна, вес и длина колоса, число колосков в одном колосе, число зерен, масса 1000 зерен). Эта методика позволяет относительно определить среднюю продуктивность сортов и широко используется при определении засухоустойчивости растений. [4, с. 943-945].

Результаты и обсуждения: 2023 году была проведена прямая и реципрокная гибридизация между образцами к-11 *v.hordeiforme*, 11272 AG-3118, к-59 *v.leucomelan*, к-43 *v.murciense*, черноостый 2, *v. apulicum*, Сорт Баракатлы 95, к-194 *v. courulenssens*, к-11 *v.hordeiforme*, к-44 *v.murciense*, к-20 *v.leucomelan*, к-48 (8) *v.melanopus*, к-183 *v. albuprovinsale* и к-42 *v.affine*.

В результате гибридизации к-11 *v.hordeiforme* х черноостый 2, *v. apulicum* было получено 21 семян. В качестве родительской формы у черноостый 2, *v. apulicum* х к-11 *v.hordeiforme* было получено 10 семян. При скрещивании образцов к-59 *v.leucomelan* х к-43 *v.murciense* было получено 9 семян. При гибридизации образцов к-43 *v. murciense* х к-59 *v. leucomelan*, к-42 *v.affine* х к-11 *v.hordeiforme* не были получены семена. Во время гибридизации К-11 *v.hordeiforme* х к-42 *v.affine* были получены два семени.

Из гибридной комбинации к-183 *v.albuprovinsale* х Сорт Баракатлы 95 взятая в качестве родительской формы, были получены 15 семян. Из гибридной комбинации Сорт Баракатлы 95 х 014 к-183 *v.albuprovinsale* зерен не оказалось. От гибридной комбинации к-11 *v.hordeiforme* х к-44 *v.murciense*, взятой как за материнскую, так и за отцовскую, в обоих случаях было получено по 52 семени. При скрещивании к-11 *v.hordeiforme* х к-48 (8) *v.melanopus* два семени, а из гибридной комбинации к-48 (8) *v.melanopus* х к-11 *v.hordeiforme* получено восемнадцать семян. Во время гибридизации образцов к-20 *v.leucomelan* х к-014-194 *v. courulenssens* получено тридцать семь семян. При скрещивании комбинации к-014-194 *v. courulenssens* х к-20 *v.leucomelan* семена отсутствовали.

Показатели засуха и солеустойчивости в листьях 21 образца твердой пшеницы (T. durum Desf.) из-за изменения количества хлорофилла

Таблица 1.1.

№	Каталог №	Название образцов	ХП (a+b) в мкг на единицу площади листа			Изменение количества хлорофилла под воздействием стресса в %		Изменение количества каротиноидов под воздействием стресса в %	
			Контроль	Засуха	Соль	Засуха	Соль	Засуха	Соль
1	11272	♀ AG-3118	5,94	6,60	8,79	111%	147%	150%	132%
2		♂ Гомур	6,60	7,94	7,03	120%	106%	110%	108%
3		Гибрид AG -3118 x Гомур	6,43	6,52	7,50	101%	116%	140%	113%
4		Гибрид Гомур AG -3118	6,45	6,65	7,52	103%	116%	130%	128%
5	k-40	♀ v.melanopus. v. courulescence	5,03	4,23	4,53	84%	90%	100%	110%
6	k-44	♂ v. murcienne	7,74	6,76	7,15	92%	87%	110%	101%
7		Гибрид v.melanopus. v. v. courulescence x v. murcienne	6,00	5,67	6,02	94%	100%	128%	103%
8		Гибрид v. murcienne x v.melanopus. v. v. courulescence x v. murcienne	6,01	5,68	6,02	94%	100%	102%	115%
9		♀ Гомур	5,66	5,13	5,31	90%	93%	109%	120%
10	K-42	♂ v. affine	7,00	5,25	5,86	102%	105%	115%	118%
11		Гибрид Гомур x v. affine	6,35	5,57	5,25	87%	82%	110%	120%
12	2382	♀ 2382 Сорт Баракатлы 95	7,30	6,58	7,08	90%	96%	112%	116%
13	K- 39	♂ v. lyubicum	17,03	15,85	16,48	93%	96%	102%	119%
14		Гибрид v. lyubicum x Сорт Баракатлы 95	8,68	7,27	8,96	96%	81%	120%	113%
15	K-42	♂ v. affine	7,82	8,50	8,72	108%	111%	125%	121%
16		♂ Гомур	6,60	7,94	7,03	120%	106%	125%	119%
17		Гибрид v. v. affine x Гомур	6,34	6,50	6,71	102%	106%	111%	137%
18		Гибрид Гомур x v. v. affine	6,35	6,55	6,76	103%	106%	110%	120%
19	k-57	♀ v. apulicum	18,21	15,27	16,04	83%	88%	113%	107%
20	K-40	♂ v. melonoliscurum	19,33	17,81	17,83	92%	92%	118%	130%
21		Гибрид v. apulicum x v. melonoliscurum	7,53	5,44	7,86	72%	104%	107%	141%

В качестве объекта исследований 2024 году были высажены семена твердой пшеницы (*T. durum* Desf.) поколения F₁ взятой с опытного участка Абшеронской научно-исследовательской базы. Исследования проведены на сочетаниях 21 формы твердой пшеницы (*T. durum* Desf.) (Отец♂, Мать♀, гибрид) и определены изменения количества хлорофилла и каротиноидов, вызванные действием абиотических стрессов (засухи, засоления) в фазе колошения.

Также изучались показатели продуктивности этих образцов (Отец♂, Мать♀, гибрид) по 6 параметрам (высота растения, длина колоса, количество колосков в колосе, количество зерен в колосе, масса зерна в колосе, масса 1000 зерен).

Десять образцов к-40 ♀ *v.melanopus. v. courulescence*; к-44 ♂ *v. murciance*; гибрид *v.melanopus. v. v. courulescence* x *v. murciance*; гибрид *v. murciance* x *v.melanopus. v. v. courulescence*; гибрид Гомур x к-42 *affine*; 2382 ♀ Сорт Баракатлы 95; к-39 ♂ *v.lyubicum*; гибрид *v.lyubicum* x Сорт Баракатлы 95; к-57 ♀ *v.apulicum*; к-40 ♂ *v.melonolucurum*; выбраны как засухоустойчивые. Степень стресс-депрессии хлорофилла колеблется в пределах 83%-96%. Один образец гибрида *v.apulicum* x *v.melonolucurum* (72%) выбран как умеренно устойчивый к засухе. Никаких чувствительных образцов обнаружено не было.

Десять из 21 изученного образца твердой пшеницы (*T. durum* Desf.): ♀ AG-3118; ♂ Гомур; гибрид AG-3118 x Гомур; гибрид Гомур x AG-3118; ♀ к-42 *affine*; ♂ Гомур; гибрид к-42 *affine* x Гомур; гибрид Гомур x к-42 *affine*; гибрид *v.apulicum* x *v.melonolucurum*; Отец к-42 *affine* были выбраны как обладающие высокой солеустойчивостью. Изменения количества хлорофилла под действием NaCl наблюдались в пределах 104–147%.

11 образцов к-40 ♀ *v.melanopus. v. v. courulescence*; к-44 ♂ *v. murciance*; гибрид *v.melanopus. v. v. courulescence* x *v. murciance*; гибрид *v. murciance* x *v.melanopus. v. courulescence*; ♀ Гомур; гибрид Гомур x к-42 *affine*; 2382 ♀ Сорт Баракатлы 95; к-39 ♂ *v.lyubicum*; гибрид *v.lyubicum* x Сорт Баракатлы 95; к-57 ♀ *v.apulicum*; к-40 ♂ *v.melonolucurum* были оценены как солеустойчивые (таблица 1.1). Среднеустойчивые и чувствительные образцы не выявлены.

Изученные комбинации форм твердой пшеницы (Мать♂, Отец♀, гибрид) показали одинаковую устойчивость как к засухе, так и к засолению, что можно объяснить тем, что гены устойчивости более активны в отношении стрессов, которым подвергается растение.

В результате воздействия стрессовых факторов (засуха, засоление) наблюдалось изменение количества каротиноидов, по сравнению с контролем. Это связано с тем, что каротиноиды играют защитную роль в восстановлении хлорофиллов, подвергшихся стрессу. Это выявляется в увеличении их количества.

Результаты исследований, проведенных на шести гибридных комбинациях, 3 из которых реципрокные, показали, что гибриды F₂ практически неотличимы от родительских форм по количеству хлорофилла и каротиноидов. Только в одной комбинации (*v. melanopus* x *murciance*) наблюдалось увеличение количества хлорофилла на 11,4% и количества каротиноидов на 13,3%. Однако в этом сочетании, как и в других, не наблюдалось увеличения показателей структурного анализа.

Согласно данным научной литературы, одной из ключевых проблем при выведении толерантных растений с использованием классических селекционных подходов является ограниченность генетических ресурсов устойчивости, а также сложная природа наследования, обусловленная полигенным контролем признаков, эпистатическими взаимодействиями и значительным влиянием факторов внешней среды. Именно по этой причине создание новых засухоустойчивых генотипов растений классическими методами селекции крайне затруднено [2, с. 272-285].

Также проведен структурный анализ урожайности (определение высоты растений, длины колоса, количество колосков в колосе, количество зерен в колосе, массу зерна в колосе, массу 1000 зерен) на изученных формах твердой пшеницы (Отец♂, Мать♀, гибрид). Среди комбинаций, состоящих из 21 формы твердой пшеницы (Отец♂, Мать♀, гибрид) ♀ AG-3118, ♂ Гомур и его гибриды (гибрид AG-3118 x Гомур; Гомур x гибрид AG-3118),

Показатели продуктивности 21 образца твердой пшеницы на Апшеронской научно-исследовательской базе

Таблица 2.

№	Каталог №	Название образцов	Высота растения см.	Длина колоса см.	Количество колосков в колосе, шт.	Количество зерен в колосе шт.	Масса зерен в колосе гр.	Масса 1000 зерен гр
1.	11272	♀ AG-118	110	13	14	65	8,00	70
2.		♂ Гомур	110	11	13	72	8,25	70
3.		Гибрид AG-3118 x Гомур	108	14	13	52	5,10	24
4.		Гибрид Гомур x AG - 3118	106	13	13	55	5,20	51
5.	K-40	♀ <i>v.melanopus</i> , v. v. <i>courulescence</i>	100	9	9	59	5,60	60
6.	K-44	♂ <i>v. turcicence</i>	107	12	11	52	5,20	55
7.		Гибрид <i>v.melanopus</i> , v. v. <i>courulescence</i> x v. <i>turcicence</i>	101	11	9	40	4,00	16
8.		Гибрид <i>v. turcicence</i> x v. <i>melanopus</i> , v. v. <i>courulescence</i> x v. <i>turcicence</i>	106	10	10	44	4,20	32,2
9.		♀ Гомур	110	13	13	74	8,5	75
10.	019 K-42	♂ <i>v.affine</i>	126	12	10	58	5,50	60
11.		Гибрид Гомур x v. <i>affine</i>	113	10	10	49	5,28	52
12.	2382	♀ Сорт Баракаглы 95	100	10	11	55	6,2	59
13.	019 K- 39	♂ <i>v.lyubicum</i>	102	10	11	53	5,15	54
14.		Гибрид <i>v.lyubicum</i> x Сорт Баракаглы 95	-	-	-	-	-	-
15.	019 K-42	♀ <i>v.affine</i>	126	14	15	65	7,71	70
16.		♂ Гомур	110	14	13	69	8,03	71
17.		Гибрид <i>v.affine</i> x Гомур	115	15	14	55	5,15	13
18.		Гибрид Гомур x v. <i>affine</i>	-	-	-	-	-	-
19.	k-57	♀ <i>v.apulicum</i>	100	8	10	45	4,5	50
20.	K-40	♂ <i>v.melonolucurum</i>	102	9	11	46	4,1	51
21.		Гибрид <i>v.apulicum</i> x v. <i>melonolucurum</i>	98	10	11	38	3,5	53,14

♀ Гомур; ♂ k-42 *affine*; гибрид Гомур х k-42 *affine* число колосков (13-15 штук), длина (13-16 см), количество зерен в колосе (56-72 штук), масса зерна в колосе (5,42-8,25г) масса 1000 зерен (гибрид AG-3118 х Гомур) (63-71г) показатели продуктивности были выше по сравнению с другими гибридами (Таблица 2.).

Заключение: Из 21 комбинации твердой пшеницы были отобраны 9 образцов, Материнская форма ♀ AG-3118, Отцовская форма ♂ Гомур, гибрид AG-3118 × Гомур, гибрид Гомур × AG-3118, Материнская форма ♀ k-42 *affine*, Отцовская форма ♂ Гомур, гибрид Гомур × k-42 *affine*, гибрид k-42 *affine* × гибрид Гомур, k-42 *Affine* ♂ устойчивых как к засухе, так и к засолению.

Было определено, что Материнская ♀, и Отцовская ♂ форма сорта Гомур показали высокую устойчивость. Таким образом, изменение количества хлорофилла из-за засухи в этих образцах составило от 101% до 120%.

Анализ двадцать один комбинации форм твердой пшеницы (♂ Отец, Мать ♀, гибрид) показал что гибридные сочетания ♀ AG-3118, ♂ Гомур и его гибриды (гибрид AG-3118 х Гомур; Гомур х гибрид AG-3118), гибрид Мать ♀ Гомур; ♂ k-42 *affine*; гибрид Гомур х k-42 *affine* демонстрируют измененную динамику содержания хлорофилла под влиянием засухи и солевого стресса. Выявлена положительная корреляция между продуктивностью и структурными параметрами, что позволило выделить наиболее устойчивые образцы. Эти образцы были оценены по двум ключевым критериям устойчивости к абиотическим стрессам и основным показателям продуктивности. В итоге: комплексная

оценка устойчивости гибридов (Т. *Desf*) к засухе и засолению позволила выделить образцы с высокой степенью толерантности. Выявленные формы могут быть использованы в дальнейших программах селекции для создания адаптированных сортов, пригодных для выращивания в условиях изменяющегося климата.

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ARTS

FROM ORAL TRADITION TO CONTEMPORARY INSTRUCTION: A PROPOSED MODEL FOR TEACHING CA TRU SINGING¹ BASED ON TRADITIONAL FOUNDATIONS

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<https://doi.org/10.5281/zenodo.15298369>

Abstract

This article explores pedagogical approaches to teaching Ca Tru singing, a traditional scholarly form of Vietnamese music, from the perspectives of musicology and music education. Based on research into the acoustic standards and vocal techniques specific to Ca Tru, the study delves into the oral teaching method traditionally practiced by master artists, characterized by the processes of listening–imitating–internalizing, individualizing the vocal expression, and integrating poetry, melody, and rhythm. Building upon these foundations, the article proposes a model for Ca Tru instruction in the modern context that harmonizes traditional principles with contemporary pedagogical tools—such as digital archiving, video-based instruction, and flexible vocal classes. Notably, the central role of the master artist in inspiring learners, guiding aesthetic perception, and evaluating artistic quality is emphasized as a key factor in the sustainable preservation of Ca Tru.

Keyword: Ca Tru, oral tradition, Ca Tru teaching method, digitalization in arts education.

1. Introduction

Ca Tru is a distinctive form of traditional Vietnamese performing art, recognized by UNESCO in 2009 as an Intangible Cultural Heritage in Need of Urgent Safeguarding. More than a scholarly musical genre, Ca Tru represents a refined form of traditional artistic thought—an intricate fusion of poetry, music, and sophisticated vocal techniques. However, in the context of modern society, the traditional oral transmission model for Ca Tru instruction faces significant challenges: constraints of time and learning space, lack of standardized materials and teaching tools for younger generations, and generational gaps between master artists and students that hinder both artistic perception and pedagogical continuity. As a result, the survival of Ca Tru is at risk if it remains reliant solely on individual oral transmission.

While numerous studies have approached Ca Tru from the perspectives of musicology, cultural studies, and heritage conservation, as evidenced in work², etc. However, most of these investigations focus primarily on musical analysis, vocal techniques, or cultural interpretation. In contrast, the pedagogical dimension - an essential aspect of safeguarding the heritage - has not yet been systematically addressed. The current teaching and learning of Ca Tru largely depends on the experiential knowledge of master artists and the oral tradition,

with limited presence of structured pedagogical models, standardized teaching materials, or support from modern educational technologies. This gap forms the foundation for this article, which aims to propose a structured instructional method for Ca Tru singing that preserves traditional vocal techniques while adapting to the demands of contemporary educational environments.

In light of this situation, clearly identifying the traditional pedagogical methods of Ca Tru and developing a teaching model adapted to modern educational conditions has become an urgent necessity—not only for the field of musicology, but also for broader efforts in the preservation and promotion of national cultural heritage. This article builds upon the research of previous scholars³ and the author's own work⁴ on the musical characteristics and vocal standards of Ca Tru, to further analyze the teaching methods employed by master artists. It seeks to identify technical principles essential for accurate performance within the traditional modes, highlight common vocal errors among learners, and propose a comprehensive set of solutions - from pedagogical approaches to supporting tools - in order to effectively preserve Ca Tru vocal techniques within contemporary educational contexts.

2.1. Theoretical foundations of Ca Tru vocal pedagogy by master artists

¹ Ca trù, often translated as ceremonial singing or song with clappers, is a traditional Vietnamese performing art that combines poetry, music, and vocal performance. Originating in northern Vietnam over ten centuries ago, it features a female vocalist (ca nương), a lute player (đàn đáy), and a percussionist using wooden clappers (phách) to maintain rhythm. Historically associated with court rituals, Confucian scholarly gatherings, and spiritual ceremonies, Ca trù is renowned for its sophisticated poetic lyrics and refined musical aesthetics. It was inscribed by UNESCO in 2009 as an Intangible Cultural Heritage in Need of Urgent Safeguarding.

² Do Bang Doan – Do Trong Hue (1962), Vietnamese Ca Tru References, Ho Chi Minh City publishing house, Ho Chi Minh City.

³ Nguyen Hien Duc (2019), The Music of Ca Tru in Ha Noi, Doctorate Thesis in Musicology, Vietnam National Academy of Music.

⁴ Nguyen Thi Tan Nhan (2023), Music Feature and Characteristics in Ca Tru Singing, International Journal of Social Science and Education Research Studies, Volume 03 Issue 10 October 2023, Page No : 2155-2159

2.1.1. Research landscape on Ca Tru, teaching and preservation Ca Tru

Studies on the general aspects of Ca Tru

There have been numerous in-depth studies on various facets of Ca Tru, *Vietnamese Ca Tru References* by Do Bang Doan and Do Trong Hue⁵, *Special Examination of Vietnamese Ca Tru*⁶, *Ca Tru in Hai Phong: Now and Then*⁷, and *A Dao: A Study on the History and Music Theory* by Bui Trong Hien⁸, etc. These works have explored the historical development, cultural contexts, modal structures, musical forms, and the tonal system of Ca Tru. Additionally, they analyze the vocal techniques involved, such as vocal timbre, diction, ornamentation, rhythmic phrasing, and the intricate interplay between poetry, music, and performance. However, there remains a lack of specialized research that delves into the pedagogical methods of teaching Ca Tru from a music education perspective..

Research on the teaching and preservation of Ca Tru

A few dissertations have addressed the instruction and preservation of Ca Tru. Notably, *The Music of Ca Tru in Hanoi* by Nguyen Hien Duc⁹ analyzes the musical structure, artistic value, and suggests preservation through performance and instruction in traditional settings such as guild houses and cultural clubs.. Further, Le Thi Bach Van's doctoral dissertation *The Transformation of Ca Tru in Contemporary Life*¹⁰ takes a sociomusicological approach, researching changes in performance purpose, audience, and instructional methods. While these studies have not yet proposed a formal pedagogical model for teaching Ca Tru, they lay an important foundation for recognizing music education as a means to preserve this heritage.

Several projects led by the Vietnam Institute of Musicology and local Ca Tru clubs have facilitated master artist-led classes for young learners. However, the systematic development of curricula, instructional materials, and standardized teaching methods is still lacking. As of now, the author has not found any comprehensive educational model that formally integrates Ca Tru into folk arts or general education curricula through a structured pedagogical framework.

The above overview reveals a significant gap in the research regarding: the development of a structured teaching method tailored to learners, the standardization of instructional materials and vocal techniques based on traditional Ca Tru performance standards (such as quan, xuyen, dan, thet, khuon, ray, dieu, voi, etc.); the design of a learning pathway with supporting tools and hybrid classroom models that blend tradition and technology; And the central pedagogical role of the master artist as a folk educator,

alongside collaboration with academic musicologists in contemporary instructional settings.

2.1.2. Folk music education and the role of the Ca Tru master artist

2.1.2.1. Characteristics of folk music education

Based on studies by authors such as Do Bang Doan and Do Trong Hue, Nguyen Duc Mau, To Ngoc Thanh, Hong Thao, and To Vu, folk music education is the transmission and reception of artistic knowledge within traditional cultural spaces. This process primarily takes place through oral instruction and hands-on practice, with the direct participation of master artists. In contrast to academic music education, which relies on theoretical frameworks, notation systems, and standardized teaching methodologies, folk music education is distinguished by the following features:

Oral transmission - Non-textualized instruction

Folk music is taught primarily through listening and imitation, without the use of written scores or fixed theoretical materials. Learners listen to the master artist's performance and imitate, phrase by phrase, tone by tone, and technique by technique, in a natural way. This process requires patience, keen perception, and a long period of immersion to internalize the skills. The learning often occurs in community settings - festivals, household spaces - rather than in formal classrooms.

Individualization – respect for vocal identity

A central characteristic of folk music education is its respect for individuality. Each learner possesses a unique vocal timbre, auditory sensitivity, and expressive style. Rather than imposing a rigid mold, the master artist guides learners in developing their personal voice within the framework of traditional techniques. This fosters creativity within the boundaries of folk aesthetics, contributing to the diversity and vibrancy of traditional music.

Attached in cultural and communal contexts

Folk music is inseparable from the context of cultural performance. Learning occurs simultaneously with participation in community events, rituals, and village-based artistic activities. The primary learning environment is the dynamic space of live performance, where learners observe the master artist's interaction with audiences and internalize the performance ethos and societal role of the art.

Qualitative assessment

Evaluation in folk music education is based on artistic sensibility rather than quantified scores or standardized criteria. The master artist provides feedback that is intuitive and figurative, such as "the voice is still harsh," "the word doesn't fall softly," or "the singing lacks emotional depth." Learners adjust through listening and continued practice, not through formal testing or semester exams as in conventional education systems.

⁵ Do Bang Doan – Do Trong Hue (1962), *Vietnamese Ca Tru References*, Ho Chi Minh City publishing house, Ho Chi Minh City.

⁶ Dang Hoanh Loan et al (2006), *Special Examination of Vietnamese Ca Tru*, National Culture Publishing House, Ha Noi.

⁷ Nguyen Duc Giang (2015), *Ca Tru in Hai Phong: Now and Then*, Literature Publishing House, Ha Noi.

⁸ Bui Trong Hien (2024), *A Dao: A Study on the History and Music Theory*, Literature Publishing House.

⁹ Nguyen Hien Duc (2019), *The Music of Ca Tru in Ha Noi*, Doctorate Thesis in Musicology, Vietnam National Academy of Music

¹⁰ Le Thi Bach Van (2023), *The Transformation of Ca Tru in Contemporary Life*, PhD Dissertation in Folklore Studies, Vietnam Institute of Culture, Arts, Sports and Tourism.

Lack of standardization – vulnerability to loss

Due to the absence of curricula, learning outcomes, or pedagogical systems, folk music education depends entirely on the expertise and dedication of the master artist. When elderly master artists pass away without transmitting their knowledge, entire systems of instruction and musical technique risk disappearing. This raises an urgent need for documentation, digital archiving, and the development of suitable educational models for preservation.

In summary, folk music education is a process of live artistic transmission grounded in experiential learning, direct perception, and maximum individualization, closely tied to local cultural contexts and characterized by high adaptability. In the modern era, preserving and promoting traditional musical forms such as Ca Tru requires a thorough understanding of these characteristics to develop teaching methods that uphold traditional essence while adapting to contemporary educational environments.

2.1.2.2. The Role of the Ca Tru Master Artist

By the end of the 20th century, Vietnam saw the emergence of several master artists whose distinct vocal styles preserved the foundational principles of Ca Tru. Figures such as Quach Thi Ho, Nguyen Thi Chuc, and Pho Kim Duc showed different interpretations of the art, yet all upheld its traditional norms. As these generations of master artists passed on, concerns arose regarding the faithful transmission of Ca Tru's core techniques. According to major scholarly works such as those by Do Bang Doan – Do Trong Hue and Nguyen Duc Mau, the role of the Ca Tru master artist is expressed through the following key aspects:

Master artist is custodian and transmitter of indigenous artistic knowledge:

In the traditional learning model, the master artist is not only a performer but also a living archive of intricate vocal techniques such as vibrato, melisma, phrasing, rhythmic precision, and drum cueing. These nuanced elements cannot be fully conveyed through written curricula but must be directly experienced through personal interaction with the master artist.

Master artist is cultural architect of the learning environment:

Beyond vocal training, the master artist recreates a culturally rich, traditional learning space that reflects the ethical and ceremonial essence of the art. This includes maintaining ritualistic teacher-student dynamics, ceremonial gestures within performance guilds (phường hát), and cultural etiquette. Such an environment fosters not only technical competence but also an artistic mindset, a sense of respect for the art form, and a commitment to preserving cultural identity.

Master artist is artistic guide and intuitive mentor

Unlike modern vocal instructors who rely on structured syllabi, master artists use intuitive and affective language to guide learners. Phrases like “make your vibrato soft” or “let the note fall gently” offer

emotional and interpretive direction rather than technical precision. This intuitive mentoring helps students not only sing correctly but also show the emotional and spiritual essence of Ca Tru.

Master artist is teacher and inspiration

In traditional Vietnamese music, the teacher is also a moral and inspirational figure. Students often learn not only how to sing, but also how to speak, behave, and live through the example set by their master artist. Figures like Nguyen Thi Chuc, Pho Thi Kim Duc, and Nguyen Thi Mui left behind more than just technical skills—they passed on a deep set of cultural values and artistic ethics to their students.

Master artist is bridge between past, present, and future of the heritage

In modern efforts to revive and preserve Ca Tru, the master artist plays a vital role in linking tradition with contemporary educational and performance practices. They contribute to documentation efforts, perform in contemporary contexts, and teach in conservatories and community clubs. Through their ongoing educational engagement, they help transmit the legacy of Ca Tru to future generations.

In general, The Ca Tru master artist is central to the preservation and education of this refined traditional art form. They are not only technical mentors but also spiritual and cultural guardians who pass on the soul, aesthetic, and discipline of Ca Tru through lived practice and personal transmission.

2.1.3. Pedagogical methods in the transmission of Ca Tru by master artists

Through a combination of document analysis, field observation, and in-depth interviews with established master artists, it has been found that the predominant pedagogical strategies in Ca Tru vocal training are oral transmission, imitation, and hands-on practice.

Oral transmission as core pedagogy

Oral transmission represents the fundamental and most widely adopted method in Ca Tru pedagogy. The master artist sings exemplar phrases, syllable by syllable, while students listen, repeat, and imitate. Learners do not engage with formal music theory; rather, they develop auditory memory and embodied understanding through sensory experience. Instructional content includes pitch release, syllabic articulation, vocal ornamentation, vibrato and pulsation techniques, and the integration of vocalization with rhythmic accents played on the beat. Throughout this process, the master provides real-time corrections grounded in perceptual sensitivity, often employing metaphorical or affective language such as: “Your tone is too rigid”, “You need to soften the phrasing”, “Your syllable release is not clear”, “The vibrato lacks delicacy.”, etc. Crucially, artists assess the expressive essence of the performance, the maturity of the voice, and its alignment with the rhythms of the trong chau¹¹

Respecting vocal individuality with traditional standards

¹¹ Interviews with Distinguished Master Artists (DMA) Nguyen Thi Ngoan, Head of the Tranh Thon Ca Tru Club; Nguyen Thi Ha, Vu Thi Ngan

A distinguishing feature of Ca Tru instruction lies in its respect for the vocal individuality of each student. Master artists do not demand absolute mimicry; rather, they guide learners to develop their own vocal timbre within the technical confines of the Ca Tru tradition. Nevertheless, learners are still required to meet established aesthetic standards rooted in centuries-old vocal criteria—such as quan, xuyen, dan, thet, khuon, ray, dieu, and voi—as articulated in prior studies¹². This approach ensures that while individual expression is fostered, students also attain traditional competencies: mastery of rhythmic phrasing, delicate and precise tonal projection, round syllabic articulation, dynamic nuance, smooth melodic inflection, tonal clarity, and an overall ability to embody the spiritual and performative essence of a Ca Tru song.

Structured curriculum with technical progression

"Learning Ca Tru is difficult," is a sentiment frequently echoed by both practitioners and scholars. According to Meritorious Artist (MA) Le Thi Bach Van, "Ca Tru vocal technique is not solely about vibrato or pulsation. One must also focus on phrase release, syllable articulation, and precise melodic intonation. Singing and percussive rhythms must be tightly synchronized. In addition to vocal skills, students must learn proper beat techniques for each stylistic form, attune their ears to the trong chau, and respond musically in real time without falling out of

rhythm¹³". Given this level of complexity, instruction cannot be fragmented or improvised; instead, it follows a structured progression, from basic to advanced levels, aligned with each learner's capacity for absorption and practice.

According to People's Artist (PA) Nguyen Thi Tam: "In the early stage, students must memorize the lyrics, then learn to strike the beat. Only after synchronizing with the lute and drum can they begin singing¹⁴". MA Luu Thi Kim Lien further elaborates: "A ca nuong must simultaneously activate four senses: sing with the mouth, recall lyrics, listen attentively to the lute and drum, and strike the beat with precision. Achieving this is tremendously difficult. Only deep passion and consistent, rigorous practice can lead to success¹⁵". Other artists affirm that beginners are first introduced to simple, memorable melodies to acclimate to the rhythmic system, and only thereafter proceed to more complex techniques and expressive nuances¹⁶.

To evaluate the current pedagogical landscape and emerging needs in Ca Tru education, in-depth interviews were conducted with 20 master artists from traditional Ca Tru guilds in Thai Ha, Lo Khe, Hang Buom, Tranh Thon, Dong Chu, among others. The qualitative data collected reflects both contemporary challenges and recommendations for methodological renewal. The results are summarized in the following table:

Table 1

Survey on Methods of Teaching Ca Tru Singing

Surveyed Content / Issue	Percentage of Agreement Among Artists	Ghi chú & trích ý kiến tiêu biểu
Ca Tru singer simultaneously sings and beats the beat	100%	"That is the most distinctive feature. Singing without the beat loses its soul."
Oral transmission remains the primary teaching method	100%	"You must listen – feel – and sing back. There is no other way."
Use of video/audio as supporting tools	60%	"Nowadays we have audiovisual devices. Teachers and students can record and edit conveniently."
Availability of official curriculum	10%	Most noted: "There is no standardized curriculum, only handwritten notes."
Feasibility of teaching Ca Tru in formal education	90%	"It is teachable, but requires specialists."
Average time to reach basic singing proficiency	3–6 months	Depending on age, talent, and dedication.
Possibility of self-learning	40%	Requires high-quality reference recordings. "Someone must correct your mistakes for it to be accurate."
Evaluation of current master artists	75% satisfied	However, 65% expressed concern: "As artists grow older, few young successors emerge."
Agreement with the model where the master artist is the core source of inspiration	100%	"Without someone to inspire, students cannot preserve the soul of Ca Tru."
Support for a multimedia teaching toolkit	95%	"Very necessary, especially video demonstrations and practice software."
Support for flexible learning models	100%	Many called for community or public classes to expand the artform's reach.

¹² Dang Hoanh Loan et al (2006), Special Examination of Vietnamese Ca Tru, National Culture Publishing House, Ha Noi.

¹³ Interview with Dr. Le Thi Bach Van

¹⁴ Interview with PA Nguyen Thi Tam, Chairwoman of the Thuong Mo Ca Tru Club, Hanoi

¹⁵ Interview with MA Luu Thi Kim Lien

¹⁶ Interviews with master artists Nguyen Thi Ngoan, Nguyen Thi Ha, and Vu Thi Ngan at Tranh Thon Ca Tru Club

Based on the interview results, it is evident that the current methods of Ca Tru transmission still heavily rely on oral instruction, emotional inspiration, and traditional apprenticeship. This approach positions the master artist not only as a technical instructor but also as the essential source of aesthetic direction and cultural spirit.

Consequently, findings from field research indicate that while traditional methods of transmitting Ca Tru remain fundamentally effective, they should be complemented, integrated, and systematized. Such a synthesis would allow for adaptation to contemporary educational settings, laying the groundwork for the standardization and sustainable preservation of this intangible heritage.

2.2. Proposing a model for teaching Ca Tru singing in the contemporary context based on traditional foundations

2.2.1. Principles for constructing a Ca Tru teaching methodology in modern society

The method for teaching *Ca Tru* singing in the new context should be based on the following principles:

Preserving core values: Distinctive elements such as techniques of word articulation vibration, single-note singing, ornamentation, and subtle accentuation must be passed down intact, without simplification or modernization to suit contemporary tastes.

Respecting learner individuality: Acknowledging differences in vocal quality, speed of acquisition, and artistic perception. The master artist plays the role of guiding technique and aesthetics, but does not impose uniformity, instead helping learners

develop their unique voice within the standards of Ca Tru..

Integrating technology to support the teaching process: Digital resources (e.g., demonstration videos of master artists, technically annotated audio recordings, online learning platforms) will enrich and visualize learning content, while expanding accessibility to a broader audience.

Organizing flexible teaching formats: Combining traditional forms (direct meetings with the master for apprenticeship and correction) with modern learning forms such as online learning, group study, video analysis, and interaction on digital platforms. This approach suits the living conditions, work, and learning habits of learners in the digital era.

Placing the master artist at the center as the source of inspiration, Master artists play a key role in preserving core techniques and transmitting the artistic spirit. In parallel, building a team of instructors with backgrounds in musicology, capable of researching and systematizing traditional knowledge and working alongside master artists to standardize content, methods, and evaluation will establish a sustainable and effective Ca Tru teaching ecosystem in the new context.

2.2.2. Proposed model for teaching Ca Tru that integrates tradition and modernity

2.2.2.1. On the learning pathway

Based on traditional teaching principles combined with modern methods, the author proposes a Ca Tru singing learning pathway consisting of three stages, from initial acquaintance to trial performance, with pedagogical content and methods appropriate to each ascending level.

Table 2:

Proposed learning pathway for Ca Tru combining traditional and modern approaches

Stage	Learning content	Teaching methods and learning support
Stage 1 (Familiarization – Orientation)	- Becoming familiar with poetic forms, rhythmic patterns, and how to enter a Ca Tru verse. - Learning simple, gentle, and popular pieces such as: Hat noi Canh ngay he, Hue tinh, Chu tam moi bang ba chu tinh. - Practicing pronunciation techniques, word articulation, breath control, and light vibration.	- Learners listen and imitate demonstration videos by master artists. - Practicing singing each line in combination with basic beat beating. - Home practice using slow-motion videos and accurate rhythmic recordings, with beat-feeling support software
Stage 2 (Technical training – Applying traditional repertoires)	- Learning pieces with rich imagery and clear melodic ornamentation such as: Hat noi Ty ba hanh, Cung oan ngam khuc, Dao Hong, Dao Tuyet, etc. - Practicing singing in combination with trong chau rhythm and dan day accompaniment. - Deepening techniques of articulation, vibrato, ornamentation, and breath control.	- Small-group direct learning with the master artist. - Recording individual singing, self-assessment and comparison with standard models, and tracking progress across sessions.
Stage 3 (Trial performance – Advanced refinement)	- Trial performance before peer learners and master artists. - Full coordination of singing, beat, trong chau, and dan day. - Deepening emotional connection with the song, expressive nuance, and the spirit of Ca Tru.	- Full video recording of the performance for overall analysis. - Participating in in-depth feedback sessions with master artists and musicology instructors. - Practicing and refining technical details: rhythmic precision, word softness, phrase release, articulation, vocal projection, lyrical expression...

This three-stage learning pathway ensures that the process of learning Ca Tru progresses along a natural developmental arc, from initial appreciation, to technical mastery, to expressive performance, aligned with an individualized learning pace that respects each learner's vocal development.

2.2.2.2. Multimedia-integrated teaching materials

To effectively support the process of learning Ca Tru singing, especially in the context of modernized and digitized education, the author proposes developing a multimedia-integrated teaching toolkit that blends tradition with technology, including the following components:

Demonstration videos by master artists

Traditional Ca Tru repertoires are professionally recorded by reputable master artists, ensuring performance authenticity. The videos feature close-up shots of mouth movements, hand gestures on the beat clappers, facial expressions, and eye movements, enabling learners to absorb both vocal techniques and performance spirit. Each video is segmented by technical sections, entry into the verse, vocal sustain, conclusion, allowing learners to practice step-by-step.

Technical analysis subtitles

Each video is embedded with specialized subtitles that directly highlight essential technical elements such as: beat entry points, vocal sustain moments, vibration, melodic ornaments; suggestions on articulation, breath control, and word emphasis; annotated phrases such as: "soft articulation – continuous vibration," "slightly delayed entry," "pause breath here," etc.

Printed/digital learning materials

Compiled into specific lessons, these materials provide step-by-step learning guides: introduction to poetic forms, song meanings, breath control, vocal placement for each line; detailed descriptions of vocal techniques like sustain, ornamentation, tremolo, and rhythmic features of each piece. Illustrated with images depicting posture, beat handling, breath flow charts, acoustic contours, and emphasized notes to support visual and physical understanding.

Learning support software

A simple, user-friendly app offering features such as: recording and comparing learners' voices with master examples; tracking individual progress across practice sessions; allowing users to mark weak sections, replay specific parts, take personal notes; integrating a verified database of standard performances by master artists.

Developing this toolkit not only standardizes the Ca Tru teaching process but also helps preserve valuable materials from current master artists; expands accessibility for younger generations, remote learners, and online students; and lays the groundwork for systematic training in traditional arts that applies technology while preserving the spirit of transmission.

2.2.2.3. Flexible Ca Tru class models

Based on field surveys and current educational trends, the author proposes three flexible models for Ca Tru classes, each with distinct characteristics in terms of learning environment, instructors, learners, and instructional goals.

Master artist – student class (traditional model in clubs)

Learning space: Ca Tru guild halls, folk art clubs, or the private residence of a master artist

Format: Direct master-to-student transmission through listening – imitation – error correction.

Teaching content: Tied to traditional methods, including singing techniques, phách beating, rhythm perception, vocal expression, and performance spirit.

Role of the master artist: Both teacher and inspiration, playing a key role in preserving original techniques and styles.

Special value: Provides a community-based learning space that transmits not only technical knowledge but also the "mindset" of Ca Tru art.

General education classes (primary to university level)

Learning space: Primary/secondary schools, art centers, or universities and colleges with music programs.

Talent Group: Students without prior Ca Tru knowledge, approaching from a basic level.

Format: A combination of music teachers with foundational Ca Tru knowledge and digitized resources from master artists; lessons utilize multimedia..

Teaching approach: Focus on appreciating Ca Tru, introducing it as an intangible cultural heritage, along with basic singing practice.

This model helps integrate heritage education into the formal education system and inspires younger generations with traditional music.

Community-based classes – oriented toward media and heritage education

Learning space: Cultural centers, village communal houses, public performance venues.

Organizing format: Run by Ca Tru clubs or folk art centers, held periodically or through community outreach projects.

Target group: Individuals interested in heritage, foreigners, traditional music lovers, etc

Teaching content: Overview of Ca Tru history and repertoire structure; instruction in basic techniques (beat, ornamentation, tremolo, single-tone singing); performance demonstrations.

Objective: Educate the public about heritage value, enhance media outreach and hands-on experiences, and provide a foundation for future generations to access Ca Tru.

The implementation of flexible class models is a necessary direction in the context of modernization and digitalization, where adaptability and connectivity are key to the sustainable dissemination of heritage. Each model can operate independently but may also be linked together into a Ca Tru teaching ecosystem in which: master artists serve as the traditional core; music educators act as knowledge transfer bridges; and digital resources function as tools for expansion and accessibility.

3. Conclusion

The method of teaching Ca Tru singing, although never systematized according to modern pedagogical standards, remains a valuable heritage, embodying indigenous knowledge of vocal techniques, rhythm,

sound aesthetics, and performance artistry. Researching and restructuring this method within the framework of contemporary education aims to support master artists in their role as inspirational teachers and as creators of traditional aesthetic standards for the younger generation.

By integrating digital tools, multimedia materials, and flexible class models, this study proposes a feasible direction for preserving the vocal techniques of Ca Tru amidst the modernization of music education. More importantly, it reaffirms the central role of the master artist. If these efforts are strategically and synchronously implemented, they will not only help sustain the vitality of Ca Tru, but also enrich the cultural identity of Vietnam in the flow of globalization.

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CHEMICAL SCIENCES

CONVERSION OF METHANOL TO C₂-C₃ ALKENES ON MODIFIED HIGH-SILICA ZSM-5-TYPE ZEOLITES

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<https://doi.org/10.5281/zenodo.15298371>

Abstract

To increase the selectivity for C₂-C₃ alkenes, catalysts based on ZSM-5 zeolite, modified with zinc, cobalt, gadolinium, and zirconium, were obtained using the impregnation method. The conversion of methanol to hydrocarbons was carried out in a flow reactor with a fixed catalyst bed in the temperature range of 300-350°C, under atmospheric pressure, in a nitrogen flow.

It has been shown that H-ZSM-5 has low selectivity for C₂-C₃ alkenes (24.0%).

The modified H-ZSM-5 with zinc, gadolinium, and zirconium improves selectivity for C₂-C₃ alkenes (52.6% - 63.6%) and reduces selectivity for C₁-C₅ alkenes (from 39.1% to 17.2% - 25.7%).

The highest selectivity for C₃ alkenes (65.5% - 68.7%) and propylene (38.4% - 42.2%) is achieved with the two-component modification of the zeolite on Gd-Zr-H-ZSM-5 and Zn-Zr-H-ZSM-5 samples.

Keywords: methanol, conversion, selectivity, C₂-C₃ alkenes, modification, zinc, gadolinium, zirconium.

Introduction

Lower alkenes C₂-C₃ are valuable raw materials for the petrochemical industry, primarily obtained in pyrolysis and catalytic cracking processes [1]. In recent years, particular attention has been paid to methods for obtaining alkene hydrocarbons from alternative raw materials in the presence of zeolite catalysts [2],[4]. One type of alternative raw material is methanol, which is produced in industry from methane through syngas.

The process of converting syngas into lower alkenes through methanol was developed by Mobil Oil Corporation, UOP, and Norsk Hydro in the presence of molecular sieve-based catalysts of the SAPO-34 type at 450-500°C [6].

However, these catalysts do not achieve a high yield of propylene [7]. A more promising candidate for the conversion of methanol to C₂-C₃ alkenes is the ZSM-5 zeolite-based catalyst, which possesses nanoscale interconnected straight (0.51 × 0.53 nm) and sinusoidal channels (0.53 × 0.55 nm). Studies [9-19] have shown that the selectivity for C₂-C₃ alkenes can be improved by modifying the ZSM-5 zeolite with phosphorus compounds and transition metals [8] [9].

The aim of this study is to investigate the effect of two-component modification of high-silica ZSM-5-type zeolite with zinc, gadolinium, and zirconium on its selectivity in the conversion of methanol to C₂-C₃ alkenes.

Experimental part

For the preparation of catalysts, ZSM-5 zeolite produced by JSC "Nijnegorodskie sorbenti" was used, with a molar ratio of SiO₂/Al₂O₃ = 33.

To obtain the H-form, the initial Na-ZSM-5 zeolite was subjected to ion exchange with a 1 M NH₄NO₃ solution at 80°C for 2 hours. The ion exchange was carried out three times using a fresh salt solution each time. After ion exchange, the zeolite was thoroughly washed with distilled water to the absence of NO₃⁻ ions [10].

Then, the sample was dried for 24 hours at room temperature, followed by drying in a thermostat at 110°C for 6 hours. Subsequently, calcination was carried out in a muffle furnace at 250°C and 500°C for 4 hours each[1].

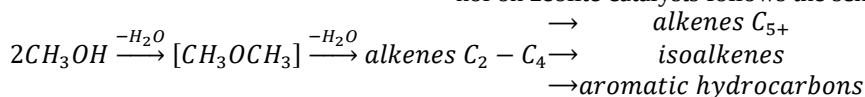
The obtained H-form of the ZSM-5 zeolite was modified using aqueous solutions of zinc acetate, lanthanum nitrate, and zirconium oxychloride [5].

The H-form of the zeolite was treated with the corresponding salt solutions under stirring and heating up to 95°C. The modified zeolites were then mixed with an alumina oxide suspension, calculated to contain 25 wt% dry Al₂O₃. The resulting extrudates were shaped, air-dried, granulated, and calcined at 500°C for 4 hours. The metal content in the catalysts was 0.5 wt%[3].

Experiments were conducted in a flow setup with a quartz reactor (length 18 cm, inner diameter 1.0 cm) with a stationary catalyst bed of 3.0 cm in length, in the temperature range of 250-450°C, with a methanol feed volumetric flow rate of 2.0-3.6 h⁻¹ in the presence of nitrogen. The reaction products were analyzed using an Agilent GC782A gas chromatograph.

Results and Discussion

In the temperature range of 300-400°C, methanol, in the presence of unmodified ZSM zeolite, is converted into a mixture of hydrocarbons with compositions ranging from C₁ to C₁₂. The conversion of methanol on zeolite catalysts follows the scheme [].



As seen in Figure 1, at a low methanol conversion of 10-20%, the main product of methanol conversion is ethylene. The ethylene content in the reaction products ranges from 61.5% to 68.8%. Increasing the reaction temperature above 300°C leads to a significant decrease in ethylene content. As the methanol conversion increases to 99.8%, the ethylene content decreases by a

factor of 4.5, reaching 18.7%. At a methanol conversion of 20%, the propylene content is only 9.9%, and no butylenes are formed. Increasing the methanol conversion to 70% results in an increase in propylene content to 21.2%. Further increases in methanol conversion do not contribute to a higher propylene content.

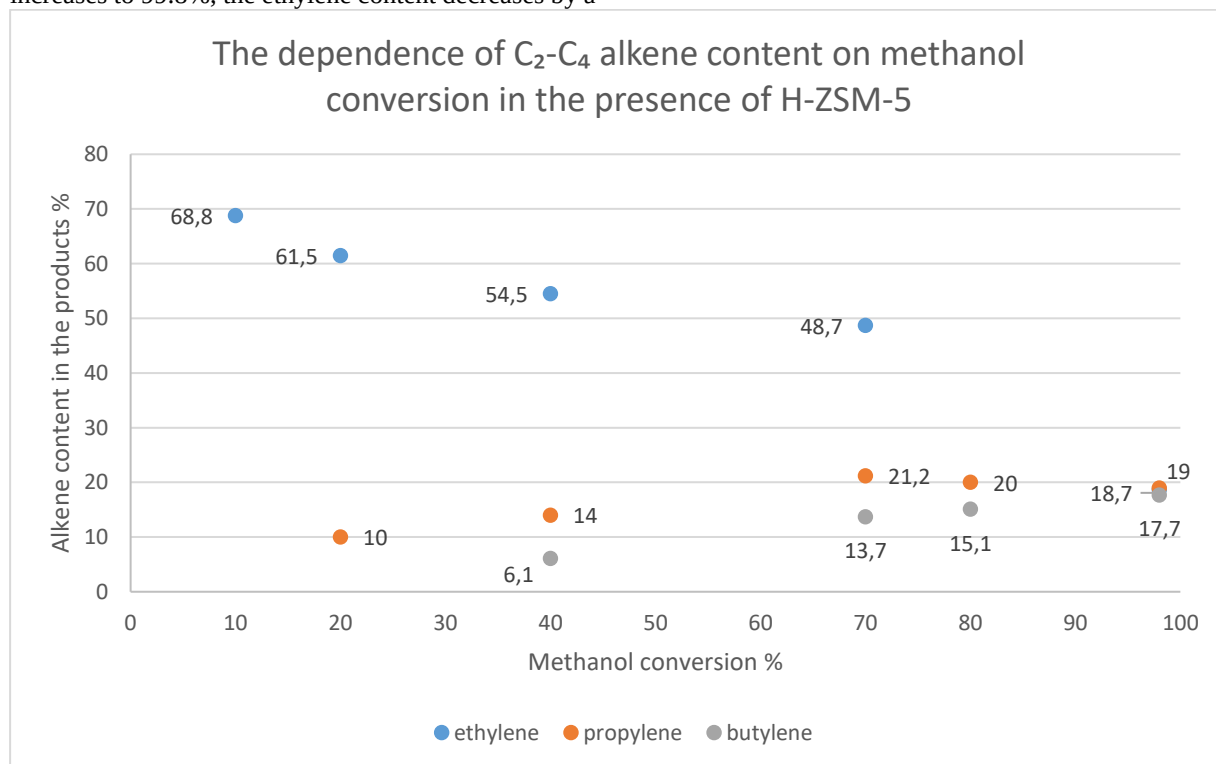


Figure 1. The dependence of C₂-C₄ alkene content on methanol conversion in the presence of H-ZSM-5

Butylenes are formed in the reaction products at a methanol conversion of 40%. The butylene content is 6.1%. Further increases in methanol conversion lead to an increase in butylene content. When the methanol conversion reaches 98%, the butylene content increases to 17.7%

Table 1.

The influence of the metal nature in H-ZSM-5 on its catalytic properties in methanol conversion to hydrocarbons.

Sample	Methanol Conversion	Gas yield %	Liquid product yield %	Composition of reaction products, wt%				
				C ₂ H ₄	C ₃ H ₆	C ₄ H ₈	C ₁ -C ₅ alkanes	C ₅ +
H-ZSM-5	80.2	55.8	44.2	15.2	8.8	4.2	34.1	32.7
Zn-H-ZSM-5	85.3	75.2	24.8	23.2	29.4	5.6	25.7	16.1
Co-H-ZSM-5	83.2	58.2	41.8	18.8	15.2	4.5	45.7	15.8
Gd-H-ZSM-5	87.1	68.9	31.1	21.7	31.4	3.9	20.8	22.2
Zr-H-ZSM-5	87.2	80.1	19.9	30.2	33.4	3.3	17.2	15.9

As seen in Table 1, the H-ZSM-5 zeolite has low selectivity for alkenes, with alkanes predominating in the hydrocarbon fraction. The content of ethylene and propylene in the reaction products is 15.2% and 8.8% by weight, respectively. Modifying the H-ZSM-5 zeolite with metals alters the catalytic properties of the catalysts. Metal modification primarily affects the selectivity for C₁-C₅ alkanes and C₂-C₃ alkenes. Zinc modification increases the content of ethylene (up to 23.2%) and propylene (29.4%). Compared to ethylene, the propylene content increases by 3.3 times. At the same time, the content of C₁-C₅ alkanes decreases to 25.7%, and

C₅+ hydrocarbons decrease to 16.1%. Cobalt modification has little effect on methanol conversion, and the content of ethylene increases by only 3.6%. However, there is a significant increase in the content of alkanes (up to 45.7%). Modification of the zeolite with gadolinium leads to a significant increase in propylene content (up to 31.4%) and a decrease in C₁-C₅ alkane content (down to 20.8%). The catalyst modified with zirconium shows high selectivity towards ethylene and propylene, with the content of ethylene and propylene

increasing to 30.2% and 33.4%, respectively. Furthermore, there is a significant decrease in the selectivity for C₁-C₅ alkanes.

Table 2.

The influence of bimetallic modification of H-ZSM-5 on the properties of catalysts in methanol conversion to hydrocarbons.

Sample	Methanol Conversion	Gas yield %	Liquid product yield %	Composition of reaction products, wt%				
				C ₂ H ₄	C ₃ H ₆	C ₄ H ₈	C ₁ -C ₅ alkanes	C ₅ +
Zn-Gd-ZSM-5	96	68.6	31.4	23.6	31.2	5.7	21.2	18.3
Gd-Zr-ZSM-5	96.4	73.2	26.8	26.5	42.2	5.2	14.2	11.5
Zn-Zr-ZSM-5	95.7	72.1	27.9	27.1	38.4	6.8	11.4	16.7

Thus, the catalysts modified with zinc, gadolinium, and zirconium exhibit higher selectivity for ethylene and propylene compared to the catalyst modified with cobalt.

The effect of two-component modified H-ZSM-5 zeolites on the selectivity of methanol conversion products is shown in Table 2.

It is evident that in all cases, the selectivity for propylene increases. The highest selectivity for propylene is observed in the Gd-Zr-H-ZSM-5 sample, reaching 42.2%. This catalyst also exhibits high selectivity for the sum of ethylene and propylene (68.7%).

Conclusion

The conversion of methanol into C₂-C₃ alkenes on the H-form of ZSM-5 zeolite proceeds with insufficient activity and low selectivity for olefins. Modification of H-ZSM-5 zeolite with zinc, zirconium, and gadolinium leads to an increase in selectivity for C₂-C₃ alkenes. The highest selectivity for C₂-C₃ alkenes (65.5% - 68.7%) is achieved as a result of two-component modification of H-ZSM-5 zeolite with gadolinium and zirconium compounds.

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CLEANING POLLUTED SOILS WITH BIOREMEDIATION

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ОЧИЩЕНИЕ ЗАГРЯЗНЁННЫХ ПОЧВ С ПОМОЩЬЮ БИОРЕМЕДИАЦИИ

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With the growth of the world population, the level of land pollution increases. Nowadays, waste management resulting from the rapid growth of industries such as food, health care and automobile is of great importance. The accumulation of pollutants in soils has serious impacts not only on soil fertility and ecosystem functions, but also on human and animal health through the food chain. Bioremediation, a method based on the use of microorganisms to prevent toxicity and breakdown of environmental pollutants, is becoming an important biotechnological approach for the elimination and prevention of environmental pollution. This paper presents a review on the cleanup of contaminated soils with the bioremediation method, which is more cost-effective than other methods. However, the long cleaning time and the inability to achieve effective results at high pollutant concentrations limit the applicability of this method.

Аннотация

С ростом населения в мире возрастает уровень загрязнения земель. В настоящее время управление отходами, возникающими в результате быстрого роста таких отраслей, как пищевая, здравоохранительная и автомобильная, имеет важное значение. Накопление загрязняющих веществ в почвах оказывает серьезное воздействие не только на плодородие почвы и функции экосистемы, но и на здоровье человека и животных через пищевую цепочку. Метод биоремедиация, основанный на использовании микроорганизмов для предотвращения токсичности и разрушения экологических загрязнителей, становится важным биотехнологическим подходом для ликвидации и предотвращения загрязнения окружающей среды. В данной работе представлен обзор об очищении загрязненных почв методом биоремедиации, который является более экономически выгодным по сравнению с другими методами. Однако длительное время очистки и невозможность достижения эффективных результатов при высоких концентрациях загрязнителей ограничивают применимость этого метода.

Keywords: bioremediation, soil pollution, remediation methods.**Ключевые слова:** биоремедиация, загрязнение почвы, методы восстановления.

Процессы биоремедиации, которые используют микроорганизмы для разрушения опасных веществ и превращения их в безвредные или менее вредные вещества, являются долгосрочными очистными процессами [1,2]. Биоремедиация — это естественный процесс, при котором микроорганизмы стабилизируют или превращают экологические загрязнители в конечные продукты.

Для того чтобы биоремедиация была эффективной, микроорганизмы должны атаковать загрязнители с помощью ферментативных реакций и превращать их в безвредные вещества. Этот метод может быть эффективен только в тех случаях, когда

экологические условия позволяют микроорганизмам расти и развиваться. Микроорганизмы, разлагающие загрязнители, должны находиться в непосредственной близости от них и в правильных местах. Если популяция микроорганизмов отсутствует, необходимо разработать инженерные механизмы, которые обеспечат контакт микроорганизмов с загрязнителями [3]. Экологические условия должны быть контролируемы, либо условия должны быть изменены для оптимизации метаболической активности и роста микроорганизмов. Для оптимизации окружающей среды для биоремедиации следует регулировать такие экологические факторы, как температура, питательные вещества

(в первую очередь азот и фосфор), электронные акцепторы (кислород, нитрат, сульфат) и pH [4].

С точки зрения здоровья и экологии, широко распространённые нефтепродукты, бензин, ПАУ, хлористые алканы (РСЕ), тетрахлорэтилен (ТСЕ) и хлористые ароматические углеводороды легко поддаются детоксикации с помощью микроорганизмов. Хотя металлы не могут быть биологически разложены, их можно преобразовать в менее вредные формы с помощью микроорганизмов, поэтому они также рассматриваются в контексте биоремедиации [5].

Техники биоремедиации, как правило, более экономичны по сравнению с другими традиционными методами, такими как сжигание. Согласно программе Агентства по охране окружающей среды США (EPA), использование биоремедиации в загрязнённых районах с опасными веществами оказывается в 10 раз дешевле, чем традиционные методы. Поскольку этот метод, основанный на естественных процессах сокращения загрязнений, он воспринимается обществом как более приемлемый по сравнению с другими технологиями. Существует два основных метода биоремедиации, основанных на транспортировке или удалении отходов. Это биоремедиация на месте (in-situ) и биоремедиация вне места (ex-situ). Однако время, необходимое для завершения восстановления, будет зависеть от того, проводится ли процесс на месте или извлечённый почвенный материал транспортируется с помощью специальных средств. Технологии экс-ситу, которые не проводятся в естественной почвенной среде, обычно более быстрые и эффективные по сравнению с методами, проводимыми на месте [4]. В данной работе приведен обзор результатов изучения процессов биоремедиации, которые считаются экономической альтернативой в устранении загрязнения почвы, а также рассмотрены существующие технологии с их преимуществами и недостатками.

Факторы, влияющие на биоремедиацию.

Разнообразие почв зависит от свойств почвенного материала, топографических характеристик района, климатических факторов, растительности и состояния организмов в почве. Успешная стратегия биоремедиации должна учитывать переменные факторы почвенных характеристик. Свойства почвы значительно влияют на поведение загрязняющих веществ в почве. Поэтому подходящий метод ремедиации должен учитывать специфические свойства почвы и условия области, требующей очистки [6]. Система биоремедиации не работает с одинаковой эффективностью при всех условиях. [7].

Влияние физической среды почвы

Физические характеристики и структура почвы могут изменяться в зависимости от химической и биологической активности. Успешная биоремедиация зависит от множества факторов, однако критическим фактором является содержание воды в почве. Содержание воды в почве контролируется её структурой и пористостью. Влажные почвы обычно бедны кислородом, что ограничи-

вает аэробную биоремедиацию. Для аэробной биоремедиации в почве необходимы достаточные количества кислорода и воды [4].

Наиболее значительным изменением в почве является снижение содержания органического вещества с глубиной почвы. Органическое вещество играет важную роль в почве. Оно является важным источником питательных веществ для микроорганизмов, и уменьшение его содержания с глубиной приводит к снижению плотности микробиальной популяции, а следовательно, к уменьшению разлагаемости токсичных химических веществ [8]. Поэтому нижние слои почвы имеют более низкую плотность микробиальной популяции и менее активные микробиальные процессы по сравнению с верхним слоем почвы.

Влияние гидравлической проводимости почвы и проницаемости на применимость биоремедиации

Для активации микробной активности необходимы источники питательных веществ и кислорода. Если почва и водоносный слой непроницаемы, микроорганизмы сталкиваются с трудностью обеспечения достаточного количества кислорода и питательных веществ для роста и дыхания. Если гидравлическая проводимость больше 10^{-4} см/с, обычно обеспечивается достаточное движение питательных веществ и кислорода. Почвы с высокой проницаемостью, однако, не подходят для биоремедиации из-за низкой микробной популяции. Тонкозернистые почвы и осадки с низкой проницаемостью также затрудняют поступление питательных веществ и кислорода для микроорганизмов [9].

Влияние температуры и влажности почвы

Эти параметры влияют на кинетику реакций в почве. Потому что микробная активность включает температурозависимые ферментативные и биохимические процессы. Оптимальная температура для биологического разложения составляет от 20°C до 30°C. Температура контролируется сезонными климатическими условиями, состоянием поверхности почвы, содержанием влаги в почве и её глубиной. Годовая температура воздуха является показателем годовой температуры почвы на глубине 1-5 м. Влажные почвы обладают высокой теплоёмкостью, и их температура меняется медленнее, чем у сухих почв. Температура почвы может быть контролируема через орошение, дренаж, растительные остатки на поверхности, искусственные покрытия или растительность.

Химическая среда почвы

Естественные характеристики почвы, концентрация загрязнителя и степень загрязнения имеют важное значение для определения вероятности успешной биоремедиации. Участки, сильно загрязнённые и устойчивые к биологическому разложению, не подходят для очистки с помощью биоремедиации. Состояние загрязнителя, его сорбция на других веществах, транспортировка и биологическое разложение влияют на биологическую активность почвы. Эти воздействия могут изменять pH почвы, её ионно-обменную способность, содержание питательных веществ, солей, тяжёлых металлов, минералов и органических веществ. Одним из

факторов, влияющих на химические характеристики почвы, являются глинистые минералы. Глиняные частицы имеют большую поверхность для взаимодействий. Глиняные минералы состоят из кристаллических частиц, аморфных материалов, солей и металлических оксидов. Кроме того, они влияют на сорбцию аполярных химикатов, обеспечивая большую реактивную поверхность. Из-за того, что их поверхности заряжены электрически, они также влияют на сорбцию полярных химикатов через ионно-обменную способность. Глиняные минералы могут задерживать химическое загрязнение, делая его недоступным для микробиального разложения. Помимо глиняных минералов, органическое вещество почвы также обладает высокой катионно-обменной способностью и оказывает существенное влияние на сорбцию тяжелых металлов и органических химикатов [6].

Почва как источник питательных веществ для растений и микроорганизмов

Почва является источником питательных веществ для растений и микроорганизмов. Она содержит макроэлементы, такие как углерод (C), азот (N) и фосфор (P), а также все микроэлементы. Необходимость в макроэлементах для микробного разложения оценивается на основе загрязненной почвы (с помощью электролитического респирометра), и измеряется биологическая потребность в кислороде (БПК). Общая БПК увеличивается с количеством азота (N) и фосфора (P), необходимым для повышения микробного питания. Обычно БПК, соотношение $\text{NH}_3\text{-N}$ и ортофосфата принимается как 100:10:1 [10].

Микроорганизмы также нуждаются в малых количествах некоторых микроэлементов для питания. Во многих областях ремедиации для обеспечения достаточного микробного питания эти микроэлементы добавляются в определенных количествах. Влияние микроэлементов на микробное питание имеет важное значение в биоремедиации [11].

Биологическая среда почвы

Почвы отличаются от других геологических материалов благодаря наличию важных биологических процессов. Интенсивная биологическая активность почвы обычно находится в верхнем горизонте. Растения, животные и микроорганизмы вносят вклад в биологическую активность почвы. Физические и химические характеристики почвы влияют на биологическую активность. Условия почвы, которые способствуют активности аэробных микроорганизмов, включают хорошую вентиляцию, достаточное количество питательных веществ и источников энергии, подходящий уровень влажности и температуру. Когда почва насыщается водой, диффузия кислорода в почечную матрицу ограничивается, и почва становится анаэробной. В этих условиях активность аэробных микроорганизмов ограничена, в то время как анаэробные микроорганизмы начинают расти и использовать органическое вещество в качестве источника энергии. Таким образом, физическая структура почвы, химические реакции, климатические условия и ис-

пользование органического вещества как источника энергии и питательных веществ влияют на биологические условия почвы [6].

Технологии биоремедиации

Биоремедиация основывается на способности микроорганизмов поглощать загрязнители и использовать их для роста и метаболической активности. Основная цель разработки биоремедиации — создание оптимальных условий для микробного роста и активности. В зависимости от уровня аэрации и насыщения зоны, могут быть использованы различные технологии.

Биоремедиация применяется двумя способами:

➤ **Метод с добавлением питательных веществ (нутриентов):** добавление питательных веществ в загрязненную область, что активирует бактерии, уже присутствующие в почве, в зависимости от бактериального состава почвы (технологии удаления на месте - *in-situ*). Этот метод используется при низких концентрациях загрязнителей.

➤ **Метод с удалением почвы:** почва выкапывается, загрязняющие вещества разлагаются с помощью новых бактерий. Условия контролируются или изменяются для оптимизации метаболической активности и роста микроорганизмов. В процессе биоремедиации для оптимизации условий окружающей среды регулируются такие факторы, как температура, неорганические питательные вещества (преимущественно азот и фосфор), акцепторы электронов (кислород, нитраты, сульфаты) и pH (технологии удаления не на месте - *ex-situ*).

Техники биоремедиации на месте (*in-situ*)

Это высококачественный метод очистки загрязненных участков с использованием природных микроорганизмов для разложения химических веществ с низкими затратами. Эта технология привлекательна из-за низкой стоимости и возможности очистки без необходимости выемки и транспортировки загрязненной почвы [12]. Однако биоремедиация на месте имеет некоторые недостатки. В сравнении с другими методами, она может занять больше времени. Микробная активность может снижаться из-за воздействия изменений экологических условий, которые невозможно контролировать, что может привести к сезонным колебаниям. Микроорганизмы могут потребовать больше энергии и питательных веществ для роста клеток. Поэтому может потребоваться добавление питательных веществ в существующие отходы [13]. Когда условия не являются оптимальными, способность к разложению может снизиться. В таких случаях, хотя предпочтение отдается природным микроорганизмам, возможно потребуются использование генетически модифицированных микроорганизмов [14]. Кроме того, биоремедиация на месте ограничена глубиной почвы, что влияет на эффективность очистки.

Техники биоремедиации на месте (*in-situ*)

С помощью техник биоремедиации на месте загрязнители разлагаются природными микроорганизмами, которые используют их как источник энергии и живут и развиваются в данной области. Биологическое разложение на месте — это процесс,

при котором с помощью циркулирующих водных растворов в почву вводятся кислород и питательные вещества, чтобы активировать бактерии, живущие в этом окружающем среде, для разложения органических загрязнителей [15].

Техники биоремедиации на месте в целом используются для удаления галогенсодержащих полуволатильных органических загрязнителей, таких как дизельное топливо и масла. Контролировать биоремедиацию на месте сложнее, чем на выемке (ex-situ), поскольку экспериментальные контролируемые меры обычно невозможны в загрязненной почве.

Аэробные микроорганизмы обладают способностью разлагать нефтяные продукты, такие как бензол, толуол, этилбензол и ксилол (ВТЕХ). Активность изолированных сообществ микроорганизмов была проверена в полевых условиях. Изолированные 4 микробных сообщества были применены на загрязненную территорию. В результате биоремедиации на месте, спустя 7 месяцев, был достигнут уровень удаления загрязнителей: 95% для бензола и толуола, 81% для этилбензола и 80% для ксилола [16].

Brito и др. [17] в своем исследовании показали, что с помощью природного бактериального консорциума (НВС) можно восстановить почву, загрязненную нефтью, в экосистеме мангровых деревьев (растение, растущее в тропических экосистемах).

Также было доказано, что почву, загрязненную полиароматическими углеводородами (РАН), которые накапливаются в природе в результате антропогенных действий, таких как сжигание ископаемых видов топлива, можно восстанавливать с помощью грибов и бактерий как в аэробных, так и в анаэробных условиях с использованием техник ин-ситу [18]. Авторы [19] в своем исследовании отметили, что загрязненная почва, содержащая взрывчатые вещества, была очищена за 12 месяцев с использованием техник ин-ситу. Несмотря на длительное время, этот метод имеет преимущество за счет низкой стоимости.

Для создания подходящих условий жизни микроорганизмов в биоремедиации на месте используются две основные техники.

Биовентиляция (Очистка загрязненной почвы с помощью инъекции воздуха в насыщенную почву)

В этом методе атмосферный воздух подается через специальные трубы в почву выше уровня водоносного слоя в насыщенной почве, чтобы обеспечить микроорганизмам необходимый кислород. В этом процессе биологическое разложение осуществляется микроорганизмами, присутствующими в почве. Введенный в почву воздух или кислород не только помогает биологическому разложению, но и выполняет функцию транспортировки летучих органических веществ и CO_2 на поверхность с потоком воздуха. Этот метод успешно применяется для очистки загрязненных почв, содержащих углеводороды нефти, хлорированные растворители, некоторые пестициды, средства защиты растений и другие органические химикаты. Однако

этот метод, как правило, не рекомендуется для очистки от неорганических загрязнителей [20].

Инъекция перекиси водорода

В этом методе кислород подается в почву в жидкой форме через инъекцию перекиси водорода. В этом методе, основанном на химическом окислении, перекись водорода используется как окислитель для преобразования углеводородов в углекислый газ и воду. Изменение типа и характеристик органических и неорганических компонентов в почве происходит благодаря окислительным процессам, инициированным радикалом $\text{OH}\cdot$ [21]. Растворенный кислород обычно ограничен в биологическом превращении органических загрязнителей. В процессе аэробного метаболизма возникает значительная потребность в биологическом кислороде. Добавление перекиси водорода увеличивает окислительную способность в загрязненной области [22]. При определении необходимой дозы перекиси водорода обязательно следует учитывать скорость утраты окислителя. Органическое вещество почвы и органические загрязнители конкурируют за перекись водорода. Поэтому органическое вещество почвы является важным фактором при определении дозы окислителя. В своем исследовании авторы [23] изучили взаимосвязь между перекисью водорода и почвой при нейтральном pH и 20°C. Они обнаружили, что в почвах с высоким содержанием органического вещества скорость разложения перекиси водорода увеличивается.

Этот метод обычно применяется для очистки ранее загрязненных подземных вод и территорий с ограниченным загрязнением.

Техники биоремедиации, не проводимые на месте (ex-situ)

Этот метод требует выемки почвы из естественного окружения. Его целью является облегчение микробного разложения. Методы экс-ситу биоремедиации, проводимые вдали от загрязненного участка, быстрее, чем методы ин-ситу. Они могут быть применены для загрязнителей, распространенных на большой площади, но являются более дорогими [4]. В исследовании [16], проведенном в лабораторных условиях с использованием аэробных культур, было установлено, что разложение нефтяных производных, таких как бензол (84%), толуол (86%), этилбензол (80%) и ксилол (82%) составило значительные проценты. В исследовании сообщается, что методы экс-ситу достигли 90% удаления хлоробензолов из почвы за 2-3 недели. Кроме того, экс-ситу техники успешно применяются для удаления углеводородов из почвы [24].

В зависимости от того, проводится ли восстановление в специальных резервуарах или на подготовленных грунтах, экс-ситу биоремедиация включает две технологии:

Процесс в водной фазе (Биореакторы)

Биореакторы являются важнейшим видом экс-ситу техники. Наилучший вариант для биоремедиации почвы, загрязненной устойчивыми и токсичными загрязнителями, с контролем условий окружающей среды — это метод биореакторов [25,26]. Уровень удаления загрязнителей зависит от способности активных микроорганизмов в системе к

разложению загрязняющих веществ [27,28]. Эти реакторы классифицируются как дискретные, полусовременные и постоянные. В общем, предпочтение отдается дискретным реакторам. Также существуют системы, использующие различные электронные акцепторы: аэробные (молекулярный кислород), анаэробные (сульфаты, метаногенные, ферментационные) и смешанные электронные акцепторы [29].

Биореакторная очистка с водной фазой является более быстрым методом по сравнению с другими методами очистки. Почва с загрязнителями извлекается с участка с помощью специализированного оборудования, затем перемешивается с водой в специальных резервуарах, где уже находятся микроорганизмы, которые естественным образом присутствуют в почве. После этого добавляются кислород и питательные вещества. Для поддержания биологической активности микроорганизмов и обеспечения оптимальных условий контролируются температура, концентрация питательных веществ и кислорода. Этот метод имеет такие преимущества, как повышение скорости переноса массы и соотношения микроорганизмов/загрязнителей/питательных веществ, возможность использования различных электронных акцепторов, увеличение разложения загрязнителей с использованием сурфактантов и растворителей, оптимизация и контроль экологических условий [30,4].

В исследовании [31] было отмечено, что биореакторы могут быть эффективным экс-ситу методом для очистки почвы, загрязненной токсичными и устойчивыми к разложению веществами, такими как углеводороды и некоторые органохлорные соединения. В исследовании [32] было показано, что возможно очищение почвы, загрязненной пиреном, в дискретных биореакторах при анаэробных-анаэробных-анаэробных условиях. В этом исследовании время ожидания было выбрано 120 часов, нагрузка — 20 кг/м³.сутки, температура — 28±2°C, и 6 различных реакторов работали с различными концентрациями субстрата. Некоторые реакторы были инокулированы бытовыми осадками для усиления биологического разложения. Результаты показали, что в реакторах с добавлением бытовых осадков разложение было более эффективным по сравнению с реакторами без добавления осадков.

Другим важным загрязнителем являются полиароматические углеводороды (ПАУ), которые могут быть удалены как в аэробных, так и в анаэробных биореакторах, как показано в исследованиях. Метаболические функции (аэробные, анаэробные, анаэробные), условия одиночного или смешанного микросреды, естественная смешанная микрофлора и условия инокуляции могут быть использованы и контролироваться в биореакторах для разложения ПАУ. Токсичность и гидрофобность ПАУ, состав почвы и гетерогенные микробиологические условия могут усложнять биоремедиацию [32]. В исследовании [33] было показано, что биореакторы, использующие экс-ситу биоремедиацию, мо-

гут быть использованы для удаления ПАУ из очистных шламов. Для ускорения биологического разложения был использован *Proteiniphilum acetatigenes*, что привело к разложению на 80% при биотических и абиотических условиях.

Каталитическая обработка твердой фазы

В этом методе загрязненная почва подвергается обработке на подготовленных площадках. Этот метод более дешев, чем методы с использованием водной фазы, но менее эффективен и требует более длительного времени. Известно, что этот метод, также называемый образованием биокуч, используется для уменьшения концентрации нефтяных дериватов, ПАУ (полиароматических углеводородов), взрывчатых веществ, пестицидов и других хлорорганических загрязнителей в почве, которая была вынута из места загрязнения [34,30,31]. Эта технология заключается в том, что загрязненная почва укладывается в кучки, в которые добавляются кислород, минералы, питательные вещества и влага для активизации микробной активности в почве.

Для реализации этого метода очистки используются две основные техники. Они следующие:

Земельное улучшение (Land Farming)

Земельное улучшение или земельное применение — это технология, которая уменьшает концентрацию загрязняющих веществ в почве путем биологического разложения [35]. Эта технология обычно включает распределение загрязненной почвы, выкопанной с загрязненного участка, на другой участок в тонкий слой, с добавлением кислорода и/или минералов, питательных веществ и влаги для стимуляции аэробной микробной активности в почве. Увеличение микробной активности вызывает разложение загрязняющих веществ, адсорбированных в почве, в результате микробного дыхания. Почва, извлеченная из естественного окружения, расстилается на специально подготовленной поверхности. Здесь для ускорения биологической активности и облегчения аэрации почва регулярно перемешивается и переворачивается.

Микроорганизмы требуют таких неорганических питательных веществ, как азот и фосфор, для поддержания биологического разложения и стимулирования их клеточного роста. Поэтому при необходимости добавляются питательные вещества. Недостаток питательных веществ и кислорода замедляет биологическое разложение [36]. Если загрязнение почвы не слишком глубоко (на глубине менее 90 см от поверхности), можно эффективно стимулировать микробную активность, не выкапывая почву. Функционирование микроорганизмов зависит от характеристик почвы, летучести загрязняющих веществ и климатических условий, которые являются определяющими факторами при применении этой технологии [37]. Эти условия должны учитываться при проектировании земельного применения и регулярно контролироваться. Для этого необходимо создать контрольный план. Этот метод обычно применяется для углеводородного загрязнения, распространившегося на глубину от 0,3 до 1 м. В течение процесса углеводороды удаляются из

окружающей среды путем испарения или комбинированного процесса биологического разложения.

Техника земельного улучшения

Техника земельного улучшения успешно применяется в жарком южном климате [38]. Например, в Австралии в ходе 12-месячного операционного исследования уровень общего нефтяного углеводорода (ТНУ) был снижен с 4644 ppm до 100 ppm [39].

Однако в холодных климатах, таких как Антарктика и Арктика, результаты применения техники земельного улучшения были различными [40,39]. Исследования показали, что микроорганизмы, находящиеся в загрязненных углеводородами территориях, могут адаптироваться к холодным условиям [41].

Авторы [42] провели исследование, взяв образцы загрязненной дизелем почвы с бывшей военной базы и создав условия для земельных экспериментов при среднем температурном режиме +3°C в летний период. В ходе исследования было спроектировано четыре пилотных участка с различными режимами аэрации: с ежедневной аэрацией, с аэрацией раз в четыре дня, с добавлением питательных веществ и с аэрацией раз в четыре дня, а также контрольный участок.

Результаты показали, что на участке с добавлением питательных веществ уровень ТНУ снизился более чем на 90%. На участках с ежедневной аэрацией и с аэрацией раз в четыре дня уровень удаления загрязнений составил 80% [42]. Эти данные подтверждаются результатами успешных исследований по технике улучшения земель, проведенными [43,44].

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ECONOMIC SCIENCES

DRIVING FACTORS FOR THE DEVELOPMENT OF REGIONAL HIGHER EDUCATIONAL SYSTEMS

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<https://doi.org/10.5281/zenodo.15298375>

Abstract

Higher education is undergoing a significant transformation in Georgia and around the world. Universities and the state have to solve complex and sometimes multidirectional problems. Analysis of theoretical studies of the types of universities and the factors that determine them allows us to form an idea of possible development drivers, and a multiparameter methodology for assessing the state of higher education will enable us to identify the factors that have the most significant impact on changes in the state of higher education. The study showed that the factors affecting the development of the higher education system depend on the university's development strategy and economic model, as well as state programs containing recommendations for developing the educational environment. The presence of a leading university in the region significantly impacts the development of regional higher education systems, since the creation of such universities was initially aimed at accelerated development. This situation is economically conditioned and explained by the high dependence of universities on the state budget. At the same time, based on the leading university, an academic environment is formed for research, teaching staff, and students. It is the activity of research and teaching staff in research activities, and students in the academic sphere, that positively affect the dynamics of the development of regional systems. The growing gap between the leading universities and other universities leads to monopolization, reduced competition, and, as a consequence, a decrease in the efficiency of activities. There is a need for structural restructuring. The private factors influencing the development of the higher education system include indicators of scientific activity and student performance. The conducted analysis allows us to assert that the recorded trends will intensify and further differentiation of regional higher education systems will be observed with a simultaneous improvement in individual universities' research and educational characteristics. However, due to the growing disproportions in their development, a separate study is needed on the feasibility of structural restructuring within regional systems.

Keywords: higher education institutions, typology, rankings, regional university, scientific and educational activities, development factors, competitiveness of the university

Introduction

Higher education is undergoing a significant transformation in Georgia and the world. At the same time, universities and the state solve multiple, sometimes multidirectional problems related to determining the place of universities in the economic system. Universities in modern realities are considered, firstly, as part of the socio-economic system of the state, solving problems of improving the quality of human resources, the compliance of graduates with the needs of the labor market, and, secondly, as independent economic entities of the economy, choosing a development strategy to increase their financial independence and competitiveness. At the same time, the domestic system of higher education in general, and universities in particular, is heavily dependent on government funding, unlike such types of foreign universities as entrepreneurial and research [1] (although for some universities, these are intertwined characteristics).

Nevertheless, both are guided by indicators that characterize their effectiveness and competitiveness in the struggle for stakeholder resources and in implementing socially significant functions assigned to the higher education system. The study presented in this article is focused on the Georgian higher education system. The research question is to form an idea of possi-

ble development drivers through the analysis of theoretical studies of the types of universities and the factors that determine them, and to identify the factors that have the most significant impact on its change in the set of specified indicators based on the multiparameter methodology for assessing the state of higher education [2]. The indicators of the state of higher education used in the method reflect all the specifics of the state policy priorities for developing higher education institutions. When conducting the study, we made several assumptions: universities are mainly financed from the federal budget of Georgia, the share of regional and local budget funds is insignificant, the activities of universities are focused on development roadmaps, state assignment indicators, and this is an indicative guideline for the development of universities. Much attention is paid to the concept of a factor or driver of organizational development in the theory of strategic management and other holistic concepts of organization management, such as the theory of evaluation and cost management [3].

According to these approaches, the drivers of an organization's development include factors of the external environment, organizational parameters, and performance standards, as well as the long-term dynamics that determine the size of income and expenses and, accordingly, the ability to invest in development. From

this point of view, the drivers of a university's development may include the number of researchers actively engaged in scientific activities, the volume and structure of the student body, the proportion of foreign researchers and teachers, the level of salaries of researchers and teachers, the level of cost per student, etc. When choosing factors for research, an important task is to form a set of indicators that allow the assessment of the phenomenon under study correctly and the formulation of hypotheses for solutions in further development. We believe the difference in using the term "driver" or "factor" is conditional.

However, the term "driver" is more often used where it is necessary to emphasize the phenomenon's primary nature for the organization's development. The term "driver" is included in the article's title. And one more important addition: the drivers are predetermined by the goals facing the universities, their development strategy, as well as potential, and therefore the drivers themselves, expressed in quantitative indicators, are included in the methods of rating, typology, and evaluation of the effectiveness of universities. For example, achieving certain positions in the rating system characterizes the university's competitiveness relative to other universities in this system. In these systems, a set of criteria is predetermined by which the activities of institutions are assessed and which, at the same time, are factors, the orientation towards which contributes to the development of universities. The situation is different with the typology of universities, designed to differentiate institutions according to specified criteria. Again, these criteria are factors in classifying a university into one type or another. Ratings and typologies have different natures of influence on the higher education system: ratings are designed to equalize universities and establish uniform criteria for all, while the boundaries of typology (for example, as in the methodology for monitoring the effectiveness of universities) and ratings level everything, reducing diversity, without which there is no development; this opinion has been expressed more than once in scientific circles (for example, [4 p. 9; 5 p. 25; 6]). There is another approach to assessing the significance of rankings, which includes the assumption that competition, high performance, and openness allow universities and higher education systems to be more sustainable and better adapt to global challenges. In contrast, scientific performance, in turn, indicates the universities' ability to produce global intellectual products. It also forms their status among other universities, future students, and financial capital [7].

As for the Georgian practice of developing universities, since domestic universities have predominantly state funding, their development is significantly influenced by state strategies. At the same time, R&D funds from scientific foundations are also state funding. However, in this entire system of differentiating universities (typification, ranking, and development strategies), there are deeper theoretical assumptions presented by theories about:

resource dependence [8, p. 222] the essence of which is that organizations are dependent on the environment external to them, and, at the same time, can influence the environments in which they operate, D.S. Elliott [10], P. Benneworth [11], K. Brown [12] on the influence of universities on regional development);

stakeholders [13], representing the organization through a set of entities that require its activities, and the organization's development is presented by considering the interests and requirements of these entities.

In general, the essence of both theories is that universities' activities depend on stakeholders' funding. Therefore, the development drivers should focus on the funded entities' requirements and interests. At the same time, Burton R. Clark [14, p. 143] introduces the concept of a coordination triangle, which unites both designated theories. Through the prism of the coordination triangle, it seems possible to consider the ongoing changes in the scale and structure of the higher education system as a result of the interaction and constantly changing degrees of influence of the three main power groups involved in management - the state, the market, and the academic community. The basics of the stakeholder approach, which consist of the fact that each structure strives to obtain the maximum benefit from the investment of its funds, allow us to conclude the belonging of the elements of differentiation of universities to powerful groups. For example, in the work of J.A. Bartelse and F.A. van Vught [4], the typology of universities is based on the criteria for stakeholders' choice of an institution. Suppose the universities' ranking system and typology are aimed at a large circle of stakeholders (households, academic communities, government bodies). In that case, the assessment of the efficiency of the universities, which is not assumed either in the typology or in the ranking, serves as an instrument of advantage for government bodies, which are the primary source of financing for Georgian public educational institutions.

Thus, the factors that contribute to the change in the state of universities and affect their activities are predetermined by the university's development strategy and its type [15]. In this regard, the factors should be divided into groups. As a result, the task of identifying these groups arises, but at the same time, a discussion arises about the purpose of the factors:

They should be used to assess the efficiency of the universities of the entire higher education system (for example, as presented in the new (2016) [16] methodology of the Carnegie Institute);

They should be used to differentiate the focus of the activities of universities by their potential and, possibly, for subsequent decisions on their further state funding and to narrow the circle of potential participants in grants from scientific foundations.

Differentiation of universities and their activity strategies

It is more logical to define factors through the prism of the diversity of universities in the context of the stakeholder approach. The following approaches to classifying universities are distinguished in international and Georgian practice.

Table 1.

Stakeholder approach to the differentiation of universities	
Name of the approach	Representative
Fixing the current state of affairs	Monitoring the effectiveness of the Ministry of Science and Higher Education of Georgia: effective, ineffective
	Classification of universities of the scientific laboratory of the UU: high, average, and low level of development [2, p. 15]
Grouping of universities Name of the approach Fixing the current state of affairs	Classification of J. G. Wissem: "educational"; "research" [19, pp. 62-63].
	Classification of M. Trow: "elite", "mass", and "universal" [20, p. 1]
	Classification of the Institute of Education of the National Research University Higher School of Economics: "niche universities" (clusters 1 and 3), "universities of uncertain position" (cluster 5), "market leaders" (cluster 2), "potential and actual scientific and educational leaders" (cluster 4), "universities in good standing" (cluster 6) [17, p. 58], as well as research and educational with the allocation of intermediate clusters only for the second type [21, p. 46]
	Classification of universities of the scientific laboratory of the UU: teaching university with a research component, a research university with a low teaching load, a teaching university, a research university with a high teaching load [15]

The first one records the current state of affairs. In this case, the specifics of the educational institution can be highlighted (for example, by the level of education, the range of disciplines studied, etc.). An example of this group is the Monitoring of the effectiveness of the Ministry of Science and Higher Education, within the framework of which universities are divided into effective and ineffective. Many scientific publications consider the second approach to classifying universities, including formal and informal classifications, considering universities' horizontal and vertical differentiation [15, 18].

The entire diversity of universities fits into these two approaches. In contrast, the second approach can, in turn, be specified into universities with clear boundaries (for example, the classifications of J. G. Wissem and M. Trow) and intermediate ones, such as scientific and educational universities. Let us outline some points that can expand the understanding of the differentiation of the higher education system and its elements (universities). Firstly, these ranking systems do not directly identify the type of universities. Still, it is assumed that every n-th group (for example, top 10, or 20, 30, 50, etc.) in the ranking can be attributed to universities of the same level or type. We found confirmation of this in the article by J. Salmi and I. D. Froumin, who note that universities included in the top 20 or top 30 have similar characteristics [22, p. 10], in addition, rankings (for example, QS, THE, ARWU) are primarily aimed at ranking research universities, since among the main criteria, the largest share (at least 60%) is made up of indicators of scientific activity of universities, academic reputation, which, is formed based on the implementation of joint research, grants, preparation of scientific articles, and recognition of the university by large research projects [2, pp. 35–43].

Secondly, the concept of the flagship university of D. Douglas [23], which acquired a new impetus with the creation of research universities, is of exceptional relevance for developing the Georgian higher education system. At the same time, these universities are the drivers of the development of regional higher education

systems. The prospects for Georgia of this format are also undeniable. Thirdly, another significant element in the differentiation system is the economic strategy for the development of the university, taking into account the financial characteristics and needs of the region and changing the direction of the activities of universities, while in the conditions of the "quasi-market" universities can independently choose a strategy for the implementation of their entrepreneurial activities[25].

In the work of B. Jongbeld [26], it is noted that there is uncertainty regarding the availability, quality, and effectiveness of higher education institutions and their entrepreneurial activities in the new conditions. It should be noted that insufficient protection of higher education institutions from unfavorable economic conditions is one of the main threats to the development of the higher education system, in connection with which there may be a need for greater government participation in maintaining the sustainability of the functioning of higher education systems.

However, the economic model for a university must be considered from a different angle. Even though Georgian state universities have entered the phase of market relations, the issue of formation and management of financial flows of universities is acute, how universities can increase the extra-budgetary part of financing (in kind) and obtain a synergistic effect from the interaction of budgetary and extra-budgetary funding by increasing the efficiency of regulation and taking into account the influence of resonance in the impact of financial flows on the development of the university. However, this article does not aim to identify the relationship between financing and the type of university and determine the factors influencing funding; we will leave this issue open for further research.

Factors Affecting the Change in the Status of Universities. Despite the differentiation of the higher education system, there is not always a clear understanding of the parameters to distinguish the types of universities and how these parameters affect the efficiency of management. However, we have repeatedly seen a lack of clear criteria.

Some works identify criteria for determining a particular type of university; among such works, we can present:

- the classification developed at the University of Twente [27, pp. 14–17], which clearly distinguishes between the indicators of scientific and educational activities;
- the typology of European universities by Bartelse, van Vught [4], one of the features of the work is the allocation of regional interaction (the number of first-year students living in the region of the university, the proportion of graduates employed in the area, the share of expenses from regional and municipal authorities);
- monitoring the performance of higher education institutions, which identifies criteria that determine the performance efficiency (educational, research, and eight blocks in total). The specified methodology considers regional characteristics (indicator: the ratio of the average salary of academic staff in an educational institution (from all sources) to the average salary in the regional economy) by the adopted threshold values, which is an advantage of the methodology. Today, there is no clear distinction between indicators by type of activity, but their typology is interesting from the point of view of threshold values for assessing the performance efficiency of universities; in fact, their classification is close to that proposed by M. Troui [20, p. 1]. M. Troui noted that elite education is characterized by an emphasis on research activities and a high intellectual level of students, while in mass education, research activities are minimal. The factors that determine a world-class university also include a highly qualified faculty, particularly successful research results, excellent quality of the educational process (teaching and learning), active involvement of state and non-state sources of funding, an international and highly talented contingent of students, academic freedom, clearly defined management structures, as well as good technical equipment for the educational and research processes, administrative management [28, pp. 5–8; 29, pp. 765–768; 30, pp. 61–74; 31]. The works of Philip G. Altbach, Jorge Balan [32], Jamil Salmi [33], and Delft Johan Wissem [19, p. 62] indicate the parameters that research universities should meet.

On the one hand, we can assume that the quality of education should be a priority factor in determining students' choice of university. But on the other hand, the findings presented in the works of Y. Morgan [35] and R. James [36] and their co-authors speak of the priority of the prestige of the university over the quality of education, in addition, James et al. point to the average scores of entrance exams as a criterion of quality in the eyes of the student. Research shows a correlation between entrance scores and students' academic performance at the university [37]. Georgian researchers say that the Unified State Exam scores explain academic

performance by 23–37% [38–39]. At the very beginning, we asked ourselves how the factors influencing the development of universities should reflect regional characteristics. We gradually concluded that the region mainly trains specialists and carries out developments, primarily for the domestic market and, in particular, for its region. Thus, the factors should reflect the state of universities:

1. taking into account the socio-economic situation of the region (for example, the adjusted salaries of the scientific and teaching staff of the university, the contingent taking into account the demographic indicators of the area, the focus of the university taking into account the natural and climatic features - agricultural, metallurgical, etc. region);

2. taking into account the priorities of government bodies, that is, the presence of flagship, federal, research universities in the region. In this case, it is necessary to highlight the contribution of these universities to the general system of higher education in the area.

3. taking into account the creation of a point of excellence in the region that can ensure maximum competence of personnel in a particular area to facilitate the development of promising projects, technologies, industries (for example, in Germany, the priority areas for support and financing are energy, the environment (ecology) and food security, the healthcare system, mobile and information technologies, in France (Grenoble) biotechnology and nuclear physics have been added to the list [40]).

Let us note important methodological points regarding further research.

Firstly, despite the entire list of indicators determining a particular type, practical studies are still limited primarily to official statistics.

Secondly, our study concerns regional higher education systems, identifying the factors that impact their condition most, based on an assessment of their overall development according to the stated indicators. Thus, on the one hand, we have types of universities that can be enclosed within uniform territorial boundaries; on the other hand, given the existing diversity, it is necessary to assess the regional higher education system as a whole. We see the solution in a multi-parameter assessment that identifies indicators characterizing each type of activity (research, education).

Thirdly, to analyze the entire system, it is erroneous to average the indicators of a typical (model) object. In this regard, the solution to the problem comes down to differentiating the system, as was shown earlier, or (from a methodological point of view) to analyzing the regional characteristics of universities [21] and educational systems [44, 45] through the identification of clusters. In our methodology, which is used to assess and identify drivers, regional characteristics are determined through differences in threshold levels [2], considering the region's socio-economic situation and the availability of priority programs, particularly for the development of educational institutions.

Table 2.

Key factors in the development of higher education systems in the constituent Regions of Georgia			
Region of Georgia	Block	Module	Indicator
Tbilisi	Block 2. The state of educational and research activities in the system of higher education	An indicator of the effectiveness of scientific research activities of the higher education system	The specific number of publications in journals indexed in the Web of Science and Scopus databases per one faculty member, units/100 people.
		An indicator of the educational and research potential of students	The specific number of students receiving personal scholarships, winners of Olympiads (competitions), %
Kutaisi (Imereti Region)		An indicator of the educational and research potential of students	The specific number of students receiving personal scholarships, winners of Olympiads (competitions), %
		An indicator of the effectiveness of scientific research activities of the higher education system	The number of publications in journals indexed in the RSCI databases per faculty member, units/100 people.
			The number of publications in journals indexed in the Web of Science and Scopus databases per faculty member, units/100 people.
Batumi (Adjara Region)		An indicator of the effectiveness of scientific research activities of the higher education system	The number of publications in journals indexed in the RSCI databases per faculty member, units/100 people.
			The specific number of publications in publications indexed in the Web of Science, Scopus databases per one faculty member, units/100 people
Gori (Kartli)		An indicator of the effectiveness of scientific research activities of the higher education system	The specific indicator of the number of supported patents per faculty member, units/1000 people
		An indicator of the educational and research potential of students	The specific number of students receiving personal scholarships, winners of Olympiads (competitions), %
Telavi (Kakheti)		An indicator of the effectiveness of scientific research activities of the higher education system	The specific number of publications in publications indexed in the Web of Science, Scopus databases per faculty member, units/100 people

Factors Contributing to a Change in the State of the Higher Education System in the Regions of Georgia. To determine the factors contributing to a change in the state of the higher education system in the subjects of Georgia, at the first stage, we conducted diagnostics using the previously developed methodology [2]. The factors that impact the state change most were identified at the second stage.

The assessment of the state of the higher education system in the subjects of Georgia allowed us to determine the TOP-10 leading regions by the final development indicator (Fig.). These subjects have demonstrated a steady improvement in the final indicator characterizing the state of the higher education system for the analyzed period of 2009–2018.

In order to achieve the goal of the article, an analysis of the top 10 regional higher education systems was conducted to determine the drivers of their development.

Based on the diagnostics of the state of the higher education system in Georgia, the factors that have the most significant positive impact on the development of regional higher education systems were identified (Table 2). We include those factors contributing to a change in the state, due to which the characteristics of the system change. The rest, which were not classified as drivers, showed relative stability and constant values over 10 years (for example, the average USE score, the workload of the teaching staff, etc.). Despite a reasonably long period, changes in the operating conditions in the infrastructure and financial sphere have not become a driver of development, as noted earlier, this indicator is one of those that are subject to fewer fluctuations and

have a stable value, which, in general, has a good value for the systems. The leading regions in the period 2019–2024 demonstrate sustainable development of their systems, and the improvement in the state occurs due to high ratings of educational and research activities in the higher education system. The main driver of higher education development for most of the analyzed entities (90%) was a significant increase in the publication activity of the academic staff. This indicator turned out to be the most changeable and responsive to higher education development strategies. The regions included in the TOP-10 are characterized by a high specific number of publications in publications indexed in the Web of Science and Scopus databases per academic staff member. At the same time, most of the analyzed entities did not occupy leading positions in the number of publications in publications indexed in the RSCI databases (except the Perm Territory and the Samara Region).

The factors that have a positive impact on the state of the higher education system of the leading regions also include the indicator characterizing the level of student training (in 2019–2024, there was a significant increase in the number of students receiving personal scholarships and winners of Olympiads (competitions)). High values for this indicator allowed 40% of regions to improve their assessment of the state of the higher education system in 2019–2024.

It should be noted that for the Belgorod Region, one of the drivers for the development of the higher education system was an increase in the level of innovative activity of the academic staff. The region is leading in the number of supported patents per research fellow.

Tbilisi is the absolute leader in assessing the state of the higher education system in 2019–2023. In 2022, the improvement in the position was due to high assessments of the effectiveness of research activities of the higher education system, in particular, due to an increase in the level of publication activity of research fellows. The capital's universities occupied leading positions in the number of publications in journals indexed in the Web of Science and Scopus databases per research fellow.

Thus, it can be noted that flagship universities (the country's leading universities) are of decisive importance in developing regional higher education systems. In contrast, the systems are more evenly developed than their elements if there are 2–3 such universities (Table 3).

Conclusion

The study's theoretical framework shows that the factors influencing the development of the higher education system depend on several factors, such as the development strategy and economic model of the university, as well as the state programs of the country for the development of the educational environment. These elements generate a diversity of universities, organized through typology, ranking, and diagnostic methods.

For example, in the system of world rankings (QS, THE, ARWU), priority is given to scientific activity (about 60%), typology in a simplified form divides universities into educational and research, mass and elite, the development of which is influenced by different factors. Thus, for mass and educational universities, the emphasis is on the number of students. The development of elite and research universities is influenced by indicators of scientific activity and the quality of human potential, including applicants, students, and academic staff. As for determining the factors affecting the development of regional higher education systems, several approaches can be distinguished in the existing practice: equalization of regions, clustering of regional systems, and diagnostics with the allocation of regional features through threshold values.

This study identifies the growth drivers of regional systems, considering regional features for a wide range of indicators. At the same time, based on a multi-year analysis, it is concluded that, despite the long analysis period, changes in the operating conditions in the infrastructure and financial spheres did not become the primary driver of development. However, this conclusion once again emphasizes the validity of the approach developed in the concepts of organization management, within which financial and economic indicators follow the dynamics of development drivers, and not vice versa.

Among the main factors influencing the development of regional higher education systems, the presence of a leading university in the region is worth noting. This situation is explained, in particular, by financing Georgian universities, which have a high dependence on the state budget. However, the presence of a leading university is significant not in itself, but as an academic environment for the activity of scientific and pedagogical workers and students. The faculty's research activities and students' scholarly activity have

significantly increased the development indicators of regional systems.

The private factors influencing the development of the higher education system include indicators of scientific activity (publication activity of the faculty and patent activity), the quality of students (their participation in Olympiads, receiving scholarships, etc.), for the regions - the leaders of the top 10 - the ratio of the designated indicators. It is indicative that the material equipment, the university's structural composition, and the teaching staff's workload are not selected among the factors; the explanation lies in the insignificant change in these indicators. The first two indicators have high ratings, which cannot be said about the last one, but we assume that this indicator predetermines the university's essential trends. The analysis of the composition of target indicators and activities of the national projects "Education" and "Science", the federal project "Personnel for the Digital Economy", allows us to assert that the recorded trends will intensify. We will observe an improvement in the parametric methodology used to assess the state. Two indicators were identified: insensitive, the value of which is stable, and for almost 10 years, its value was constant; sensitive, which turned out to be sensitive to university reform measures. Thus, an essential conclusion of individual universities' research and educational characteristics. However, a separate study on the feasibility of structural restructuring within regional systems concerning the growing imbalances in their development is needed. The events of the first half of 2020 exacerbate many imbalances and increase the relevance of such studies. At the same time, it will be necessary to consider the specifics of the non-profit sector and public entrepreneurship, which are actively discussed today by experts and researchers, considering both the federal and regional components.

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RESEARCH ON THE DEVELOPMENT PROSPECTS OF AUDIT ACTIVITIES IN THE CONTEXT OF ECONOMIC DIGITALIZATION

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<https://doi.org/10.5281/zenodo.15298377>

Abstract

With the vigorous development of the digital economy, audit activities are facing unprecedented opportunities and challenges. This paper delves into the challenges brought about by economic digitalization to audits, including data complexity, technological updates, personnel transformation, and data security. Additionally, the article looks ahead to long-term opportunities for the audit industry in areas such as stricter regulation, technological reshaping, and internationalized services, providing a useful reference for the future development of audit activities.

Keywords: economic digitalization; audit activities; development prospects; intelligent audit; data governance

1.Introduction

In today's era, the digital economy has become a core force driving global economic development. It uses data resources as key production factors, leveraging the effective application of modern information networks and information communication technologies to achieve efficiency improvements and deep optimization of economic structures.

1.1Challenges Brought by Economic Digitalization to Audits

As shown in Table 1.1 below Economic digitalization has brought new opportunities and challenges to audit activities. Some data volumes displayed by the various types of structural risks

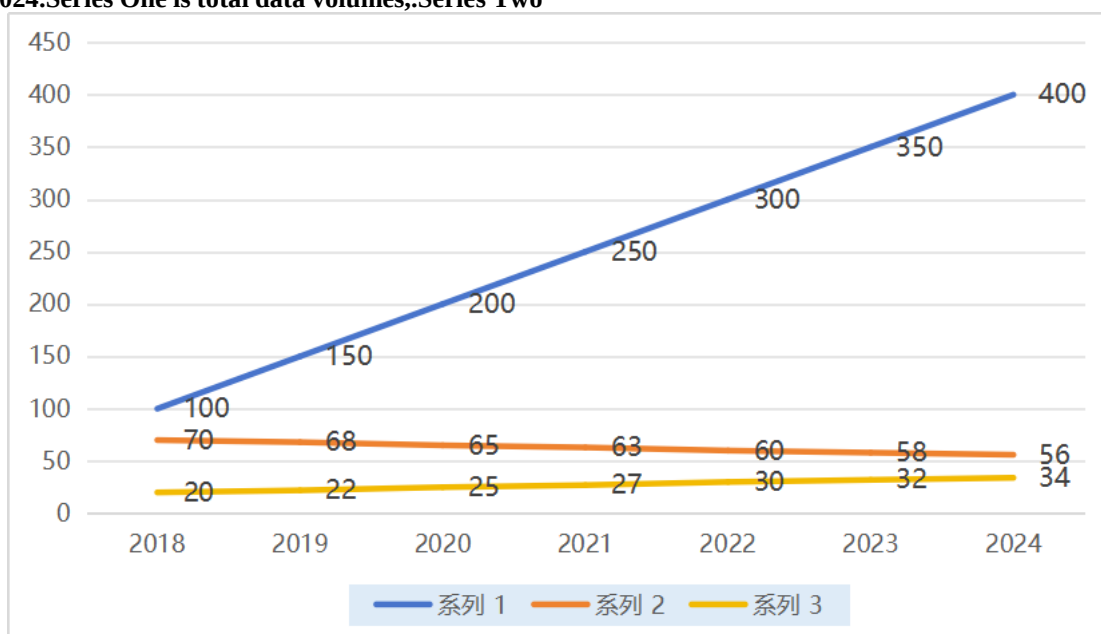
Table1.1 Some economic challenges from 2018 to 2024.Series One is total data volumes, Series Two

is structured Data(%) , Series Three is unstructured Data(%).

Table 1.1 surance:Analyze the structure in volumes of accounting and audit in recent years in xinhua netw.ork.

In the process of economic digitalization, various types of financial and business data exhibit explosive growth, with diverse data types encompassing structured and unstructured. These data not only come from a wide range of sources, external market data, but also come in various formats.

1.2 Development Strategies for Audit Activities in the Context of Economic Digitalization



As shown in Table1.2 to adapt to the development of digital technologies, audit work should accelerate technological application innovation to enhance the intelligence levels of audit work.

Accelerating Technological Application Innovation in Audits	
Strategy	Implementation status (2018-2024)
Technological Application Innovation	Gradually Increasing
Comprehensive Quality Enhancement of Auditors	Continuously Improving.
Process and Model Optimization	Continuously Optimizing
Strengthening Data Governance and Information Security	Continuously Strengthening

Table 1.2 surance: Analyze the development of digital technology in accounting and audit in the past five years in economic knowledge network.

1.3 Optimizing Audit Processes and Models

As shown in Table1.3, professional ethics and legal education should be enhanced. Auditors need to

continuously strengthen professional ethics and legal education to improve their professionalism and legal awareness, ensuring the fairness and objectivity of audit work

Table 1.3

Percentage of each data type proportion structure from 2018 to 2024.			
Year	Structured(%)	Unstructured(%)	Semi-Structured(%)
2018	70	20	10
2019	68	22	10
2020	65	25	10
2021	63	27	10
2022	60	30	10
2023	58	32	10
2024	56	34	10

Table 1.3 surance: Analyze the structure of accounting and audit for the audit of the consolidated financial statements in Newspapers and periodicals

To improve the quality and efficiency of audit work, audit processes and models should be optimized. On the one hand, remote audit models can be promoted. Remote audit models can break time and space constraints, enhancing the flexibility and efficiency of audit work. Through remote audits, auditors can access and analyze data in the information systems of audited entities in real-time, reducing the time and cost of on-site audits.

2. Long-Term Opportunities for Audit Activities in the Context of Economic Digitalization Regulatory-Driven Professional Transformation

With the implementation of the new Securities Law and the advancement of the registration system reform, the China Securities Regulatory Commission (CSRC) and the Ministry of Finance have significantly increased penalties for financial fraud and audit negligence. In the short term, compliance costs for firms have risen, and small and medium-sized institutions may exit the market due to difficulty in bearing risks. However, in the long term, strict regulation will drive the industry from "price competition" to "quality competition."

The popularization of automated tools and the explosion in demand for data audits have brought new development opportunities to the audit industry. For example, Deloitte's "Argus" platform can automatically analyze financial data anomalies, reducing basic workload by approximately 30% and allowing auditors to focus on high-risk areas. Meanwhile, the digital transformation of enterprises has driven demand for IT audits and data security audits. Institutions with relevant technologies will gain an advantage, pushing the audit industry towards higher levels of development.

3.Conclusion

Economic digitalization has brought numerous challenges to audit activities, such as data complexity, technological update needs, personnel transformation pressures, and data security. However, it has also provided new opportunities for the development of audit activities, such as technological application innovation, personnel quality improvement, process model optimization, and data governance. By accelerating technological application innovation in audits, enhancing the comprehensive quality of auditors, optimizing audit processes and models, and strengthening data governance and information security, audit activities can better adapt to the requirements of economic digitalization.

Meanwhile, the audit industry should seize long-term opportunities such as regulatory-driven professional transformation, technology reshaping audit models, and internationalization and diversified services, continuously improving its competitiveness and service levels to provide higher-quality audit services for economic development.

In the future, with the continuous development of the digital economy, audit activities will face more opportunities and challenges. Audit institutions and auditors should closely monitor the development trends of the digital economy, continuously learn and master new technologies, actively respond to various challenges, seize development opportunities, and promote the sustained and healthy development of the audit industry.

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THE IMPORTANCE OF ACCOUNTING INFORMATION IN MAKING MANAGERIAL DECISIONS**Cui Yuxiao,***Master student, 7M04118 —Accounting and audit
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Kazakh National University (Almaty, Kazakhstan)*<https://doi.org/10.5281/zenodo.15298379>**Abstract**

This paper will deeply discuss the construction mechanism of accounting information base, management strategy and its supporting role to enterprise decision-making, aiming at providing theoretical guidance and reference for enterprise managers. In modern enterprise management, accounting, as the core tool of enterprise decision information base, plays an increasingly prominent role. With the globalization of economy, the intensification of market competition and the rapid development of information technology, enterprises are faced with increasingly complex business environment and decision-making needs. Accounting information is not only a record of the financial status and operating results of an enterprise, but also an important basis for enterprise management and decision-making. Through the construction and management of efficient accounting information base, enterprises can better cope with market changes, optimize resource allocation, and improve decision-making efficiency.

Keywords: Accounting information, Accounting information base, Enterprise decision-making, Decision-making efficiency

Introduction

In modern enterprise management, accounting, as the core tool of enterprise decision information base, plays an increasingly prominent role. With the globalization of economy, the intensification of market competition and the rapid development of information technology, enterprises are faced with increasingly complex operating environment and decision-making needs. Accounting information base plays a vital role in modern enterprise management. It is not only the storage center of enterprise financial data, but also the core tool of enterprise decision support system. With the rapid development of information technology and the increasingly complex business environment, building an efficient and accurate accounting information base has become a common challenge and goal faced by enterprise managers.

The importance of accounting information

Through systematic information generation, processing, storage, transmission and application, accounting information provides enterprises with comprehensive, accurate and timely financial data support, and becomes an important basis for enterprise managers to optimize decision-making process and improve management efficiency. Accounting information is the basis of enterprise decision-making, and provides the management with comprehensive and accurate financial data and analysis reports. Through financial statements, cost accounting and budgeting, enterprises can clearly understand their financial position and operating results. Accounting information management plays an important role in enterprise management. With the help of accounting informatization, enterprises can efficiently process financial data, accurately calculate costs, and scientifically manage budgets, thus providing solid and reliable decision support for decision makers.

Accounting information is an important tool for the internal control of enterprises. By establishing a sound accounting system and internal control system, enterprises can effectively prevent and control financial risks. For example, through regular financial audits and internal control assessments, enterprises can detect and correct financial problems in a timely manner to ensure the authenticity and integrity of financial information. In addition, the accounting information system can monitor the financial activities of enterprises in real time, timely warn the potential financial risks, and help enterprises to take preventive measures.

The importance of accounting information management to enterprise management is self-evident. Through accounting informatization, enterprises can realize efficient processing of financial data, accurate accounting of costs, scientific management of budgets, and provide scientific support for decision-making. High-quality accounting information is a reasonable guarantee for the usefulness of enterprise decision making. A digital management platform can be built to realize the synchronization of industry and finance, share data and information, and refine the information content according to the needs of managers [1].

The key role of accounting information in enterprise management decision

The theoretical model of accounting information for enterprise decision support aims to provide scientific basis and method for enterprise decision making, its core is to build a systematic framework, accounting information and enterprise decision process is closely linked. This model forms a dynamic information support system by integrating the generation, processing, transmission and application of accounting information, so as to enhance the scientific and effective decision making of enterprises. If you don't take more account of accounting information, you won't make effective decisions. Management should emphasize the use

of accounting information to improve the effectiveness and efficiency of the organization's operations.

First of all, the generation of accounting information is the basic link of the model. Accounting information is generated through the recording and accounting of enterprises' daily economic activities, including financial statements, cost accounting, budgeting, etc. This information must comply with accounting standards and regulations to ensure its accuracy and reliability. Secondly, the processing of accounting information is the key link of the model. Through the accounting information system, the original data are classified, summarized and analyzed, and the financial indicators and analysis reports with decision-making value are generated. Finally, the transfer of accounting information is the guarantee link of the model. The effective information transfer mechanism ensures that the accounting information can be timely and accurately transmitted to the decision-makers within the enterprise. This includes the establishment of information sharing platforms, regular reporting systems and real-time monitoring systems. For example, companies can visually present key financial metrics to management through management cockpits or dashboards, enabling them to quickly access information and make decisions.

To sum up, the theoretical model of accounting information supporting enterprise decision-making integrates the processes of information generation, processing, transmission and application, providing a systematic decision-making support framework for enterprises [2]. This model not only enhances the scientificity and effectiveness of enterprise decision-making, but also boosts the decision-making efficiency within the enterprise. It provides a solid theoretical foundation and practical guidance for the sustainable development of enterprises.

Improving the quality of accounting information is conducive to the decision-making of enterprises

Accounting information quality is the core of enterprise financial reporting and serves as an important basis for investors, creditors and other stakeholders to make economic decisions. However, the frequent occurrence of financial fraud incidents and the problem of accounting information distortion in recent years have exposed the severe challenges faced by accounting information quality. Improving accounting information quality is not only an important topic in accounting theoretical research but also an urgent need in practice. This article will systematically explore how to enhance accounting information quality from multiple aspects such as systems, personnel and technology.

The main requirements for accounting information quality mainly include reliability, relevance, understandability, comparability and other core principles [3]. These principles form the basis of accounting information quality and any measures to enhance quality should be based on these principles. Accounting standards are the cornerstone of accounting information quality. The reform of accounting standards is an important measure to improve accounting information quality and standardize accounting calculation behaviors [4]. With the changes in economic environment

and the emergence of new economic businesses, accounting standards need to be continuously revised and improved. For example, in response to emerging fields such as digital economy and green accounting, relevant standards should be promptly formulated to fill the institutional gaps. At the same time, efforts should be made to align with International Financial Reporting Standards (IFRS) to ensure the international compatibility of domestic accounting standards.

The professional ethics of accountants serve as the intrinsic guarantee for the quality of accounting information. Through ethics training and case analysis, the professional conduct of accountants should be enhanced [5]. For instance, regular ethics lectures should be organized to share real cases and help accountants establish correct values. The professional ability of accountants directly affects the quality of accounting information. Accountants should be encouraged to continuously learn new knowledge and master the latest accounting standards and information technologies. For example, by participating in professional training, obtaining professional qualifications such as Certified Public Accountant (CPA) or Certified Management Accountant (CMA), their professional level can be improved. Similarly, accountants should possess the ability to think independently and analyze problems. In teaching, case analysis and problem-oriented teaching methods should be emphasized to cultivate students' critical thinking. For instance, by analyzing abnormal data in enterprise financial statements, students can be guided to think about the underlying economic essence and improve their problem-solving abilities.

Big data and artificial intelligence technologies can significantly enhance the generation and supervision efficiency of accounting information [6]. For instance, by using big data technology to monitor and analyze accounting data in real time, abnormal information can be detected promptly; through artificial intelligence algorithms, audit efficiency and accuracy can be improved, and human errors can be reduced.

Improving the quality of accounting information is a systematic project that requires coordinated advancement from multiple aspects such as systems, personnel, technology, and big data. By implementing measures such as improving accounting standards, strengthening internal control, enhancing the professional quality of personnel, and leveraging modern information technology, the reliability, relevance, comprehensibility, and comparability of accounting information can be effectively enhanced. This is also an important basis for investors, creditors and other stakeholders to make economic decisions.

Conclusion

Accounting work, as a crucial part of financial management, serves as an important medium connecting various production and operation activities of enterprises and institutions. It plays a significant role in achieving centralized management, allocation, and sharing of resources. Accounting information holds an important position in enterprise management. By providing timely and accurate financial information, it enables enterprises to respond quickly to market changes, optimize resource allocation, and thereby en-

hance decision-making efficiency. Through cost accounting and budget management, enterprises can rationally allocate resources, improve the efficiency of fund utilization, and optimize resource allocation. In modern enterprise operations, accounting and financial analysis processes play a key role in decision-making

effectiveness. With the changes in market environment and the improvement of management requirements, the value of accounting information and analysis systems continues to increase, providing real-time, complete, and reliable data for management to make strategic and operational decisions[7].

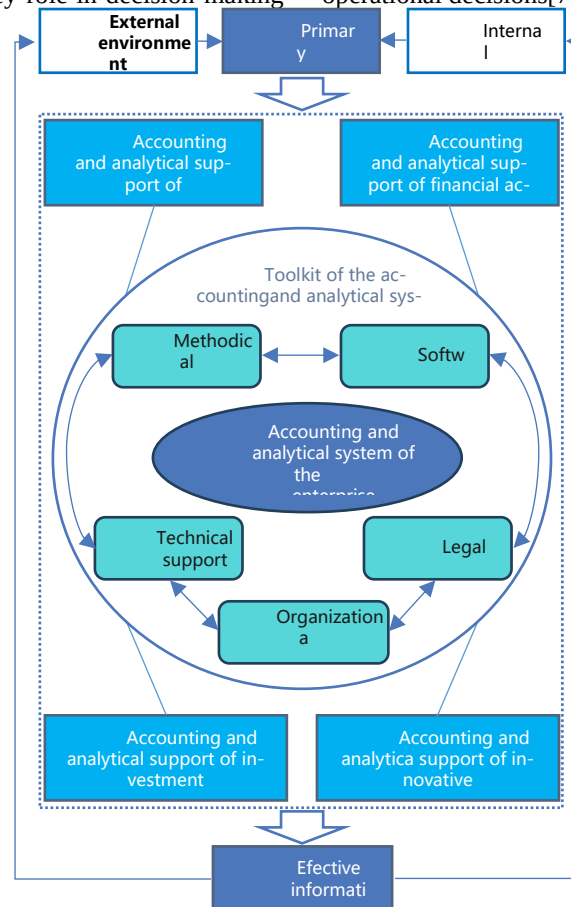


Figure 1. Location of the subsystem of accounting and analytical management of economic[7]

Information systems in a company should provide all necessary information to support decision-making. The requirement for improving the quality of accounting information not only helps enhance the management level and market competitiveness of enterprises, but also provides a solid guarantee for the healthy development of the capital market. In the future, with the changes in the economic environment and the advancement of technology, the improvement of the quality of accounting information will face new challenges and opportunities, and it is necessary to continuously explore and improve the relevant mechanisms.

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THE NATURE OF INTERNAL AUDIT AND ITS RELATIONSHIP WITH THE INTERNAL CONTROL SYSTEM

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<https://doi.org/10.5281/zenodo.15298381>

Abstract

In this article, the essence of internal audit, its role in the implementation of economic activities and the interrelationship of internal audit with the internal control system are discussed.

Keywords: internal audit, internal control, economic entities, financial condition, stability, income, strategy, costs.

Introduction. Currently, the direction of internal audit is actively developing all over the world. In many countries, internal audit is widespread in various areas of economic activity. Instead of using consulting services or outsourcing the same tasks, companies prefer to have their own structural units whose main task is to conduct internal audits.

A number of advantages of internal audit allow to focus the attention of entrepreneurs and public sector employees of Uzbekistan on this type of activity. Interest in this field is growing. Because internal audit is a cheap and effective resource that allows to increase the efficiency of the enterprise with minimal risks. Nevertheless, the field of internal audit is still not paid enough attention, as a result of which its distribution in Uzbekistan is not at the required level.

However, modern economic conditions lead to the active development of internal audit, proving once again that it is one of the crucial tasks of any organization. Uzbek companies are not only becoming a part of the world market and economic processes, but also establishing new international relations. Accordingly, the activities of companies focused on integration into global processes must comply with certain requirements and standards, with a strong focus on internal audit.

Analysis of literature on the topic.

In the COSO model, internal control and internal audit are distinguished. "Internal control is a process carried out by the highest policy-making body of the enterprise, senior management and all other employees, which adequately and reasonably ensures that the enterprise achieves the following goals:

1. Expediency and financial efficiency of activity (including preservation of assets).
2. Reliability of financial statements.
3. Compliance with legal and regulatory requirements"[1].

Internal control is "a process aimed at achieving the company's goals and is the result of the management's efforts to plan, organize, and monitor the activities of the entire company and its individual units"[1].

Internal control "includes" all the operational activities of the organization, helps to achieve the goals of the business entity as much as possible. Internal control in the enterprise constitutes a specific system.

Internal control is a process organized and carried out by the owners, management, as well as other

employees of the audited object to ensure sufficient confidence in the achievement of goals in terms of the effectiveness and efficiency of business operations and the compliance with regulatory legal documents of the audited entity's activities in terms of the reliability of financial (accounting) reports. This means that the organization and operation of the internal control system is aimed at eliminating any risks of economic activity that threaten the achievement of one of these goals.

If we turn our attention to the analysis of economic literature, we can see that there are different views on internal audit.

According to american scientists E.A. Arens and J.K. Lobbbeck, internal audit is an audit that provides management with valuable information to make decisions about the effective operation of the "business". [2].

K. B. Akhmedyanov, one of the economists of our country, says that "Internal audit is an independent system that helps economic entities to achieve the goals set on the basis of risk management, control and an acceptable approach to the corporate governance system, and provides objective guarantees and advice aimed at increasing the efficiency of financial economic activity." [3]

One of our economists, S.U. Mehmonov, paying special attention to the characteristics of budget organizations, defined the internal audit as follows, i.e. "Internal audit is an activity aimed at verifying compliance with legislation and monitoring the preparation and implementation of estimates by the organization, ensuring the reliability of financial reporting data, compliance with budget-estimate discipline, targeted and rational spending of funds".[4]

The analysis of the above definitions allows us to emphasize that internal audit contains a certain dualism, which, on the one hand, internal audit should be a mechanism for evaluating and analyzing the internal control system, and on the other hand, it should serve the purposes of improving the effectiveness of the internal control system. On the other hand, internal audit is a part of the internal control system.

Based on the conducted research, the author's definition of internal audit was developed, in which *three main principles of internal audit are taken into account: corporate governance, business process efficiency and risk management.*

Internal audit is an activity conducted within an organization to serve the interests of the owners and management. It is regulated by internal documents and involves monitoring and analyzing all aspects of business activities for compliance with current legislation. The purpose is to improve the internal control system, assess effectiveness, and develop recommendations aimed at reducing risks to an acceptable level based on audit results. Additionally, it includes consulting with employees on business matters within the scope of the auditor's authority.

Research methodology.

Our study was conducted with the aim of improving the internal audit, and tasks for the organization and improvement of the internal audit were determined. In the course of research, conclusions and proposals were developed using methods such as comparison of practical materials and statistics.

Analysis and results

Audit is closely related to internal control. Initially, internal control appeared in North America and Europe. The rapid development and spread of internal audit and internal control around the world also happened due to the unscrupulous approach of some external audit professionals to their profession. We all know the scandals that have taken place in the matter of submitting false audit reports or concluding dubious contracts for the provision of auditing services. For example, in 2011, tenders were held for the provision of audit services to Vneshekonombank, Rosselkhozbank, and "Yaku ts k e nergo" JSC.

Audit organizations that offered 13-16% of the initial price won each of them"[7]. In this case, it can be considered that audit services were provided in low quality due to the fact that the service price was deliberately lowered. The goals of such an audit will not be clear from the point of view of objectivity and efficiency, as it is carried out in the interests of the audited entity.

As another confirmation of the fact that the external audit does not carry out its activities in good faith, the following analytical research of the Bloomberg agency can be cited:

"Since 1996, there have been 673 major bankruptcies in the West, and in 54% of cases, auditors gave positive conclusions about the condition of insolvent companies before the bankruptcy" [8].

This research data proves that even the "Big Four" international audit firms have provided a biased opinion for large sums of money without adhering to the principle of impartiality in the audit of large companies.

Undoubtedly, the development of internal control and audit was motivated by the loss of assets of business entities. Therefore, they must be objective and independent in assessing the financial condition of the economic entity, especially large business representatives. The regulation that had a significant impact on the development of internal control is the "Integrated Internal Control Concept". This concept is also referred to as the COSO model for short, or the COSO model, which was developed in 1992 by the Committee of Sponsoring Organizations of the Treadway Commission.

According to the COSO framework, internal control is a process carried out by the board of directors (i.e., the company owners), management (senior executives), and other employees of the company. Its purpose is to ensure the reliability of financial reporting, compliance with legal requirements and regulatory bodies, and, in addition, to ensure the rationality and efficiency of the company's business activities.

The main aspect of the COSO model is that the implementation of internal control is the responsibility of the management of the business entity. The COSO model assumes that the internal control system is not an end in itself and is a mechanism that helps the economic entity achieve its goals. Any employee of the company is a part of the internal control system, so its effectiveness directly depends not only on internal rules and methods, but also on employees working at all levels of the team.

It would be a mistake to think that the creation and implementation of an effective internal control system in the company is an absolute guarantee that protects the business entity from various risks. Owners and management of an economic entity should remember that internal control can provide sufficient assurance, but never achieve absolute results.

It should be noted that internal control and audit ensure the achievement of a specified goal or several goals in the relevant areas of activity. But this type of activity cannot cover the entire spectrum of business processes in large companies. The COSO model later served as a basis for revising new international auditing standards. Because many new requirements have been imposed on auditors working in the field of external audit. One of the ways out of this situation is to strengthen the interaction between the internal control system and the external audit. External auditors are assigned the task of evaluating the quality of internal control in the enterprise. In addition, external auditors should find an answer to the question whether the internal control system in the enterprise prevents serious errors in accounting (financial) reports.

Today, COSO strives to develop a variety of rules, recommendations, and guidelines to manage risks, improve internal controls, and eliminate various forms of fraud and theft. Based on the set goals, the COSO model is being developed in the following directions:

1. Management of operational activities.
2. Internal control.
3. Enterprise risk management.
4. Prevention of various frauds in the preparation of financial reports.

In addition, special attention should be paid to the Sarbanes-Oxley law, which is widely used in the assessment of legislation regulating the field of internal control and auditing in the West. This legislation was adopted in the United States of America on July 30, 2002 and applies to public limited liability companies. This piece of legislation resonated for America because it significantly changed and tightened federal securities laws for the first time in sixty years.

Another important aspect to consider is the introduction of the term "Audit Committee." This refers to a committee (or equivalent body) established by the

board of directors of the issuer from among its members to oversee the rules and procedures for maintaining accounting records and preparing financial statements of the issuer. Additionally, the committee is responsible for conducting an audit of the issuer's financial statements or the full board of directors of the issuer (if no such committee exists within the issuer's structure).

The main task of the committee is to supervise the preparation of financial statements, to check compliance with accounting principles and internal control processes. In addition, the selection of the auditing company and monitoring of their activities is also the task of the committee.

The activity of the committee is directly related to the internal audit department, because in order to achieve the set goals, a part of the authority should be transferred to an independent and objective structural unit of the organization.

One of the main provisions of the Sarbanes-Oxley Act regarding internal control and auditing is Section 404, Management's Evaluation of Internal Control.

The main issue in this section is the obligation to include internal reports of the enterprise in the annual report of the joint-stock company. According to him, the managers of the economic entity are maximally responsible for the implementation of internal control procedures, which, in turn, serves to improve the effective management system.

This section sets out the necessary provisions for the annual report on internal control prepared for the company's management. These provisions include "management's responsibility for establishing and maintaining appropriate internal control systems and procedures over financial reporting" and "assessing the effectiveness of the issuer's internal control systems and procedures over the most recent fiscal year-end financial statements issued by the issuer." [9]

At the initial stage, companies want to solve the following problems with the help of the internal audit department:

1. Increasing the efficiency of the enterprise.
2. Optimization of business processes.
3. Formation of objective information about the state of the legal entity for the owners.
4. Increasing the investment attractiveness of legal entities.
5. Identification of risks in the activity of a legal entity and formation of methods of reducing these risks.

The next step is to clarify the relationship between internal audit and internal control. The concept of internal control is widely covered in current regulatory documents. Therefore, it is important to address the following questions: Is audit considered part of the internal control system, or is it a separate form of control within the enterprise? Are the concepts of internal control and internal audit synonymous?

Finding answers to these questions is of significant importance.

Analysis.

The internal control system is represented by organizational structures, methods and various procedures used by all employees. Thus, each employee can affect the effectiveness of the entity.

Creating a reasonable and effective internal control system in the enterprise depends on the following factors:

1. Organizational-legal form of the enterprise.
2. Network affiliation.
3. Form of ownership.
4. Enterprise size.
5. Specific features of the legal entity structure.

Organization of the internal control system in the enterprise is a very complex and interesting process. It is necessary to take into account the factors that make it possible to create a rational, reliable and efficient system. The creation and organization of the internal control system is part of the authority of management of economic entities.

In order to achieve the economic stability of the company, it is necessary to pay attention to the fact that the internal control system should be organized in such a way as to respond to deviations and errors in a timely manner and allow them to be eliminated as much as possible. Otherwise, widespread continuous control over the activity of each employee, each process will not give a positive result, but will lead to the consumption of additional resources and will lead to the deterioration of the psychological environment in the team.

The feasibility of creating and implementing internal control in the enterprise should be compared with the costs of its organization and implementation.

The creation of an internal control system implies that the control function in the enterprise is performed not only by a specific structural unit or a responsible person (depending on the criteria listed above), but by each employee in accordance with his powers and work duties.

The internal control system consists of the following elements:

1. Management environment.
2. The process of risk assessment by the person conducting the audit.
3. Information system (including the preparation of financial (accounting) reports);
4. Control flows.
5. Monitoring of management tools.

Based on the above, the internal control system can be viewed as a system that allows the employees of the economic entity to achieve their goals using the necessary methods and procedures.

The interaction of internal audit and internal control system is shown in Figure 1.

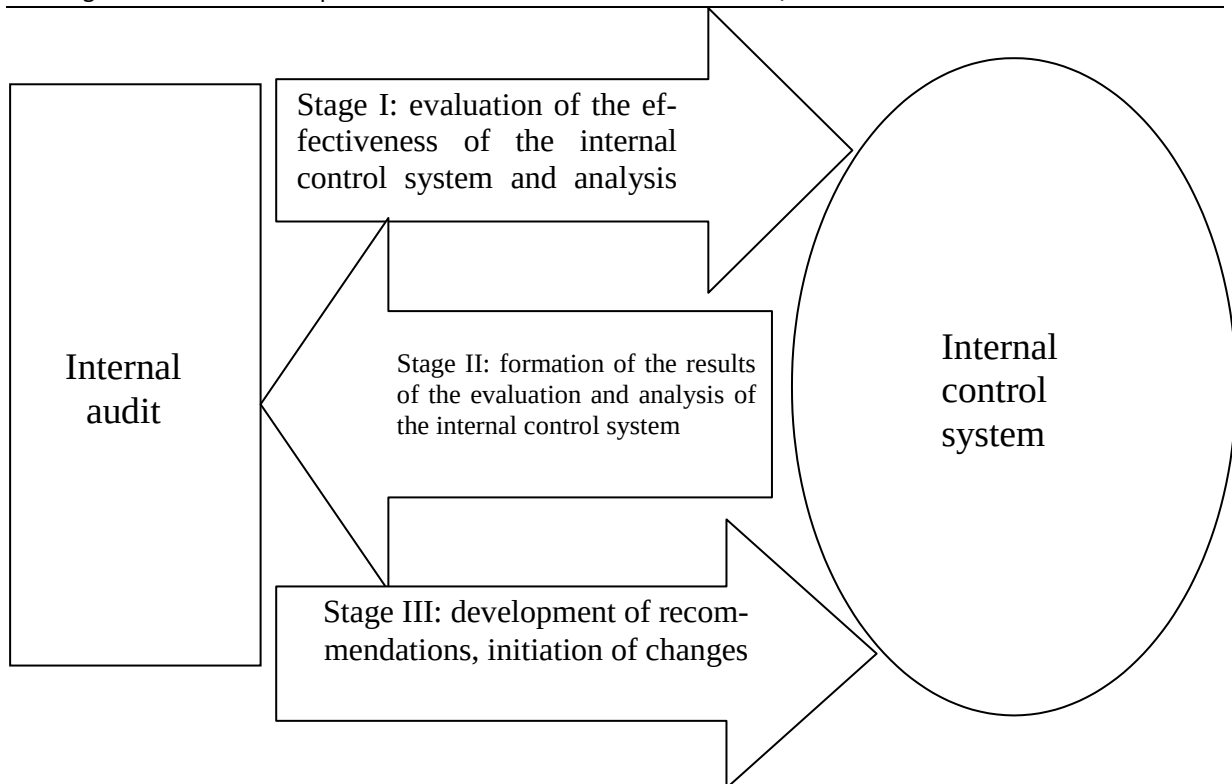


Figure 1 . The interaction of internal audit and internal control system in assessing the reliability and effectiveness of the internal control system (compiled by the author).

Conclusions and suggestions.

The need for an internal audit system is related to the fact that this activity allows you to identify risks and initiate various changes aimed at improving efficiency within the organization. The need for such changes may be related to the results of an internal audit or an assessment of the internal control system.

The second important task of the internal audit system, which is directly related to the internal control system in the enterprise, is to organize control in order to prevent the loss of the organization's assets. As mentioned above, every employee participates in the internal control system in one way or another. In this regard, there is a risk of bias in conducting control measures. Therefore, the presence of an independent department or employee in the organizational structure that evaluates the internal control system and conducts audits according to the instructions of the management or owners allows to reduce this risk to an acceptable and acceptable value.

The internal audit system also serves to form the investment attractiveness of a legal entity. Carrying out control activities aimed at identifying various inconsistencies with the current legislation, reducing risks to an acceptable level on the eve of external audits and other inspections, providing advice to employees of other structural units are activities that allow indirect investment attraction.

In addition to control and analytical functions, the internal audit system can also perform information and advisory functions. This means giving advice to employees of all structural units and heads of organizations on issues within the competence of internal auditors. For example, finance, economics, tax, etc. advice is given in the field.

Conducting an internal audit is an activity directly related to the functions of the internal control system. Its purpose is to confirm the reliability of financial reports, to identify violations in the financial and economic activity of a legal entity, to identify the guilty persons and the reasons that led to errors, and to formulate relevant recommendations and various proposals that allow to eliminate the identified violations or minimize the risks .

It is worth noting that the involvement of organizations whose main activity is related to external audit in the assessment of the effectiveness and reliability of the internal control system may lead to conflicts in the future.

By performing this function, internal audit indirectly solves the problem of establishing the most reasonable and optimal system of internal control in the enterprise. It should be noted that the creation of an internal control system is the task of managers of a legal entity. If there is an existing system in place, the internal audit service should focus on evaluating efficiency and reliability. When errors and malfunctions are detected in the system, it is necessary to optimize its operation as much as possible by identifying the causes. Duties include developing recommendations and making proposals for various system changes.

In this way, the relationship between internal audit and internal control system was established. It was found that depending on the functions and tasks performed, the internal audit may have different proportions with the internal control system of the business entity.

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VIDEO GAME INDUSTRY AS A PART OF CREATIVE AND DIGITAL ECONOMICS**Semenchenko N.,***Doctor of Economic Sciences, Professor, Professor at the Department of Economic Cybernetics, Igor Sikorsky Kyiv Polytechnic Institute, Ukraine***Melnychuk V.,***Ph.D. in Economics, Associate Professor at the Department of Economic Cybernetics, Igor Sikorsky Kyiv Polytechnic Institute, Ukraine***Zaporozhchenko A.,***Bachelor's student at the Faculty of Informatics and Software Engineering, Igor Sikorsky Kyiv Polytechnic Institute, Ukraine***Molchanov M.***Bachelor's student at the Faculty of Informatics and Software Engineering, Igor Sikorsky Kyiv Polytechnic Institute, Ukraine*<https://doi.org/10.5281/zenodo.15298383>**Abstract**

The article is devoted to studying video game industry as a part of creative and digital economics at the macrolevel. The aim of the article is to identify trends in digital and creative economics, prerequisites and cost-benefit factors for game development on examples of indie and AAA studios. The current state of the game market, the distribution of profits between gaming platforms and the involvement of global users are analyzed. Analysts' approaches to solving current problems and opportunities for generating higher revenues in the industry are determined. The key differences between indie and AAA studios are considered, in terms of developers' level of freedom of action, approaches to attracting investments and the structure of development costs. Particular attention is paid to analysing these characteristics in the context of their impact on the game creation process and the business model of each type of studio. An analysis of profitability and risks is carried out for each type of studio, and a comparison of the economic models used by indie and AAA studios is carried out. The impact of modern technologies on studios' economic efficiency and creative approach is assessed, including changes in production processes and strategic approaches.

Keywords: video game industry; creative economics; digital economics; game development; game production; AAA studios; indie studios; game studio business models.

Introduction

The video game industry has evolved from a niche hobby into a global cultural and economic powerhouse, playing a significant and multifaceted role in creative and digital economies. Its influence extends beyond mere entertainment, impacting technological innovation, job creation, consumer spending, and even the broader digital landscape. Moreover, nowadays, the video game industry is a colossal economic engine, generating hundreds of billions of dollars annually through game sales, in-game purchases, subscriptions, and esports. This substantial revenue contributes significantly to the GDP of numerous countries.

The video game industry, from the late 20th century until today, has evolved from a marginalized entertainment format for a narrow circle of gamers to a leading sector of the global creative economy. Today, its scale, investment appeal and cultural impact surpass many traditional media industries, including cinema and the music market. Billions of people worldwide turn to video games as a primary form of leisure, and the combined annual revenues of developers, publishers and related services reach tens of billions of dollars.

The development of the industry has become possible due to technical progress, the expansion of network infrastructure, the reduction in price and popularization of powerful gaming hardware (consoles, PCs, mobile devices), as well as the spread of digital distributions. The increase in the competitive environment has pushed developers to diversify business models and

form different game creation approaches. Therefore, currently, we can outline two conditional "categories" of development studios, which are most often used in professional and semi-professional terminology: indie studios (independent studios) and AAA studios [1].

Indie studios are typically small, independent teams with minimal to moderate budgets, limited production facilities, and limited staff. They are known for their creativity, originality of ideas, unconventional approaches to gameplay, and willingness to experiment, which often defines their competitive niche. The indie sector typically implements creative concepts, demonstrating flexibility in production processes, and responding quickly to feedback from the gaming community. However, financial instability, limited marketing budgets, and difficulties implementing high-tech solutions make it difficult for them to achieve widespread recognition [2].

On the other hand, AAA studios are large corporations or divisions of large companies with significant financial and human resources. A high level of graphic perfection, large worlds, complex narratives, and content usually characterize their products. AAA projects become a kind of "flagships" of the industry, setting technological standards and shaping the idea of innovation in game design. However, the scale of production of AAA games is accompanied by high risks, significant budgetary costs, complex organizational processes and pressure from investors and the media [3].

The article will consider economic models, production processes, marketing strategies, sources of financing, the level of creative freedom and the possibilities of applying innovations. Particular attention will be paid to the analysis of general trends in the impact of technologies on the profitability of different types of studios, as well as the assessment of their strengths and weaknesses, opportunities and threats. Such a comprehensive approach will allow to form a more complete picture of the specifics of the modern game market from the point of view of economic processes, will provide a theoretical basis for further research and will help novice developers or investors to assess the prospects of their entry into a particular sector of the industry.

Purpose of the article

The article aims to identify trends in digital and creative economics, prerequisites, and cost-benefit factors for game development, using examples from indie and AAA studios.

Presentation of the main research results

The global video game industry has shown dynamic growth in recent decades. According to a report by the analytical company Newzoo, the total gaming

audience as of August 2024 will reach over 3.4 billion users, with a significant share of revenue (49%) generated by mobile platforms [4].

The videogame industry generally has three main gaming platforms: game consoles, personal computers (hereinafter called PC) and mobile devices. Compared to the previous year, the profitability of mobile games increased by 3.0%. Console games are in second place in profitability (28%). The PC gaming segment is the least profitable compared to the above (23%), but its profitability increased the most among the three compared to 2023 (+4.0%) [4].

In 2027, the number of players worldwide will reach 3.759 billion people. This is 0.485 billion more players than in 2023. This growth is predicted to be driven by an increase in the number of players on all platforms, particularly PC players. Newzoo analysts are convinced that the gaming market continues to develop and expand every year. At the same time, it is believed that this growth is insufficient to ensure a sufficient return on developers' investment. One proposed way to solve this problem is to develop shorter-term games, the profits from which can be redirected to longer and more demanding projects [4].

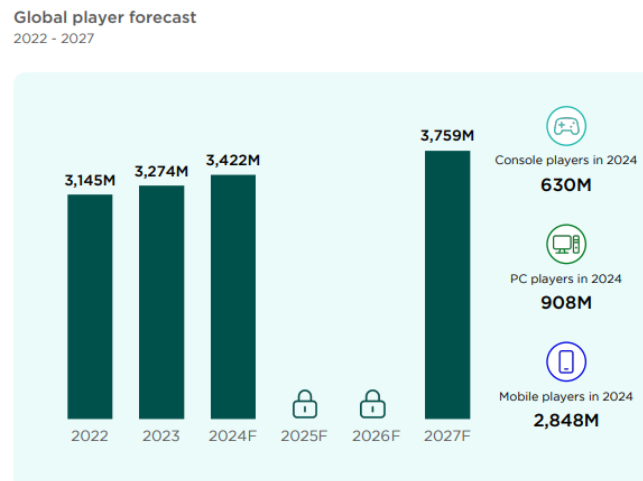


Fig. 1. Forecast of the number of players worldwide and the share of players among platforms [4]

The main market players can be divided into several categories:

- Major AAA publishers and developers (Ubisoft, Electronic Arts, Sony, and others). They are characterized by a significant staff, large-scale investments, and extensive marketing campaigns [5].

- Indie studios: Numerous small teams that operate as independent developers. According to a study by VGI, about 99% of all games released on Steam in 2024 will be created by indie developers [6].

- Mobile developers, including companies of various sizes (from Tencent to small startups).

- VR/AR content developers, which still constitute a relatively small segment, but the growth in sales of VR headsets (Oculus, HTC Vive) indicates a promising direction [7].

Technological trends, such as cloudy gaming, streaming, development, artificial intelligence in game design, and more, affect ways of creation, distribution and consumption of games. In this context, a comparison

between indie and AAA studios becomes especially important because it gives the opportunity to see how different business models adapt to new realities.

The division into indie and AAA studios is arbitrary but dominates professional terminology [8]. The main criteria are:

1. Production scale and team size.
2. Sources of funding and level of independence.
3. Level of technological resources.
4. Availability of well-known brands and franchises.
5. Marketing investment volumes.

Indie studios, by definition, usually operate independently of major publishers. Indie teams often start their activities with their own savings or through crowdfunding [9]. Their budgets can range from a few thousand to several hundred thousand dollars, and the teams consist of a small number of specialists (from 2–3 to a few dozen people). Despite limited financial and technical resources, indie developers are able to create

unique games with non-standard mechanics and stylish visual execution.

AAA studios, on the other hand, are large-scale companies with many years of history or are part of large holdings. The AAA team can consist of hundreds or even thousands of specialists of various profiles [1]. The budgets of such projects are tens or even hundreds of millions of dollars (including marketing), and the production cycle can last 2–5 years. Despite the significant opportunities, AAA development is associated with great risks: in case of failure, investors and company owners can lose huge sums.

One of the key differences between indie and AAA studios is the structure and scope of game development costs. Costs can be roughly divided into:

- Personnel costs: salaries of developers, artists, programmers, designers, producers.
- Technology costs: licenses for game engines (if not using free or proprietary ones), software, server hardware, testing tools.
- Content costs: the creation of 3D models, animations, sound, music, scripts and localization.
- Marketing and distribution: costs for advertising campaigns, participation in exhibitions, cooperation with influencers and media.
- Administrative expenses: legal support, accounting, office space, consulting, hosting.

According to Game Research Center Developers Conference (GDC) data, an average indie project can have a budget of around \$50,000–\$500,000, while AAA games often cost \$50 million or more. The main cost items are personnel (hundreds of highly skilled developers, artists, musicians, and screenwriters), complex infrastructure (office buildings, equipment), licenses for expensive software packages, and maintenance of internal servers. Marketing AAA games involves large-scale advertising campaigns, TV commercials, offline events, and collaborations with famous actors, musicians, and marketers [10]. Indie developers often rely on free (or share-free) engines and freelancers and can also work remotely without needing large offices. Marketing is usually limited to social networks and collaborations with small streamers and journalists. At the same time, the cost of one product unit (for example, one copy of the game) after a digital launch is quite low [5].

Funding sources vary significantly between indie and AAA studios. Indie studios often rely on the founders' funds, crowdfunding, grants from cultural gaming foundations, or government agencies (such as Creative Commons). Europe) and platform-independent developer support programs (e.g. ID@Xbox, PlayStation Indies, etc.) AAA studios receive funding from major publishers (Sony, Microsoft, EA), attract investments and loans, and have significant reserves within holding companies.

Revenues and profits also vary. Indie studios can break even with a relatively small number of copies sold, as their costs are lower. Some indie projects become real “hits” that suddenly sell millions of copies with minimal costs (for example, Minecraft was once an indie project). However, most indie games remain niche, selling a few thousand or tens of thousands of

copies and barely covering their costs due to the intense competitive environment on digital platforms. AAA studios need millions of game sales to break even, as their budgets are extremely large. The high price of AAA titles (the full price of a game is usually \$60-70) allows for significant revenue, but the risks are also high. Investors suffer huge losses if a project receives negative reviews or fails at launch. According to an official UK government report on the deal between Microsoft and Activision Blizzard, the cost of developing one of Activision's major franchises, Blizzard's revenue was \$660 million, while marketing costs were nearly \$550 million. [11]

In the future, we can expect a strengthening of the technological factor and market diversification. According to DFC Intelligence, the growth of mobile and cloud platforms will contribute to the emergence of new business models. At the same time, the traditional PC and console market will remain a stable source of revenue [12].

The indie sector benefits from further reductions in development tools and new monetization formats (subscriptions, early access). In addition, thematic platforms and niche communities help indie ideas quickly find a target audience.

The AAA market will continue to integrate with streaming and tech giants (e.g. Microsoft's acquisition of Activision Studios and Blizzard), which will allow reaching an even larger audience of viewers and gamers [13]. At the same time, development costs and risks of failure will increase, which may lead to greater consolidation of companies.

Conclusions

In conclusion, the video game industry is not just a form of entertainment but a dynamic and integral component of creative and digital economics. Its ability to generate significant revenue, drive technological innovation, create diverse employment opportunities, and foster new forms of digital interaction solidifies its crucial role in shaping the economic landscape of the 21st century and beyond. As technology evolves, the gaming industry is poised to expand its influence further and contribute even more significantly to the global creative and digital economies.

Comparing indie and AAA video game development studios reveals significant differences in budgets, business models, marketing strategies, risks, and opportunities. Indie developers, working with limited resources, have great creative freedom, which allows them to experiment and create unique products. AAA studios, on the other hand, have the financial and human resources to create high-tech blockbusters, but they face significant financial risks and pressure from investors.

New technological environments, including artificial intelligence, cloud computing, and VR/AR, constantly change the industry landscape. For indie studios, these technologies can catalyse innovation and, for AAA, a tool for strengthening leadership. At the same time, increasing competition, rising audience expectations, and increasing development costs are becoming serious challenges for all market participants.

Ultimately, the success of both indie and AAA studios depends on the ability to choose the right strategies

and niche, effectively work with their audience, and respond to technological and economic changes promptly. Further research could be aimed at a more detailed analysis of specific cases of success and failure in each segment, as well as studying the impact of new formats (e.g., meta-universes and blockchain technologies) on the structure of the video game market.

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MATHEMATICAL SCIENCES

OSCILLATION CONDITIONS OF ONE TYPE OF ELLIPTIC EQUATIONS

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<https://doi.org/10.5281/zenodo.15298387>

Abstract

In this paper, the oscillatory properties of an elliptic equation are considered, that is, its ability to oscillate. As you know, an oscillating solution to an equation is one that changes its sign with an unlimited increase in the value of a variable.

One of the key tasks in studying these equations is to determine their oscillatory characteristics. The paper presents and proves theorems on the oscillation of solutions, which is of considerable interest to mathematicians.

Keywords: oscillatory properties, elliptic equation, function, inequality, theorem, proof.

The paper examines the oscillatory characteristics of the elliptic equation.

$$\Delta^{m+1}U + \Delta^m U + P(x)|U|^\lambda \operatorname{sign} U = 0 \quad (1)$$

Assuming that... , $m \geq 1$, $\lambda > 1$, $x \in R_a^n$

$$R_a^n = \{x \in R^n : |x| > a\}$$

And the theorem on the oscillation of all solutions to equation (1) has been proved if $n > 2m$, n is an odd number. Equation (1) was previously studied only at , $\lambda > 1$ [1] and for any n in [2].

Consider equation (1), where $R_a^n = \{x \in R^n : |x| > a\}$, $a > 0$

The equation

$$\Delta^m U + P(x)|U|^\lambda \operatorname{sign} U = 0$$

was studied in more detail in [3, 4].

In [3], a necessary and sufficient condition for the oscillation of all solutions for $\lambda > 1$ is given, as well as a theorem on the oscillation of all solutions for the value λ : $0 < \lambda \leq 1$

Sufficient oscillation conditions for $\lambda > 1$ are also given in [4].

Definition 1. Function $U(x)$ is called the solution of equation (1) if $U(x) \in C^{2m}(R_a^n)$ and satisfies equation (1).

Definition 2. The solution of equation (1) is called oscillating if it changes sign $\forall a > 0$ в R_a^n , and non-oscillating otherwise.

Let $U(x)$ be the solution of equation (1). Denote

$$U(x) = \frac{1}{\omega_n} \int_{|\varphi|=1} U(r, \varphi) d\varphi,$$

(r, φ) – spherical coordinates of point $x \in R^n$, ω_n – area $(n-1)$ the dimensional unit sphere $|\varphi| = 1$, $\varphi = (\varphi_1, \varphi_2, \dots, \varphi_{n-1})$.

If $U(x) \geq 0$, then according to Jensen's inequality [5, p.32] for $U(x) \geq 0$ и $\lambda > 1$ and we have

therefore, it is valid for $U(x) \geq 0$

So in this case

$$L\omega + P(r)U^\lambda \leq 0 \quad (2)$$

L – an ordinary linear differential operator of order and

$$\omega(r) = \Delta_r U + U, \quad \Delta_r = \frac{d^2}{dr^2} + \frac{n_1}{r} \frac{d}{dr}, \quad (3)$$

Δ_r – the radial part of the Laplace operator.

Lemma 1. If $U(x) \geq 0$ is R_a^n , then $\omega(r) \geq 0$ и $\left(r^{\frac{n-2}{2}} \omega(r)\right)' \geq 0$ в R_a^n , $a > 0$.

Proof. First, we prove that $\omega(r) \geq 0$ for $r \geq a$. In equation (3), we replace $U = F(r) r^{\frac{2-n}{2}}$, then we get

$$F'' + \frac{1}{r} F' + \left(1 - \frac{(n-2)^2}{4r^2}\right) F = \omega(r) r^{\frac{n-2}{2}} = \omega_1(r). \quad (4)$$

Let $\omega(r) < 0$ be at $r > r_1 > a$. Then from (4) we have

$$F'' + \frac{1}{r} F' + \left(1 - \frac{(n-2)^2}{4r^2}\right) F \leq 0$$

Or

$$(rF')' + r \left(1 - \frac{(n-2)^2}{4r^2}\right) F \leq 0.$$

Hence, at a high r , we get

$$(rF')' \leq 0.$$

In this case, there are two possible options: $rF' \leq 0$, or $rF' \geq 0$. If $F' \leq 0$, then the function is negative and does not increase, therefore

$$rF' < -c, \quad c = \text{const} > 0 \quad \text{at} \quad r > r_2 > r_1.$$

From here we find

$$F(r) < -c \ln r + c_1 \rightarrow -\infty \quad \text{at} \quad r \rightarrow \infty,$$

which contradicts the condition $F(r) > 0$. So, $rF' \geq 0$. Now let's prove that $F''(r) \geq 0$. Let $F''(r) < 0$. By virtue of the conditions $F' \geq 0$, $F \geq 0$ from (4), we have

$$F'' < -\frac{1}{2}F.$$

From here we easily come to the inequality

$$F'(r) < -\frac{1}{2}F(r_1)(r - r_1) + F'(r_1) \rightarrow -\infty$$

for $r \rightarrow \infty$, and this contradicts the already proven fact that $F' > 0$. Thus, it was proved that $\omega(r) > 0$

Now let's prove that $\omega'_1 = \left(r^{\frac{n-2}{2}} \omega\right)' \geq 0$. If $U(r) \geq 0$, then from (2) we get that $L\omega \leq 0$. In this inequality, we replace $t = \ln r$, $\omega = z \exp\left(\frac{2m-n}{2}t\right)$. Then the roots of the characteristic polynomial of the equation $L\omega = 0$ are [6, 7]

$$\pm \left(\frac{n-2m+4i}{2}\right), \quad i = 0, 1, 2, \dots, m-1.$$

It follows that

$$Lz = \sum_{i=1}^m \beta_{2i} z^{(2i)}, \quad \beta_{2i+1} = 0, \quad \beta_{2i} = (-1)^i |\beta_{2i}|, \quad i = 0, 1, 2, \dots, m.$$

Since $z \geq 0$, we have

$$L_1 z = \sum_{i=1}^m \beta_{2i} z^{(2i)} \leq 0.$$

For the characteristic polynomial of the equation $L_1 z = 0$ all roots are valid. Moreover, as follows from the results of [4, tasks 36, 47], there are $m - 1$ different roots. Since the polynomial in question is an even function, if α is its root, then $-\alpha$ will be its root. Thus, the characteristic polynomial has different roots and one double root equal to 0.

Let $0 < \alpha_1 < \alpha_2 < \dots < \alpha_{m-1}$
be the roots of this characteristic polynomial, then

$$-\alpha_{m-1} < -\alpha_{m-2} < \dots < -\alpha_1 < \alpha_1 < \alpha_2 < \dots < \alpha_{m-1}.$$

Thus, the fundamental system of solutions of the equation $L_1 z = 0$ has the form

$$z_1 = 1, \quad z_2 = t, \quad z_3 = \exp(-\alpha_{m-1}t), \quad z_4 = \exp(-\alpha_{m-2}t), \quad \dots, \quad z_{2m} = \exp(\alpha_{m-1}t).$$

Now we note the following fact from the theory of ordinary differential equations. If the linear equation is $L_2(y) = 0$ is non-oscillatory, then it can be represented as [8, 9]:

$$L_2(y) = q_{2m}(t) \frac{d}{dt} q_{2m-1}(t) \frac{d}{dt} \dots q_2(t) \frac{d}{dt} q_1(t) \frac{d}{dt} q_0 y, \quad (5)$$

and

$$q_0(t) = \frac{1}{W_1(t)}, \quad q_k(t) = \frac{W_k^2(t)}{W_{k-1}(t)W_{k+1}(t)}, \quad k = 1, 2, \dots, 2m-1; \quad q_{2m}(t) = \frac{W_{2m}(t)}{W_{2m-1}(t)} \quad (6)$$

here $W_k(t)$ is the Vronsky determinant of solutions $y_1, y_2, \dots, y_k$, with $W_k(t) > 0$ ($k = 1, 2, \dots, 2m$), $W_0(t) = 1$. For our case, the functions $q_k(t)$ are easily found

$$\begin{aligned} q_0(t) &= 1, \quad q_1(t) = 1, \quad q_2(t) = \exp(-\alpha_{m-1}t), \\ q_k(t) &= \exp(\alpha_{m-k+1} - \alpha_{m-k+2}), \quad (k = 3, 4, \dots, m-1), \\ q_{m+1}(t) &= \exp(-2\alpha_1 t), \quad q_{2m}(t) = \exp(\alpha_{m-1}t). \\ q_{m+k}(t) &= \exp(\alpha_{k-1} - \alpha_k) t, \quad (k = 2, 3, \dots, m-1) \end{aligned}$$

Let's introduce the notation

$$\begin{aligned} V_0 &= q_0 \cdot z, \quad V_1 = q_1(t) \frac{d}{dt} q_0 z, \quad V_k = q_k(t) \frac{d}{dt} V_{k-1}, \\ (k &= 1, 2, \dots, 2m-1), \quad V_{2m} = \frac{d}{dt} V_{2m-1}. \end{aligned} \quad (7)$$

Offer. If $z \geq 0$, $V_{2m} \leq 0$, then there are numbers $t_{2k+1} = 2k + 1$ such that inequalities occur

$$\begin{aligned} V_k(t) &\geq 0, \quad k = 1, 2, \dots, l, \quad l = 2k + 1, \quad 0 \leq k \leq m-1 \\ (-1)^i V_{i+l} &\geq 0, \quad i = l + 1, l + 2, \dots, 2m - l \end{aligned} \quad (8)$$

Proof. From $z \geq 0$ and $V_{2m} \leq 0$ follows $V_{2m-1}(t) \geq 0$, or $V_{2m-1}(t) \leq 0$. If $V_{2m-1}(t) \leq 0$, then the function $V_{2m-1}(t)$ is non-positive and decreasing, so $V_{2m-1}(r) < -c$, $c = \text{const} > 0$ for $t \geq t_1$, integrating the inequality

$$\frac{dV_{2m-r}}{dt} < -\frac{c}{q_{2m-1}(t)}$$

from t_1 to t , we get

$$V_{2m-2}(t) < V_{2m-2}(t) - c \int_{t_1}^t \frac{d\tau}{q_{2m-1}(\tau)} \rightarrow -\infty$$

for $t \rightarrow \infty$, therefore $V_{2m-2}(t) < 0$ for $t \geq t_2 > t_1$. Similarly, we obtain that $V_{2m-3} < 0$ for $t \geq t_3 > t_2$, etc. Finally, we obtain that $V_0(t) < 0$ for $t \geq t_{2m}$, which contradicts the condition of lemma $z(t) > 0$.

Thus, $V_{2m-1}(t) \geq 0$. Now either $V_{2m-2} \geq 0$ or $V_{2m-2}(t) \leq 0$. If $V_{2m-2}(t) \geq 0$, then it is easy to obtain that $V_i(t) \geq 0$, i.e. $l = 2m - 1$. If $V_{2m-2}(t) \leq 0$, then $V_{2m-3}(t) \geq 0$. Then either $V_{2m-4}(t) \leq 0$, or $V_{2m-4}(t) \geq 0$, etc.

If $V_{2m-4}(t) \geq 0$, then we get $l = 2m - 3$. If $V_{2m-4}(t) \leq 0$, then $V_{2m-5}(t) \geq 0$. So, there is a number l for which inequalities (8) take place.

From inequalities (8), we obtain that $V_1 = q_1 \frac{d}{dt} q_0 z >$, but $q_0(t)=1$ and $q_0(t) = 1$, which means $z'(t) > 0$, since $z'_t = z'_r \cdot z'_t \geq 0$, then $z'_n(r) > 0$. So,

$$\left(\omega(r) r^{\frac{n-2m}{2}} \right)' = \left(\omega' + \frac{n-2m}{2} r^{-1} \omega \right) r^{\frac{n-2m}{2}} > 0$$

or

$$\omega' + \frac{n-2m}{2r} \omega > 0.$$

But

$$\omega' + \frac{n-2}{2r} \omega \geq \omega' + \frac{n-2m}{2r} \omega > 0$$

Therefore

$$\left(\omega r^{\frac{n-2}{2}} \right)' > 0.$$

Lemma 1 is proved.

Lemma 2. If $U(r) \geq 0$, then

$$\lim_{r \rightarrow \infty} \frac{u(r)}{\omega(r)} = 1.$$

Proof. The equation

$$F'' + \frac{1}{r} F' + \left(1 - \frac{(n-2)^2}{4r^2} \right) F = 0$$

It is a Bessel equation and has a fundamental system of solutions [10, p.185]

$$\begin{aligned} F_1 &= \sqrt{\frac{2}{\pi r}} \sin(r - \mu) + O\left(r^{-\frac{3}{2}}\right), \\ F_2 &= \sqrt{\frac{2}{\pi r}} \cos(r - \mu) + O\left(r^{-\frac{3}{2}}\right), \\ \mu &= \frac{(n-2)\pi}{2} + \frac{\pi}{4}. \end{aligned}$$

Then the Cauchy function $K(r, s)$ of equation (4) will have the form

$$\begin{aligned} K(r, s) &= \frac{2}{\pi} \sqrt{\frac{1}{r \cdot s}} \sin(r - s) + \varphi(r, s), \\ \varphi(r, s) &= O\left(r^{-\frac{3}{2}}\right) + O\left(s^{-\frac{3}{2}}\right). \end{aligned}$$

According to the Cauchy formula, we have

$$F(t) = \sqrt{\frac{2}{\pi r}} \sin(r - r_1) + O\left(r^{-\frac{3}{2}}\right) + \frac{2}{\pi \sqrt{r}} \cdot \int_{r_1}^r s'^{-\frac{1}{2}} \sin(r - s) \omega_1(s) ds + \int_{r_1}^r \varphi(r, s) \omega_1(s) ds.$$

Consider the integral

$$I = \int_{r_1}^r s^{-\frac{1}{2}} \sin(r-s) \omega_1(s) ds.$$

Integrating in parts, we will have

$$\begin{aligned} I &= \omega_1(r)r^{-\frac{1}{2}} - r_1^{-\frac{1}{2}}\omega_1(r_1) \cos(r-r_1) - \int_{r_1}^r \omega_1'(s)s^{-\frac{1}{2}} \cos(r-s) ds + \\ &+ \frac{1}{2} \int_{r_1}^r \omega_1(s)s^{-\frac{3}{2}} \cos(r-s) ds. \end{aligned}$$

Next, we have

$$\begin{aligned} \left| \int_{r_1}^r \omega_1(s)s^{-\frac{3}{2}} \cos(r-s) ds \right| &\leq \omega_1(r)r^{-\frac{1}{2}} \\ \left| \int_{r_1}^r \omega_1'(s)s^{-\frac{1}{2}} \cos(r-s) ds \right| &\leq r^{\frac{1}{2}}|\omega_1(r) - \omega_1(r_1)|. \end{aligned}$$

Thus

$$\begin{aligned} |I| &= \left| \int_{r_1}^r \sin(r-s) \cdot \omega_1(s) ds \right| \leq r^{-\frac{1}{2}}\omega_1(r) - r_1^{-\frac{1}{2}}\omega_1(r_1) \cos(r-r_1) + \\ &+ r^{\frac{1}{2}}\omega_1(r) + r^{\frac{1}{2}}\omega_1(r_1) + r^{-\frac{1}{2}}\omega_1(r). \end{aligned}$$

According to Lemma 1, we obtain

$$\left| \int_{r_0}^r \varphi(r,s)\omega_1(s)ds \right| \leq K_1\omega_1(r)r^{-\frac{1}{2}}, \quad K = \text{const} > 0.$$

Thus

$$|F(t)| \leq \sqrt{\frac{2}{\pi r}} \sin(r-r_1) + O\left(r^{-\frac{3}{2}}\right) + r^{-1}\omega_1(r) + r_1^{-\frac{1}{2}}r^{-\frac{1}{2}}\omega_1(r_1) + \omega_1(r) +$$

Therefore, we finally have

$$\lim_{r \rightarrow \infty} \frac{|F(r)|}{|\omega_1(r)|} = 1,$$

since, $F(r) = U \cdot r^{\frac{n-2}{2}}$, $\omega_1(r) = \omega(r)r^{\frac{n-2}{2}}$, then

$$\lim_{r \rightarrow \infty} \frac{|U(r)|}{|\omega(r)|} = 1.$$

Lemma 2 is proved.

Now we turn to the consideration of inequality (2), which, after replacing $t = \ln r$ will take the form ($U \geq 0$)

$$L\omega + P(t)U^\lambda \exp(2mt) \leq 0. \quad (9)$$

The fundamental system of solutions of the equation $L\omega = 0$ has the form:

a) if $n > 2m$, or n is any odd number, then

$$\begin{aligned}\omega_k(t) &= \exp(2k - n), & (k = 1, 2, \dots, m), \\ \omega_{m+k}(t) &= \exp(2k - 2)t, & (k = 1, 2, \dots, m)\end{aligned}$$

b) if $2 \leq n \leq 2m$ and n is an even number, then

$$\begin{aligned}\omega_k(t) &= \exp(2k - n)t, & \left(k = 1, 2, \dots, \frac{n}{2}\right); \\ \omega_{\frac{n}{2}+2k}(t) &= \exp(2k), & \left(k = 1, 2, \dots, m - \frac{n}{2}\right); \\ \omega_{\frac{n}{2}+2i+1} &= t \exp(2it), & \left(i = 0, 1, \dots, m - \frac{n}{2}\right); \\ \omega_{2m+1-\frac{n}{2}+i}(t) &= \exp(2m - n + 2i)t, & \left(i = 1, 2, \dots, \frac{n}{2} - 1\right).\end{aligned}$$

To find the functions $q_k(t)$, first we calculate the determinants $W_k(t)$ ($k = 1, 2, \dots, 2m$)

If $n > 2m$, or n is any odd number, then

$$\begin{aligned}W_k(t) &= c_k \exp[k(1 + k - n)t], & (k = 1, 2, \dots, m) \\ W_{m+1}(t) &= c_{m+1} \exp[m(m - n + 1)t] \\ W_{m+k+1}(t) &= c_{m+k+1} \exp[(m(m - n + 1) + k(k + 1))t], & (k = 1, 2, \dots, m - 1).\end{aligned}$$

If n is even and $2 \leq n \leq 2m$, then

$$\begin{aligned}W_k(t) &= c_k \exp[k(k - n + 1)t], & \left(k = 1, 2, \dots, \frac{n}{2} - 1\right), \\ W_{\frac{n}{2}}(t) &= c_{\frac{n}{2}} \exp\left[-\frac{n(n-2)}{4}t\right], & W_{\frac{n}{2}+1}(t) = c_{\frac{n}{2}+1} \exp\left[-\frac{n(n-2)}{4}t\right], \\ W_{\frac{n}{2}+2}(t) &= c_{\frac{n}{2}+2} \exp\left[\left(-\frac{n(n-2)}{4} + 2\right)t\right], \\ W_{\frac{n}{2}+2k+1}(t) &= c_{\frac{n}{2}+2k+1} \exp\left[\left(-\frac{n(n-2)}{4} + 2k(k+1)\right)t\right], & \left(k = 0, 1, \dots, m - \frac{n}{2} + 1\right), \\ W_{\frac{n}{2}+2k}(t) &= c_{\frac{n}{2}+2k} \exp\left[\left(-\frac{n(n-2)}{4} + 2k^2\right)t\right], & \left(k = 0, 1, 2, \dots, m - \frac{n}{2} + 1\right), \\ W_{2m-\frac{n}{2}+k+1}(t) &= c_{2m-\frac{n}{2}+k+1} \cdot \\ &\cdot \exp\left[\left(-\frac{n(n-2)}{4} + (2m - n + 2)\left(m - \frac{n}{2}\right) + k(2m - n + k + 1)\right)t\right], \\ &\left(1 \leq k \leq \frac{n}{2} - 1\right).\end{aligned}$$

Now substituting $W_k(t)$ into formula (6), we find

$$\begin{aligned}1) \quad q_0(t) &= \exp[(n-2)t], \quad q_i(t) = c_i \exp[(-2t)] \quad (i = 1, 2, \dots, 2m-1) \\ q_{2m}(t) &= c_{2m} \exp[(2m-2)t] \quad q_m(t) = c_m \exp[(2m-n)t],\end{aligned}$$

for $n > 2m$, or n is any odd number:

$$\begin{aligned}2) \quad q_0(t) &= \exp[(n-2)t], \quad q_i(t) = c_i \exp(-2t), \quad \left(i = 1, 2, \dots, \frac{n}{2} - 1, \frac{n}{2} + 1\right) \\ q_{\frac{n}{2}+2k+1}(t) &= c_{\frac{n}{2}+2k+1} \exp(-2t) \quad \left(k = 1, 2, \dots, m - \frac{n}{2}\right)\end{aligned}$$

$$q_{\frac{n}{2}+2k}^n(t) = c_{\frac{n}{2}+2k}^n \left(k = 0, 1, 2, \dots, m - \frac{n}{2} + 1 \right)$$

$$q_{2m-\frac{n}{2}+i+1}^n(t) = c_{2m-\frac{n}{2}+i+1}^n \exp(-2t), \left(i = 1, 2, \dots, \frac{n}{2} - 2 \right)$$

$$q_{2m}^n(t) = c_{2m}^n \exp[(2m - 2)t].$$

for $2 \leq n \leq 2m$ and n is an even number.

By virtue of the introduced notation (7), inequality (9) will take the form

$$V_{2m}(t) + P(t)U^\lambda \exp(2t) \leq 0 \quad (10)$$

Before giving the main results, we present the following Lemma.

Lemma 3. If $U(t) \geq 0$ and $V_{2m}(t) \leq 0$, then there are numbers l and $t_l \geq t_0$ such that for $t \geq t_1$ inequalities (8) and

$$V_l(t) \leq 2^{l-1}(l-1)! V_l(t)[1 + o(1)] \exp[-2(l-1)t], \quad (11)$$

if $n > 2m$ or n is any odd number and $l < m$.

$$V_l(t) \leq 2^p p! (n - 2m + 2p) \dots [n - 2m + 2(l-2)] (1 + o(1)) V_1(t) \cdot \exp[-(n - 2m + 2(l-2))t] \quad (12)$$

if $l = m + p, p \geq 1, n > 2m$, or n is an odd number;

Proof. Let's prove inequality (11). The function $V_l(t)$ is non-negative and does not increase. We have

$$V_{l-1}(t) \geq \int_{t_0}^t V_l(s) \exp(2s) ds \geq \frac{1}{2} V_l(t)[1 + o(1)] \exp(2t)$$

$$V_{l-2}(t) \geq \frac{1}{2} \int_{t_0}^t V_l(s)[1 + o(1)] \exp(4s) ds \geq \frac{1}{2} \cdot \frac{1}{4} V_l(t)[1 + o(1)] \exp(4t)$$

.....

$$V_1(t) \geq \frac{1}{2^{l-1}(l-1)!} V_l(t)[1 + o(1)] \exp[2(l-1)t]$$

hence the inequality (11).

The proof of inequality (12) is similar to proof (11), only taking into account that

$$V_m(t) = \frac{dV_{m-1}}{dt} \exp[(2m - n)t].$$

If $U(x)$ is a non-oscillating solution of equation (1), then by definition it has no zeros in R_a^n for some $a > 0$. Therefore, we can consider $U(x) > 0$ в R_a^n . Then, according to Lemma 1, $\omega(r) > 0$ в R_a^n .

Theorem 1. If $\lambda > 1, n > 2m$, or $n = 2k + 1$ then for all solutions of equation (1) to fluctuate, it suffices that the conditions $a(x) \geq P(r) \geq 0$ and

$$\int_{r_0}^{\infty} P(r) r^{2m+n-\lambda(n-2)} dr = \infty. \quad (13)$$

Proof. Let's assume that equation (1) has a non-oscillating solution $U(x)$. Then we can consider $U(x) \geq 0$ in $R_{r_0}^n$. For this solution, inequality (2) holds, which, after the above substitution $t = \ln r$ and the introduced notation (7), takes the form (10). Multiply inequality (10) by

$$(\omega \exp(n-2)t)^{-\lambda} \exp[(2m+n-4)t]$$

and integrate from t_0 to t :

$$\int_{t_0}^t \frac{V_{2m}(s) \exp[(2m+n-4)s]}{(\omega(s) \exp[(n-2)s])^\lambda} ds + \int_{t_0}^t P(s) \left(\frac{U}{\omega \exp(n-2)t} \right)^\lambda \exp[(2m+n-2)t] ds \leq 0.$$

We integrate the first integral in parts, then applying Lemma 2 we get

$$\frac{\Phi(t)}{(\omega(t) \exp[(n-2)s])^\lambda} - \int_{t_0}^t \Phi(s) d[\omega(s) \exp[(n-2)s]]^{-\lambda} + \quad (14)$$

$c = \text{const}$, where

$$\Phi(t) = V_{2m-1}(t) \exp[(n+2m-4)t] - (n+2m-4)V_{2m-2}(t) \exp[(n+2m-6)t] + \dots + \quad (15)$$

$$Q(t) = (n+2m-4)(n+2m-6) \dots (2l-2)V_l(t) \exp[2(l-1)t] \quad (16)$$

for $n > 2m$ either $n = 2k+1$, ($k \geq 1$), and $l < m$,

$$\begin{aligned} \Phi(t) = & V_{2m-1}(t) \exp[(n+2m-4)t] - (n+2m-4)V_{2m-2}(t) \exp[(n+2m-6)t] + \dots + \\ & + (-1)^{i-1} (n+2m-4)(n+2m-6) \dots (n+2m-4-2(i-2))V_{2m-2}(t) \cdot \\ & \cdot \exp[(n+2m-4-2(i-1)t)] + (n+2m-4)(n+2m-6) \dots (n-2m+2l-2) \cdot \\ & \cdot V_l(t) \exp[(n-2m+2l-2)t]. \end{aligned} \quad (17)$$

$$Q(t) = (n+2m-4)(n+2m-6) \dots (n-2m+2l-2)V_l(t) \exp[(n-2m+2l-2)t]. \quad (18)$$

For $l > m$, $l \geq 2m - \frac{n}{2} + 1$, $2 \leq n \leq 2m$.

Inequality (7) implies that $\Phi(t) \geq 0$. Consequently, from (14), by virtue of Lemma 3, we obtain

$$\int_{r_0}^r P(s)[1+o(1)] \exp[(2m+n-2)-\lambda(n-2)s] ds \leq C + \int_{t_0}^t \frac{Q(s)ds}{[\omega(s) \exp(n-2)t]^\lambda},$$

where $c = \text{const}$ ($n > 2m$ or $n = 2k+1$).

If $l < m$, then according to equalities (15), (16) we have

$$\begin{aligned} \int_{t_0}^t \frac{Q(s)ds}{[\omega(s) \exp(n-2)s]^\lambda} &= (n+2m-4)(2+2m-6) \dots (2l-2) \int_{t_0}^t \frac{V_l(s) \exp(2ls)}{[\omega(s) \exp(n-2)s]^\lambda} \leq \\ &\leq (n+2m-4)(n+2m-6) \dots (2l-2) 2^{l-1}(l-1) \int_{t_0}^t [1+o(1)] \frac{d[\omega(s) \exp(n-2)s]}{[\omega(s) \exp(n-2)s]^\lambda} = \\ &= (n+2m-4)(n+2m-6) \dots (2l-2) 2^{l-1}(l-1)! [1+o(1)] \frac{1}{1-\lambda} [V_0^{1-\lambda}(t_0) - V_0^{1-\lambda}(t)]. \end{aligned}$$

where $V_0(t) = [\omega(t) \exp(n-2t)]$.

Since $\lambda > 1$ and $V_0(t)$ increases, it follows from the latter inequality and by virtue of Lemma 3 that

$$\int_{t_0}^{\infty} \frac{Q(t)dt}{[V_0(s)]^\lambda} < \infty,$$

Therefore

$$\int_{t_0}^t P(t)[1+o(1)] \exp[(2m+n-2)t - \lambda(n-2)t] dt < \infty.$$

From here, passing from t to r , we have

$$\int_{r_0}^{\infty} r^{2m+n-3-\lambda(n-2)} P(r) dr < \infty,$$

which contradicts condition (15) of the theorem.

In the case of $l > m$, it is treated similarly. In this case, instead of equalities (15), (16), equality (17), (18) should be used, respectively, and inequality (12) should also be used instead of inequality (11).

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PEDAGOGICAL SCIENCES

TECHNOLOGIES FOR USING ARTIFICIAL INTELLIGENCE IN SOLVING MATHEMATICAL PROBLEMS

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Abstract

In recent years, artificial intelligence (AI) has been actively used to solve mathematical problems ranging from simple computations to theorem proving. This paper reviews current AI techniques used in mathematics, including machine learning, neural networks, and symbolic computation. The advantages and limitations of these methods are analyzed, as well as the prospects for their further development.

Keywords: artificial intelligence, machine learning, mathematical problems, neural networks, symbolic computing.

Introduction: Mathematics has traditionally been considered a field requiring a high degree of abstract thinking and logic. However, with the development of computing technology, artificial intelligence has become an important tool for solving complex mathematical problems. Modern AI systems are capable not only of performing calculations, but also of finding patterns, proving theorems, and even proposing new hypotheses.

The purpose of this article is to review AI technologies used in mathematics, analyze their effectiveness and discuss their development prospects.

Research results: Modern artificial intelligence technologies offer a variety of approaches to solving mathematical problems, from elementary algebra to complex theoretical studies. These methods can be roughly categorized into three major areas: symbolic computation, machine learning, and neural network models. Each of these approaches has unique advantages and is applied depending on the type of problem being solved.

Symbolic Computing and Computer Algebra

One of the most traditional yet powerful AI tools in mathematics is symbolic computation (Computer Algebra Systems (CAS)). Unlike numerical methods, which operate with approximate values, symbolic computing works with mathematical expressions in analytical form, preserving their accuracy. This allows you to perform complex algebraic transformations, find exact solutions to equations, and even prove theorems.

Key systems such as Wolfram Alpha, Mathematica, Maple, SymPy, and Maxima use a combination of artificial intelligence algorithms to perform the following tasks:

- Simplifying expressions (e.g., reducing complex polynomials to canonical form);
- Solving equations and systems (linear, nonlinear, differential);
- Symbolic differentiation and integration (including multivariate and parametric cases);

- Proving identities (trigonometric, algebraic, logical);

- Working with matrices and tensors (inversion, diagonalization, calculation of eigenvalues)

These systems are based on pattern matching algorithms, heuristic methods for finding solutions, and knowledge bases with mathematical rules. For example, when solving integrals, AI can apply different strategies: substitution of variables, integration by parts, or searching a table of known primes.

One of the promising directions is hybridization of symbolic methods with machine learning. For example, neural networks can predict which simplification or integration method will be the most effective, and symbolic systems can check the correctness of the obtained results. This approach combines the speed of ML models with the accuracy of classical computer algebra algorithms[8].

However, symbolic computation has limitations:

- Computational complexity - some problems (e.g., solving complex nonlinear equations) require exponential time;

- Non-universality - not all mathematical problems can be formulated within strict algebraic rules;

- Dependence on predefined rules - systems can get "stuck" on problems outside their knowledge base.

Despite this, symbolic computation remains a fundamental tool in mathematical AI, especially in education, engineering and theoretical research.

Machine Learning in Mathematics

Machine learning (ML) revolutionizes the approach to solving mathematical problems by offering

The main directions of MO applications include[5]:

1. Classification and recognition of mathematical structures

- Automatic determination of types of differential equations
- Classification of graphs and topological spaces
- Recognition of mathematical notations in handwritten texts

2. Prediction and hypothesis generation

- Predicting properties of numbers (e.g., distribution of prime numbers)
- Hypothesis generation in knot theory and algebraic geometry

- Predicting convergence of numerical methods

3. Optimization of computational processes

- Acceleration of brute force in combinatorial problems

- Optimization of parameters of numerical algorithms

- Allocation of computational resources for complex computations

A particular breakthrough in this area is associated with the emergence of transformer architectures (GPT-f, Minerva)[6], capable of:

- Analyzing mathematical texts
- Generating formal proofs
- Finding analogies between sections of mathematics
- Proposing new research directions

Neural network approaches in mathematics[4]

Modern neural network technologies open new horizons in fundamental mathematics, demonstrating the ability to:

1. Generating new mathematical knowledge
 - AlphaGeometry system (DeepMind) shows the level of Olympiad problems in geometry
 - Neural network models offer original combinatorial constructions

- Generative models create new examples in algebraic topology

2. Analysis of complex mathematical structures

- Detection of patterns in the distribution of prime numbers

- Classification of multidimensional manifolds
- Analysis of symmetries in physical and mathematical models

3. Formal verification of mathematical proofs

- Integration with automatic proof systems (Lean, Coq)[7]

- Checking correctness of long chains of reasoning

- Searching for gaps in complex proofs

Hybrid intelligent systems

The most promising direction is the combination of different approaches:

1. Symbolic Neural Network Architectures

- Symbolic Knowledge Distillation method

- Neuro-symbolic Integrators

- Hybrid Differential Equation Solvers

2. Combined proof systems

- Combining logical inference and ML-predictions

- Using neural networks to generate lemmas

- Using CAS to verify results

3. Multimodal mathematical assistants[3]

- Processing natural-language formulations

- Visual analysis of mathematical diagrams

- Translation between formal proof systems

These approaches overcome the limitations of individual methods:

- Compensate the "black box" of neural networks with formal verification

- Eliminate the rigidity of symbolic systems through learning

- Increase the interpretability of results

Prospects for development

Practical achievements and application cases

AlphaGeometry (DeepMind, 2024)

A breakthrough system combining neural network and symbolic methods demonstrates:

- Solving 25 problems out of 30 at the International Mathematical Olympiad[1].

- Generation of human-readable proofs in Euclid format

- Autonomous construction of auxiliary constructions

Applications: automation of Olympiad papers verification, a tool for training mathematicians.

GPT-4 and specialized language models

Modern LLMs show new capabilities:

- Finding counterexamples to hypotheses in graph theory

- Generating alternative proofs of known theorems

- Analyzing mathematical texts with 80% accuracy

Limitation: requires verification through formal systems (Lean, Coq).

IBM Watson in mathematical research[2].

The cognitive system is used to:

- Analyzing 250,000+ mathematical articles in arXiv

- Identifying hidden connections between sections of mathematics

- Predicting promising research directions

Result: discovery of 3 new hypotheses in number theory in 2023.

Key Challenges and Constraints

Interpretability Problem

- Inability to trace the logic of neural network solutions

- Risk of "hallucinations" in complex proofs

- Need for symbolic verification of results

Shortage of qualitative data

- Shortage of marked-up mathematical corpora

- Problem of representing abstract concepts

- Limited open high-level problem sets

Ensuring xml rigor

Conclusion: Promising directions for development . Educational Technologies

- Adaptive Mathematics Learning Systems

- AI tutors for personalized training

- Automatic generation of personalized problems

Research Automation

- Fully formalized proof systems

- AI co-authors in mathematical publications

- Predictive models for choice **研究方向**
- Professional assistants
- Intelligent environments for handling proofs
xml-ph-0

Artificial intelligence is becoming a powerful tool in mathematics, complementing human thinking. Despite existing limitations, further development of AI technologies opens new opportunities for solving complex mathematical problems.

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PHILOLOGICAL SCIENCES

VERBAL IMAGE IN POLITICAL DISCOURSE: A CASE STUDY OF KAMALA HARRIS

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Abstract

Political discourse is not merely a vehicle for conveying policies but a strategic instrument for power acquisition and authority projection. The article investigates the intricate relationship between linguistic strategies and political influence through a detailed examination of Kamala Harris's verbal image across her debates, speeches, and interviews. Drawing on theoretical frameworks established by scholars such as Sheigal, the study categorizes political discourse into ritualistic/epideictic, orientational, and agonistic genres, each serving distinct communicative functions. Employing a multifaceted methodology — including content analysis, comparative evaluation, and statistical data processing — the research identifies how Harris's rhetorical choices adapt to various settings. The findings reveal that the deliberate construction of a politician's verbal image is essential for reinforcing leadership qualities and resonating with the electorate. Ultimately, this study contributes to the broader discourse on political rhetoric by demonstrating that nuanced linguistic techniques are central to shaping political narratives, establishing credibility, and influencing electoral outcomes.

Keywords: political discourse, verbal image, linguistic strategies, rhetorical devices, speech analysis, discourse genres, image construction.

Political discourse serves as a central mechanism in the struggle for power, shaping the way politicians communicate, persuade, and establish authority. Sheigal argues that political discourse encompasses any speech formations related to the political sphere, with its primary intention being the acquisition, maintenance, and redistribution of power [1, p. 34]. It functions not only as a medium for ideological expression but also as a strategic tool for political dominance and influence.

Political discourse encompasses a variety of genres, each serving distinct functions and characterized by different levels of preparation and spontaneity. Broadly, these genres can be categorized based on whether politicians deliver their own words or rely on speechwriters, and whether the speech is premeditated or impromptu.

In many formal settings, politicians present speeches meticulously crafted with the assistance of professional speechwriters. These speeches are designed to convey specific messages, persuade audiences, and often undergo multiple revisions to achieve clarity and impact. The collaboration between politicians and speechwriters ensures that the content aligns with policy objectives and resonates with the intended audience.

Conversely, there are scenarios where politicians must articulate their thoughts without prior preparation, often in high-pressure environments. These include debates, press conferences, and interviews where immediate responses are required. In such contexts, the politician's idiolect — their unique language style — is more apparent, as they navigate the stress and spontaneity of

the situation. The impromptu nature of these interactions can reveal authentic speech patterns, distinct from the polished language of prepared addresses.

Teun A. van Dijk, in his work "What is Political Discourse Analysis?", does not provide a strict classification system for political discourse but instead focuses on defining political discourse and analyzing its key characteristics. However, he does highlight important dimensions that can serve as a basis for classification [2, p. 13-23]. These include classifications by context, by power and ideology, by discursive strategies, and by genre and modality.

Context relates to political actors and institutions involved. In this framework, parliamentary discourse includes debates, speeches, and discussions that occur within legislative bodies. Governmental discourse comprises official statements, policy documents, and executive communications that convey the positions and decisions of state institutions. Media political discourse emerges through political talk shows, interviews, and news reports, often shaping and reflecting public opinion. Party political discourse, meanwhile, encompasses party manifestos, campaign speeches, and internal communications, serving as a vehicle for promoting ideological agendas and mobilizing supporters.

Another classification considers the relationship between discourse, power, and ideology. Dominant (or hegemonic) discourse supports existing power structures and legitimizes prevailing ideologies, typically aligning with the interests of governing elites. In contrast, oppositional (or counter) discourse challenges these dominant narratives and is often utilized by opposition parties, activists, and marginalized groups seeking change.

From the perspective of discursive strategy, political discourse can also be divided into several types. Persuasive discourse aims to convince audiences and secure support, commonly found in campaign rhetoric and public addresses. Legitimizing discourse seeks to justify political actions or policies, such as government rationales for war or economic reforms. In contrast, manipulative discourse employs rhetorical techniques that obscure the truth or mislead the audience, often blurring the boundaries between information and persuasion.

Finally, political discourse may be differentiated by genre and modality. Formal political discourse refers to institutional and structured communication, including legal texts and official reports. Informal political discourse, on the other hand, occurs in more casual settings, such as social media platforms or political talk shows.

Additionally, political discourse may appear in written form, as in legislation or manifestos, or as spoken communication, such as speeches and debates. Diverse communicative purposes shape distinct genres of political discourse. Sheigal argues they can be classified into three main categories: ritualistic/epideictic genres, orientational genres, and agonistic genres.

Ritualistic/epideictic genres – This category includes inaugural speeches, anniversary addresses, and traditional radio messages. Their primary function is to foster social unity through phatic communication.

Oriental genres – These genres serve an informational and prescriptive purpose, including party programs, constitutions, presidential addresses on the state of the nation, reports, decrees, and agreements. Their goal is to provide direction and establish governance frameworks.

Agonistic genres – Encompassing slogans, campaign speeches, election debates, and parliamentary discussions, these genres emphasize competition and ideological struggle. The ultimate aim of agonistic discourse is to establish intellectual, psychological, or moral superiority, which can translate into political power, public influence, or material gain [1, p. 323].

Agonality in political discourse manifests in three primary forms - confrontational, discussion-based, and playful. Confrontational Agonality can be both met in personal and public interactions. In interpersonal settings, it can take the form of domestic disputes characterized by emotional expression and conflict resolution. In the public sphere, it manifests itself as political or social scandals aimed at undermining an opponent's reputation and reducing their status. This type of discourse is often aggressive and intolerant, with victory signifying dominance over an adversary, whether politically or psychologically. Discussion-Based Agonality is usually structured debate, where the primary goal is the pursuit of truth. Victory in such exchanges is perceived as the triumph of factual accuracy and logical reasoning. Political debates, including parliamentary discussions and presidential debates, exemplify this category, as they facilitate the examination of multiple perspectives to establish the most valid position. Playful Agonality involves competition within a more entertaining or intellectual context, such as quiz shows, comedic competitions, and rhetorical games. The primary communicative intent is amusement, with success

bringing intellectual satisfaction and recognition rather than political or material advantages [3, p. 147].

Agonality is a fundamental characteristic of political discourse, particularly in contexts where power struggles are prevalent. Whether expressed through confrontational aggression, structured debate, or playful competition, political communication serves not only to inform and persuade but also to assert dominance and influence within society. Recognizing these dimensions of agonality allows for a more in-depth analysis of political discourse and understanding that political debates serve as one of the most revealing platforms for showcasing a politician's verbal image and individual style. Unlike prepared speeches or controlled media appearances, debates require real-time responses, rhetorical agility, and the ability to engage with both opponents and the audience. It is in this high-stakes setting that a politician's linguistic choices, voice techniques, and communication strategies are tested and displayed most vividly.

In political communication, a politician's verbal image plays a crucial role in shaping public perception and influencing voter attitudes. Unlike visual or symbolic representations, which rely on appearance and gestures, verbal image is constructed entirely through speech, encompassing linguistic style, rhetorical strategies, and voice characteristics. According to Volkova, verbal image reflects the perception of an individual based on their use of language [4, p. 49]. It serves as a defining element of a politician's public persona, shaping credibility, authority, and relatability.

A carefully crafted verbal image aligns with political goals, resonates with the electorate, and reinforces leadership qualities. Through speeches, debates, and media statements, a politician's linguistic choices influence how they are perceived – building trust, establishing authority, and shaping voter attitudes. Beyond personal appeal, the verbal image also functions as a tool of political strategy. As Sheigal emphasizes, the primary role of political discourse is to serve as a tool for wielding political power. [1, p. 4]. Political communication, therefore, extends beyond mere information exchange; it is a calculated effort to shape narratives, assert influence, and ultimately achieve power.

Verbal image is deeply intertwined with stereotypical thinking, as political figures must align their speech with the expectations and perceptions of the electorate. As Otts highlights, political image "*must be simple, accessible, and correspond to the population's positive notions of a leader*" [5, p. 26], i.e. a politician's rhetoric should not only be persuasive but also resonate with the cultural and ideological preferences of their audience.

Larionova further expands on this idea by describing verbal image as the impression formed through an individual's 'linguistic passport' and paraverbal characteristics [6, p. 41]. This encompasses elements such as vocabulary, syntax, speech patterns, and even non-verbal cues like tone, pitch, and speaking tempo. In this sense, the verbal image is one of the most significant components of a politician's overall image, as it directly affects public perception and engagement.

According to Ovchinnikova and Shulga, the verbal image consists of several key components, including voice and speech techniques (breathing, articulation, diction, tempo, pauses, intonation), lexical choice, and communicative skills such as the ability to listen and respond effectively [7, p. 24]. These elements contribute to the overall impression a politician leaves on their audience, shaping how they are perceived in terms of competence, trustworthiness, and leadership ability.

In political debates, these verbal image components take on even greater significance. The structured and highly scrutinized nature of debates places a spotlight on a politician's speech patterns, lexical choices, and rhetorical techniques. The way they construct arguments, formulate responses, and handle interruptions all contribute to their perceived authority, confidence, and persuasiveness. Thus, debates serve as a key platform where verbal image is not only projected but actively tested in real time.

The key elements of verbal image in debates are:

1. Voice and Speech Delivery
 - Tone, pitch, and rhythm significantly impact how a politician's message is received.
 - A strong, steady voice conveys confidence, while hesitation or monotony can weaken credibility.
 - A well-modulated voice with strategic pauses enhances impact and persuasion.
2. Rhetorical Strategies
 - The use of repetition, metaphors, analogies, and rhetorical questions strengthens arguments.
 - Politicians often employ contrast techniques to make their points more compelling.
 - Emotional appeals, combined with logical reasoning, make messages more memorable.
3. Word Choice and Lexical Features
 - A politician's vocabulary reflects their ideological stance and personal style.
 - The use of simplified, direct language appeals to a broader audience, while technical or policy-heavy language positions a candidate as knowledgeable but may alienate some voters.
 - Colloquialisms and humor can humanize a politician but must be used carefully to maintain credibility.
4. Interaction with Opponents and Audience
 - Debates test a politician's ability to defend their position, challenge opponents, and maintain composure under pressure.
 - Non-verbal cues such as gestures, eye contact, and posture reinforce verbal messages.
 - A politician's ability to listen and respond effectively is crucial for demonstrating leadership and relatability.
5. Improvisation and Adaptability
 - Unlike scripted speeches, debates require quick thinking and adaptability to unexpected questions or attacks [7, p. 43].

Politicians with a strong verbal image are often able to turn challenges into opportunities by employing wit, humor, or sharp counterarguments to gain a rhetorical advantage. Political debates, in particular, offer a unique platform for politicians to showcase their verbal image and individual style within an unscripted, high-

pressure environment. As debates frequently serve as pivotal moments in political campaigns, the ability to construct and project a compelling verbal image can be a decisive factor in achieving electoral success. In most genres of political discourse, a politician's verbal image must be carefully crafted to align with their established public persona. It should meet the expectations of their supporters, reinforce credibility, and maintain coherence across different communicative contexts. This is especially crucial in prepared speeches, where rhetorical devices, lexical choices, and structural elements are strategically selected to enhance both authority and relatability. Nevertheless, even in spontaneous settings such as debates and interviews, politicians must navigate their responses with precision to preserve their established image while adapting to the dynamic nature of real-time discourse.

The article studies the features of the verbal image of the politician Kamala Harris focusing on both her most notable speech characteristics and the difference in the word choice in her prepared and spontaneous discourse. We applied frequency analysis with Antconc 4.3.1 on her debates [8, 9], speeches [10, 11, 13], and interviews [12, 14, 15, 16], covering the period from 2018 to 2024. Some of these materials, such as debates are spontaneous, while others, like prepared speeches, official addresses are carefully pre-written. We analyzed the general characteristics of all the speeches in order to identify the features specific to Kamala Harris's rhetorical style. The choice of this theme is based on the idea that Harris' verbal image must be carefully crafted, as she represents not only herself but an entire political party and a considerable segment of the electorate. Harris' verbal image is shaped by a combination of strong voice control, strategic rhetorical techniques, and assertive communication style. Her background as a prosecutor is evident in her structured speech patterns, clear enunciation, and sharp questioning style – features that contribute to her authoritative and confident public persona. Harris' tone and vocal modulation play a significant role in reinforcing her image as a strong leader. She often employs a steady, deliberate speech tempo and measured pauses to emphasize key points, ensuring her words resonate with the audience, e.g., in the 2020 Vice Presidential Debate against Mike Pence, Harris famously asserted, "*Mr. Vice President, I'm speaking*", effectively using her voice and composure to reclaim control of the conversation when interrupted. This moment became a defining example of firm yet composed leadership, reinforcing her ability to stand her ground under pressure.

Given the varying communicative demands of different political settings, such as the spontaneity of interviews and debates versus the calculated precision of prepared speeches, it becomes essential to examine how rhetorical strategies shift across these contexts. This observation leads to the central hypothesis of the study: politicians adapt their rhetorical strategies based on the context (prepared vs. impromptu) and the communicative medium (debates, speeches, interviews), leading to measurable differences in the frequency and type of rhetorical devices used.

An analysis of Kamala Harris's speeches, including two debates, three formal speeches, and four interviews, reveals key patterns in her rhetorical strategy. The most frequently used words and phrases in her discourse include:

- "we" – 566 occurrences;
- "people" – 253 occurrences;
- "the American people" – 78 occurrences;
- "the United States" – 98 occurrences;
- "we have" – 97 occurrences;
- "Trump" – 160 occurrences;
- "you know" – 76 occurrences;
- "country" – 80 occurrences;
- "I will" – 58 occurrences;
- "Biden" – 56 occurrences;
- "we need" – 42 occurrences;
- "be clear" – 50 occurrences;
- "[they prefer] to run on a problem, instead of fixing a problem" – 14 occurrences;
- "we have so much more in common than what separates us" – 12 occurrences;
- "commander-in-chief" – 9 occurrences;
- "I'm the only person (one) on the stage" – 6 occurrences;
- "who have nothing in common, but (and) have everything in common" – 4 occurrences;
- "failure of this administration" – 3 occurrences.

A notable quote: "As a prosecutor, when I would talk with a victim of crime or a witness, I never asked them, are you a democrat or a republican? The first thing I'd always ask them is, are you okay?" has 4 occurrences.

These frequency counts highlight her emphasis on collective identity ("we"), national unity ("people," "American people," "United States"), and political contrasts (mentioning "Trump" and "Biden"). Additionally, her rhetorical style blends assertiveness ("let me be clear," "I'm the only person on the stage") with appeals to moral authority and empathy, particularly in references to her background as a prosecutor.

In terms of linguistic analysis, the most frequently used words reveal interesting patterns. During the debates, the most common word was "we", accounting for 1.54% of all words, followed by "people" (0.86%), "president" (0.84%), and "our" (0.8%). These frequencies suggest a strong emphasis on collective identity and leadership. In comparison, speeches and interviews also highlighted "we" even more prominently at 1.81%, with "our" at 0.87% and "people" at 0.72%, indicating a consistent rhetorical focus on inclusivity and representation across different forms of political communication. According to our analysis of Kamala Harris's debates, interviews and speeches, the frequency of rhetorical devices is as follows:

Table 1.

Kamala Harris's Use of Rhetorical Devices in Public Speaking

Rhetorical Device	Debates (2020 & 2024)	Interviews & Speeches
Anaphora	10.1%	8.9%
Epiphora	1.9%	3.5%
Detachment	3.2%	5.6%
Anadiplosis	1.6%	4%
Symploce	0.3%	2.2%
Antithesis	1.6%	1.1%
Idioms	0.3%	1.1%
Tricolon	1.6%	2%
Prolepsis	0.3%	0.2%
Metaphor	0.5%	3.3%
Gradation (Climax)	0.5%	0.4%
Parcellation & Ellipses	0.6%	3.4%
Rhetorical Questions	2.8%	2.5%
Tautology	-	1.5%
Hyperbole	-	0.5%

Anaphora – repetition of initial phrases for emphasis. Anaphora is a powerful tool in which a phrase or word is repeated at the beginning of successive clauses or sentences to reinforce a particular idea or call to action. Harris often uses this technique to emphasize key themes such as leadership, justice, and action.

– "You respect the American people when you tell them the truth. You respect the American people when you have the courage to be a leader [8]."

Epiphora – repetition at the end of sentences. Epiphora creates a rhythmic and reinforcing effect. Harris uses this technique to leave a lasting impact on her listeners, emphasizing crucial points.

– "It is a strength we have that has lasting effect. So all that work that you did that was about engaging with other people, engaging with perfect

strangers and in their face seeing a neighbor that has lasting effect [10]."

Symploce – combination of anaphora and epiphora. Symploce blends anaphora and epiphora, repeating a word or phrase at both the beginning and end of successive clauses. Harris uses this strategy to create powerful, resonating statements that highlight both a sense of urgency and a connection between the beginning and end of her arguments.

– "A fight for freedom and opportunity that did not end on November 5th. A fight for the dignity of all people, that did not end on November 5th [10]."

Anadiplosis – repetition of the last word of one clause at the beginning of the next. Anadiplosis is a subtle yet effective device where the last word of one clause is repeated at the beginning of the next. Harris

uses this device to create continuity and cohesion within her speeches.

– *"He has repeated it many times, and you and I both know that. And you and I both know that he has talked about turning the American military on the American people [15]."*

Idioms – figurative language used for rhetorical impact:

– *"The stakes are even higher [13]."*

– *"He fanned the flames [11]."*

Metaphors are used to create vivid, relatable images that make abstract ideas more tangible. Harris frequently uses metaphors to inspire and motivate her audience, as seen in the following examples:

– *"Turn the page on this same old tired rhetoric [9]."*

– *"Our small businesses are the backbone of America's economy... [12]"*

Antithesis – contrasting ideas in parallel structure. Antithesis is a rhetorical device where two contrasting ideas are placed together to highlight their differences. Harris uses antithesis to frame her arguments by positioning her vision for the future against her opponent's actions or policies.

– *"...my plans will strengthen America's economy. His plans will weaken America's economy [16]."*

Rhetorical questions – questions that do not expect an answer. Rhetorical questions are designed to provoke thought and engage the audience. Harris uses them to challenge her listeners, inviting them to reflect on pressing issues.

– *"And one must ask, why exactly is it that they don't trust women? [11]"*

Prolepsis:

– *"...you know, Joe, he, I think he said it quite well [8]."*

– *"My mother, she worked long hours [11]."*

Detachment:

– *"We must be able to also, as it relates to China, continue to do the work that we have begun to deal with the flow of fentanyl coming into the United States [14]."*

Parcelling is a rhetorical device where a larger statement or argument is broken down into smaller, digestible pieces. Harris often uses this to slow down her message and ensure each point lands with emphasis.

– *"Vote. Please vote. Vote early. Come up with a plan to vote [8]."*

– *"And her life was taken. Unjustifiably and tragically and violently [8]."*

Ellipsis is used to omit parts of a sentence, often creating suspense or giving the audience space to fill in the blanks. This device allows Harris to maintain a conversational tone while encouraging listeners to reflect on what is not being said.

– *"...I will proudly sign it into law. Proudly [13]."*

– *"I am so sorry for her loss. Sincerely [15]."*

Tricolon (rule of three) – grouping ideas in threes for impact. The tricolon is an effective way of emphasizing key points, with three parallel ideas that are easy

to remember and impactful. Harris often uses this device to make her message more persuasive and compelling.

– *"The freedom to live safe from gun violence... the freedom to love who you love... the freedom to breathe clean air and drink clean water [11]."*

– *"...which include the need for humanitarian aid, the need for this war to end, and the need for a deal to be done... [14]"*

Hyperbole – exaggeration for effect:

– *"The most extraordinary story ever told [11]."*

– *"And, you know, when I was Attorney General, the words I spoke could move markets [14]."*

Climax – building up intensity. Climax involves arranging ideas in an ascending order of importance, often heightening intensity or urgency as the argument progresses. Harris uses climax to leave her audience with a strong final statement that carries emotional weight.

– *"...that he is unfit to serve, that he is unstable, that he is dangerous... [15]"*

Tautology involves repeating an idea in different words, often to emphasize a point or make it memorable. Harris uses this to ensure that her messages are clear and undeniable.

– *"...and the President of the United States of America and the Commander-in-Chief of the United States of America [14]."* Here, the repetition emphasizes the importance and authority of the President's role, reinforcing the weight of the office.

Tautology in appended statement:

– *"...I truly believe in the promise of America. I do [14]."*

Parallelism is a rhetorical device where successive phrases or clauses follow the same grammatical structure, which makes the argument easier to follow and more impactful.

– *"...your vote is your voice, and your voice is your power... [13]"*

Kamala Harris' speech in Wisconsin is structured around repetition, with key phrases and ideas reiterated throughout. Nearly every section reinforces central themes – her vision for leadership, commitment to equality, and policy priorities – through repeated wording and parallel structures. This rhetorical strategy not only strengthens her message but also enhances its memorability and emotional impact on the audience.

"And we will win. And we will win. And we will win [13]."

"Never again! Never again! Never again! [13]"

"...and now the baton is in our hands. Now it's in our hands. It's in our hands [13]."

A similar rhetorical strategy is evident in Kamala Harris' interviews for 60 Minutes and FoxNews. Just like in her Wisconsin speech, her responses are structured around repetition, with key phrases and central themes reiterated throughout.

"...I truly believe in the promise of America. [...] I believe in large part it is because of our character and our belief in the promise of America [14]."

"They want support. They want support and that's what that border security bill would have done [15]."

Framing with "I get it": *"I think they're frustrated and I get it. They want support. They want support and that's what that border security bill would have done. These guys down at the border, these men and women, they're working hard. They're working around the clock. I get it [15]."*

A comparative analysis of rhetorical device usage in Kamala Harris's debates (2020 and 2024) versus her interviews and speeches reveals notable stylistic distinctions shaped by context and communicative intent. Certain rhetorical strategies are more frequently employed in debates, such as anaphora (10.1% in debates compared to 8.9% in interviews and speeches), which emphasizes structured repetition to enhance rhetorical force. Antithesis also appears slightly more often in debates (1.6% vs. 1.1%), reinforcing contrasts and sharpening arguments. Devices like prolepsis (0.3%) and gradation or climax (0.5%) show marginally higher usage in debates than in interviews (0.2% and 0.4%, respectively), pointing to a stronger emphasis on anticipation and intensity in formal, confrontational settings.

Conversely, several devices are more commonly used in interviews and speeches, reflecting a more conversational, expressive, or persuasive tone. Epiphora is used nearly twice as often (3.5%) as in debates (1.9%), suggesting a preference for end-of-phrase repetition in less formal contexts. Metaphor (3.3% vs. 0.5%) and ellipses (3.4% vs. 0.6%) are significantly more prevalent, indicating greater use of figurative language and a looser, more reflective speaking style. Idioms (1.1% vs. 0.3%) reinforce relatability and informality, while anadiplosis (4% vs. 1.6%) reflects a more deliberate effort to link ideas for rhetorical emphasis.

Some rhetorical devices appear exclusively in interviews and speeches. Symplote (2.2%), which combines anaphora and epiphora, is absent from debates, perhaps due to its complexity and suitability for longer, prepared remarks. Tautology (1.5%) and hyperbole (0.5%) also appear only in these contexts, highlighting a shift toward emphatic or emotionally charged language.

A few devices remain infrequent across both settings; e.g., idioms, prolepsis, and gradation show relatively low usage overall. Tricolon maintains a consistent, though modest, presence (1.6% in debates and 2% in interviews), underscoring its role as a stable structural element across genres.

The analysis confirms that political discourse is a vital instrument in the struggle for power. It serves not only to articulate policy and ideology but also to assert dominance and reshape public opinion. This multifaceted role underlines the strategic importance of language in political leadership.

Kamala Harris's verbal image is carefully crafted to adapt to different communication settings, balancing structured rhetoric in debates with a more dynamic and engaging style in interviews and speeches. In debates, she relies on anaphora, antithesis, and structured repetition, reinforcing key messages and strengthening arguments. Her speech in these settings is deliberate, emphasizing clarity, authority, and contrast to persuade the audience and challenge opponents effectively. In interviews and speeches, her verbal image becomes more

flexible and engaging. The higher frequency of metaphors, epiphora, ellipses, and idioms suggests a more conversational and relatable tone. The presence of symplote, tautology, and hyperbole – absent in debates – further enhances this impression, making her speech more expressive, persuasive, and adaptable to different audiences. Harris's verbal image combines strategic precision with rhetorical versatility, allowing her to project both strength in formal settings and charisma in public discourse. This dual approach helps her maintain credibility while fostering a connection with voters and supporters. The frequent recurrence of key phrases and collective pronouns reinforces themes of unity and shared identity. This strategic repetition not only aids in message retention but also aligns the politician with the values and aspirations of the electorate, fostering a sense of community and common purpose.

Ultimately, the verbal image of a politician is not merely a reflection of their communication style but a deliberate construct that influences public trust, credibility, and political success. As political discourse continues to evolve with new media and technological advancements, further research could explore how digital platforms shape the perception of political figures and redefine traditional rhetorical strategies.

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Bachelor's student, Foreign Languages Department, Kazakh American Free University<https://doi.org/10.5281/zenodo.15298393>**Abstract**

The article describes some recent developments in political journalism, namely, shift to interpretive journalism, characterized by strategic framing, increased focus on conflict and negativity, and a blending of factual content with analytical commentary. The linguistic dimension of Tucker Carlson's rhetorical style, focusing on the persuasive techniques and recurring themes in his televised speeches from 2021 to 2023 is examined. An in-deep analysis of Carlson's verbal strategies reveals a consistent thematic framework centered on societal decline, threats to traditional values, and elite-driven narratives, achieved with such rhetorical devices as repetition, contrast, rhetorical questions, hyperbole, irony, and historical analogies which contribute to eliciting emotional engagement of the audience, particularly through appeals to fear, outrage, and mistrust.

Keywords: political journalism, interpretive journalism, rhetorical techniques, polarization, communication strategies, non-cooperative strategy, Tucker Carlson, political discourse.

Political journalism is considered one of the most significant spheres of the media, which has a significant impact on the functioning of democracy. It includes the collection, coverage, and analysis of news related to public administration, political processes, and legislation. The main goal of political journalism is to provide to citizens reliable information about recent events, monitor the activities of the authorities, and create a platform for political discussion, and exchanging different points of view. Nevertheless, the question of its effectiveness remains unresolved, since both internal and external factors affect the media [1].

Political journalism is influenced by many factors that can be considered at various levels. At the systematic level, the political, economic and legal environment in which the media function is constitutive. The organizational level includes the internal structure of newsrooms, editorial standards and the economic model of media. Concurrently, individual factors such as journalists' professional values and working style also play a key role. Furthermore, political journalism is closely related to the political context, where the interests and strategies of different groups can significantly involve the content of news stories [2].

About the content, researchers have identified several key trends that characterize political journalism in western democracies. Firstly, there has been a tendency to portray politics as a strategic game that focuses on the tactics and maneuver of politicians rather than on discussing the substance of issues. Secondly, there has been a rise in interpretive journalism, with analytical articles and opinion pieces gradually replacing neutral news reporting. A further distinctive feature of political journalism is its emphasis on conflicts, scandals and negative aspects of political life. This aspect of journalism is often characterized by drama and provocativeness, but studies demonstrate that structural and situational factors have a greater impact on the content of the news agenda than the overt political prejudice of journalists. The issue of media prejudice is a relevant one in this context, however, and it is important to note

that research shows that prejudice impacts news reporting more significantly than other forms of prejudice [3].

The field of political journalism has experienced major transformations in recent decades because of digital media expansion and changing news audience behavior and declining public trust in established media outlets [4]. The modern journalism industry is transforming its fundamental principles which include objectivity, factuality and neutrality. News standards that originated from balanced reporting with reliable sources and clear opinion/news separation face changes because of new information dissemination trends. This interpretive style, evident in analytical articles, extensive reports and even conventional news stories, involves supplementation of factual information with interpretive elements [1]. Fact-checking plays a pivotal role in this process, serving not only to combat misinformation but also becoming an integral component of the analytical approach.

Contrary to traditional journalism, characterized by impartiality, the interpretive style is marked by a more pronounced journalistic voice, the inclusion of value judgements and an expanded contextualization of events. This transition has been shown to have a multifaceted impact on the political sphere. On the one hand, it could reinforce negative views of politics by portraying it as a calculated endeavor that prioritizes the political maneuvers over the issues at hand. However, mass media have the power to shape public opinion and guide public conversation by shedding light on specific aspects of political processes. With growing information flow and the propagation of misinformation, interpretive journalism offers journalists an opportunity to maintain their independence from political elites and to analyze events in greater depth, thereby assisting audiences in more effectively navigating complex political processes [1].

The present time is characterized by a marked tendency within the sphere of political journalism to prioritize the coverage of adverse events and conflicts. This phenomenon can be attributed to the strategic intent of appealing to audiences by presenting such reports as

being more profound and substantial [4]. Recent research findings indicate that news media are more likely to disseminate news if it features accounts of crisis situations or generates a sense of threat. This phenomenon aligns with broader trends in contemporary media consumption and dissemination [2]. The phenomenon is largely related to the peculiarities of human psychology, as people instinctively react to information about potential risks. It is important to distinguish between negativity and conflict in news stories, although these concepts are close. Negative coverage may include criticism of authorities, revelations of corruption and scandals, while conflict-centricity focuses on confrontations between political forces. According to Lengauer, Esser and Berganza (2012), there are several hallmarks of negative journalism. These include a pervasive critical tone directed towards political actors, an accentuated focus on conflicts, the leveling of accusations against individuals or political entities and a tendency towards pessimistic prognostication.

Proliferation of negative and conflict-oriented journalism has been identified as a major contributing factor to the spread of such reporting, with the process of commercialization of media recognized as a key element in this phenomenon. This phenomenon exerts a substantial influence on the nature of news coverage, compelling private media outlets to prioritize sensational and controversial stories. Commodification of media services has been identified as a significant factor in the propagation of deleterious trends. Private media outlets have been shown to exhibit a higher propensity to engage in the dissemination of sensational and contentious narratives, a tendency that is purportedly driven by a pursuit of heightened viewership ratings and an enlargement of their demographic reach. In countries characterized by intense market competition among media outlets, this phenomenon is especially evident [5]. This strategy of news coverage has been demonstrated to have a considerable impact on public opinion: a constant focus on crises and conflicts contributes to the development of a political outlook marked by cynicism and distrust of state institutions. While journalism based upon the principles of objectivity and impartiality fulfils a vital function within a democratic society, it can also contribute to the development of a polarized public and levels of public discontent [4].

Therefore, it may be concluded that negative news constitutes an integral element of political journalism; however, the prevalence of such reporting is determined by a variety of factors. Such factors may be categorized as including country-specific characteristics and media market strategy. The phenomenon remains a subject of active research, as its impact extends beyond the scope of individual events and affects public sentiment on a broader scale. From a theoretical standpoint, politics is regarded not solely as an object, but also as an active subject, utilizing diverse communication mechanisms to shape, maintain, and transform social reality. In this context, the function of political journalism is pivotal in serving as a conduit between politicians and their respective audiences, with journalists operating as intermediaries who dictate the manner in

which information is disseminated, whether in its entirety or in a redacted form, and in an affirmative or negative light [2].

The goals of the political organization dictate the choice of a communication strategy, which may be either cooperative or confrontational. The cooperative approach is all about ensuring effective interaction, where the primary goal is the generation of high-quality communication and the secondary goal is adaptation to the specific situation. The implementation of this strategy, if done well, will help in the achievement of both of these goals. On the other hand, non-cooperative strategies involve more forceful methods of engagement, which include strategies for open conflict, credibility destruction, and controlling the communication process. These approaches are applied in all types of political discourse, both monologic and dialogic forms of communication [6].

Research findings show that news programs, with a heightened and more adversarial tone, tend to overestimate audience interest [18,6]. Such programs are an "echo chamber," offering a daily news source for their audiences, which in turn seek validation of their perspectives from other news sources. In addition, the research indicates that social networks as a source of news create isolated information bubbles [18,12]. In addition, there is a general overestimation of the frequency of news consumption: For example, 45% of the participants report that they consume the news 5-7 times a week, whereas observational data reveal that this percentage is merely 20% [18,6]. Moreover, studies show that individuals who regularly consume content containing conspiracy theories or fake news tend to use social media as the main source of information [18,12]. The potential to tailor algorithms to suit particular user interests has been cited as a cause of this trend because it optimizes audience participation and gets a better reaction. So, the popularity of news shows that are characterized by combative rhetoric, such as "Tucker Carlson Tonight," may be attributable to several reasons. The above dynamics could include the echo chamber effect, the consumption of customized content through social media outlets, and an inflated self-assessment of news consumption patterns by audiences. These dynamics act to enhance polarization in society and the spread of false narratives in the news environment.

A clear illustration of non-cooperative strategies at play in the field of journalism is presented by the corpus of work by the American political commentator Tucker Carlson. The defining aspects of his work are marked by a skeptical questioning of official discourses and biting polemics, along with a strong tendency towards confrontational argumentation. These aspects render Carlson's work a relevant illustration of an aggressive communication style. Over time, Mr. Carlson has managed to gain a large following due to his presence on television programs and internet media platforms. This, in turn, has enabled him to wield a great deal of influence over public opinion. Peaking at 2020 with an average of 4.2 million viewers per week, his program Tucker Carlson Tonight on Fox News has been one of the highest-rated news programs on US cable television

[7]. After leaving Fox News in 2023, Carlson established his own media company called the Tucker Carlson Network. This helped him solidify his place in the media via independent digital avenues. His podcast quickly became the second most popular podcast on Spotify, with the debut episode on Twitter having garnered nearly 120 million views. Later episodes, however, witnessed a decline in the interest of viewers [11]. Carlson's personality is a personality that is not without controversy: the traits he is also renowned for are his forthrightness and his willingness to raise issues that are considered sensitive, as well as his willingness to confront the mainstream media. He is thus seen as an alternative voice in the media world [9]. Meanwhile, he has also been blamed by critics for being responsible for the dissemination of conspiracy theories, slanted reporting, and the exploitation of journalism as a tool for political manipulation [12].

Tucker Carlson is a unique media figure with millions of fans and haters worldwide. Known for his uncompromising and dynamic approach, demanding direct answers and keeping interviews energetic, effectively connecting with viewers and creating memorable moments, combining political analysis with personal views, focusing on topics of significant public resonance, he has long become one of the most influential political journalists [10]. His interviewing style and rhetoric, public persona and perception as well as the themes he discusses and people he interviews have provoked heated debate in mass media and attracted numerous researchers. Tucker Carlson's distinctive and contentious approach to journalism has elevated him to the status of a leading figure in the field.

His unconventional style has garnered significant attention, with numerous studies examining the content of his publications and the rhetoric he employs on his eponymous talk show, Tucker Carlson Tonight. Consequently, a number of studies have been conducted by media outlets such as NPR and Politico, examining the content of his publications and his rhetoric on the Tucker Carlson Tonight show. A research study conducted by journalists at The New York Times analyzed all 1,150 episodes of Tucker Carlson Tonight from 2016 to 2021 in order to identify consistent storylines and patterns of presentation [14]. The study revealed that Carlson's rhetoric was designed to evoke feelings of cognitive dissonance in viewers by contrasting the 'ruling class' ('them') and the Fox News audience ('you'). The analysis showed that Carlson's rhetoric was intended to instil fear and distrust in viewers towards elites and progressive movements. In April 2021, he overtly endorsed a conspiracy theory concerning 'replacing whites' through immigration, and an analysis revealed that the topic had been raised over 400 times since 2016. In general, the researchers stated that his assertions frequently entwined factual information with fictional elements [15]. The New York Times created a database that captured the key themes and rhetoric of Carlson's show, including data on the time spent on each topic, as well as guests and their agreement or disagreement with the host [14]. Over time, the programme became increasingly aggressive and straightforward, becoming an 'echo chamber' where Carlson's ideas were presented without criticism [16]. The jury

recognized the efficacy of Carlson's utilization of his own words in conjunction with visual components, a combination that rendered the article particularly appealing and persuasive. The investigation revealed the impact of the gradual introduction of ideas on the formation of public opinion, thereby demonstrating the influence of the media on public opinion. Notwithstanding the boycott by major advertisers, the show maintained its commercial success, largely due to its loyal audience.

Carlson's capacity to articulate contradictory assertions in disparate programmes while sustaining the confidence of his audience attests to his proficiency in rhetoric. He adroitly escalated tensions by depicting liberal journalists, Hollywood celebrities, Democrats and progressive youth as adversaries. Additionally, Carlson has overtly endorsed far-right politicians such as Viktor Orbán, Jair Bolsonaro and Andrzej Duda, as well as Donald Trump.

The influence exerted by Carlson on public opinion is defined not only by his oratory skills, but also by his ability to create vivid and memorable moments for the media. Even his final broadcast on Fox News was meticulously planned, involving the consumption of substandard pizza, a discussion on the 'heroic delivery man', and the promotion of a new documentary. Carlson's ability to evoke a wide range of emotions in viewers, from outrage to pride, was the result of a deliberate strategy [17].

Despite being harshly criticized for his controversial and theatrical manner, with frequent interruptions and moralising, divisive rhetoric, often pitting "ordinary people" against "globalists" or "elites," reliance on sarcasm and performative anger (which, as critics argue, misrepresent complex issues), he has unparalleled influence on mass audience maintaining their loyalty through assertiveness and emotional appeal. He is seen by many as a voice against mainstream liberal narratives, representing an "anti-elite" perspective, who tackles issues of public resonance with a bold perspective. This makes him project simplicity and relatability to everyday citizens despite a privileged background [17]. It can be seen from the above-mentioned, that Tucker Carlson is a confrontational personality; however, it must be mentioned that he possesses abilities as an excellent journalist. The rhetorical strategies employed by Tucker Carlson incite controversy and yield charges of combative rhetoric, but his style is definitely effective.

In contrast to previous studies, this research tackles the linguistic dimension, specifically the words and processes used by Tucker Carlson in his verbal speeches. The sources of the research are a collection of speeches made by Tucker Carlson from 2021 to 2023 [22-30]. Through the close examination of the materials, we were capable of determining not just rhetorical strategies used by the speaker but as well as prevailing themes that recur in successive speeches. One dominating theme among the materials is recognizing the perilous course of modern political, social, and worldwide trends. This perspective is characterized by the feeling that Western society is undergoing a period of grave instability, signaled by the erosion of customary values,

the restriction of freedom of speech and the enforcement of policies by political and economic elites that culminate in an environment of turmoil. The texts under scrutiny adopt a conservative and critical stance, centering on three primary issues: gender identity problems and their implications, increasing military conflicts (including threats of nuclear war), and the role of the media, politicians, and big business. Of particular concern is how the understanding of gender is being transformed. Tucker Carlson's orations view this as a questioning of biological facts and traditional values. Tucker Carlson's talks correlate with Christine Ellingsen's case, who is a self-proclaimed Norwegian feminist that has criticized drugs interfering with puberty among children. Through this, she sheds light on the potential consequences of such medical intervention, which include being sterilized and other irreversible outcomes [23]. One other point made in another statement is that children as young as 10 years old are being injected to stop puberty and then given hormones of the opposite sex that make them infertile. This statement, 'Billboard Chris: This is the "biggest child abuse scandal" in modern medicine', claims that all these are being projected as 'gender-supportive medicine'. The speech also claims that one of the biggest scandals of forced sexual transformation of kids is now taking place in the medical field. It contends that these procedures are referred to as 'gender-supportive medicine,' although in reality they inflict irreversible harm on children [24].

The second significant topic is military conflicts, specifically the situation surrounding Ukraine and the growing threat of nuclear war. In the article 'Tucker talks American and Ukrainian borders with Rep. Salazar', we find that the chances of war with Russia are on the rise as U.S. leaders are supporting a strong approach and are not ready to think about peaceful solutions to end the crisis. A majority of people see that a huge war with Russia is inevitable since most powerful individuals support it. The nuclear warming theory argues that humanity's biggest threat is not global warming but nuclear weapons. In his address titled 'Trump warns of modern-day weaponry: Our biggest problem is "nuclear warming"', the President points out that if the leading world powers continue to fuel wars without restraint, it may result in a catastrophe even greater than what we anticipate of global warming. The speech compares the issue of global warming to the threat of nuclear weapons and claims that global warming is assumed because of nuclear weapons. It argues that the most significant threat should be nuclear warming and not the much-debated topic of global warming [26].

The third theme is about criticism of the media, large corporations, and politicians. The authors feel that these institutions manipulate society and suppress freedom of speech. In his article 'Diversity trainers weaponise critical race theory to systematically attack the unifying ideals of America', Chris Rufo claims that critical race theory has been introduced in US public institutions. It is being done, according to him, to polarize society along racial lines, which enhances current conflicts. Rufo believes that hired diversity trainers are slowly eroding the things that hold the nation together, dividing Americans against each other based on the color of their skin. The topic that we are discussing is

how the media can strengthen a particular belief by silencing other opinions, as well as the vast power of large corporations in dictating political agendas and derailing democratic processes. Others state that no corporation should be that powerful in relation to politics to overrule what the voters want [27]. The overall argument in these documents is that there is a lack of trust in the story that is being told by the politicians and the media. The overall assumption is that there is a crisis in Western society. The crisis is linked with changing ideas, the demolition of traditional institutions, and straying from the principles of free speech.

An analysis of Tucker Carlson's speeches demonstrates the active use of specific techniques in an attempt to become more convincing and emotionally appealing with his arguments. These techniques act synergistically to alter the manner in which the audience thinks, cast doubt over the official narratives, and stimulate the sense of urgency and frustration. One of the conventional ways of driving a point home is by repetition. This is seen from the repeated use of statements like *"for months, the public have been told."* or *"we have heard time and time again."*. This creates an impression that there is an information campaign that has been well planned. This is seen in one section: *"For the last 14 months, you've heard two things about the war in Ukraine."* [25]. This technique of expressing the message illustrates that the audience has been provided with a universal message that can be misleading. By indicating how widespread and persistent these comments are, the speaker renders them less trustworthy and elicits disappointment and suspicion. The rhetorical device of contrast, the antithesis, is related to a frequent theme of repetition throughout the texts, in which two opposing forces are repeatedly set alongside one another: the powerful and the people, truth and lies, and reality and illusion [19]. As shown by the statement that *"He revealed the crimes, therefore he is the criminal"*, such a contrast between antithetical forces operates to reinforce a pervasive theme of regime dishonesty and oppression. This is a rhetorical technique that specifically accentuates the contradiction inherent in the situation, evoking a critique of the rationale for the decisions of those with power. Such an effect is also created through the utterance, *"Telling the truth is the only real sin,"* which suggests the notion that speaking the truth gets punished, thus supporting the prevalent theme of systematic dishonesty and oppression [28].

The employment of rhetorical questions has been shown to be an extremely effective way of appealing to the audience and guiding their thoughts [20]. Rather than presenting direct assertions, the texts pose inquiries such as *"Why would we fight Russia? Wouldn't making Russia our enemy drive Putin into the arms of China?"* or *"Who are these officials who lied to Reuters?"* [26; 29]. These interrogations subtly suggest that there are straightforward but unnoticed solutions, thereby prompting the audience to challenge dominant discourses. The use of these interrogatives by the speaker aims to provoke critical thought as well as lead the audience towards a particular conclusion. Hyperbole is a rhetorical device that heightens emotive appeal by exaggeration [20]. A pertinent illustration is provided by the following: *"They are treating him like*

Osama bin Laden. Maybe worse, actually."[28]. This increased comparison is done to enhance the feeling of perceived injustice in the case, evoking a gut response from the audience. In the same vein, the rhetoric of fear becomes effective by employing, for instance, the line *"The animals are dying, the water is glowing" when describing a nationwide environmental disaster* [29].

This type of language is employed to invoke anger and dramatize the crisis. Appealing to fear in speech is common when referring to geopolitical war [19]. The most obvious example of this is stating that *"this is a hot war between the two leading nuclear superpowers on Earth"*, which brings about the feeling of an imminent catastrophe [29]. By portraying the conflict as a serious danger, the speaker is making the audience increasingly anxious. Using fear in a speech is a very effective way of convincing people. One of these techniques is to show that the people are against the elite class, e.g., *"Us versus them."* They reaffirm this through such remarks as *"News agencies print what they are told to print by the intelligence agencies."* [29].

This implies that the mass media does not come into being as an independent institution but as a voice for the powerful and therefore plays a role in creating a gap between the masses and the elite, and consolidating the feeling of antagonism and suspicion against the latter. Additionally, the contention that *"the media are completely determined to suppress the truth"* works to reiterate the implication that the listeners are being actively deceived, and thus creates a sense of camaraderie amongst listeners who believe they have a common enemy [29]. Of note, the texts use irony and sarcasm, techniques which, as widely documented, work to ridicule oppositional argument whilst simultaneously debilitating its credibility. We can look, for example, at the sentence *"Our senile president has just given some kind of medal to a sitcom actress, purportedly for courage"*, which satirizes governmental action by bringing it down to its most ridiculous characteristic. In the same manner, the expression that *"Respect indigenous knowledge, don't drive our cars"* is used to illustrate how, in the author's view, the above arguments are not sincere [30].

The use of mockery in the form of the statement *"And the amazing thing is—it's kind of working"* is used to satirize environmental policies by implying their irrationality and counter-effectiveness [26]. Such a derisive tone not only amuses but also bolsters ideological identification by rendering opposition ridiculous. The use of absolute rhetoric has also been recognized as rhetorical tactics are characterized by the deliberate diminution of the field of debate by the introduction of diametrically opposed terms; for instance, the words *"This is the worst act of war I have ever seen us commit"* and *"This is the most dishonest war in history"* work to introduce the speaker's opinion as the sole valid opinion by diminishing the field of debate [29]. This style of rhetoric is especially useful in reducing complex matters and thereby rendering them more appealing to the listeners [20].

One of the prominent characteristics of the texts under scrutiny is that they utilize anecdotal proof and selective framing. The account often uses isolated incidents – for example, the derailed train in East Palestine,

Ohio – to demonstrate overall systemic breakdowns [30]. By sharing these occurrences and contrasting them with the expense of foreign aid, the speaker reaffirms the opinion that the government is more interested in foreigners' interests than the country's citizens are in their own health. Further, the texts demonstrate a strategic use of direct audience participation [20]. These kinds of utterances as *"Are we really meant to believe this?"* or *"What will they say now that we know the truth?"*, for example, have an interactive effect and thus bring about a feeling of personal involvement in the debate on the part of the audience [27]. This direct address helps to create a sense of joint discovery and also helps to bolster the idea that the audience is an enlightened minority that can see beyond deception. Because the texts repeatedly use historical analogies to offer parallels between current and past events (e.g. comparisons with the Cold War and past wars) they create a context backdrop to introduce geopolitical matters, thus making them more understandable and credible. Historical analogy is employed to make the case that the same mistakes of past foreign policy are being made in the present crisis, citing *"what occurred in 1960 with Fidel Castro and JFK"* [25].

It can be seen from the above analysis that Tucker Carlson is a confrontational personality; however, it must be mentioned that he possesses abilities as an excellent journalist. The rhetorical strategies employed by Tucker Carlson incite controversy and yield charges of combative rhetoric, but his style is definitely effective. As Carlson's career continues and encounters more challenges, it is only natural to anticipate that his style will change over time.

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Mugamat Kh.*Associate professor of the Department of Language & Literature,
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The internationalization of a native language is a matter of critical significance, particularly in the context of safeguarding national identity and contributing meaningfully to the cultural mosaic of the globalized world. This process refers to the deliberate and systematic promotion of a national language beyond its domestic boundaries, facilitating its functional presence in diverse international arenas. For smaller linguistic communities especially, internationalization is not merely a cultural aspiration but a strategic necessity to ensure linguistic vitality in an increasingly interconnected global environment. In recent years, the Azerbaijani language has witnessed a growing international presence, extending its utility and influence across multiple sectors, including but not limited to science, education, technology, politics, culture, economics, and tourism. This expansion is indicative of a broader national effort to elevate the language's status within global communication networks and to enhance its role as a medium of scholarly and cultural expression on the international stage.

The responsibility for advancing the global profile of the Azerbaijani language largely falls on key national institutions, most notably the Ministry of Culture of the Republic of Azerbaijan, the Heydar Aliyev Foundation, and the State Committee on Work with Diaspora. These bodies play a pivotal role in implementing language policy, promoting Azerbaijani culture abroad, and facilitating transnational linguistic exchange through various projects, initiatives, and collaborations. This research critically examines the principal methods and strategic directions aimed at increasing the global visibility and communicative capacity of the Azerbaijani language. A particular focus is placed on the role of digital platforms—educational, cultural, literary, informational, and social media in creating spaces for Azerbaijani language use in virtual environments. These platforms serve not only as vehicles for dissemination but also as tools for linguistic innovation and engagement with younger, tech-savvy generations.

Moreover, the study underscores the necessity of enriching the terminological base of the Azerbaijani language, particularly in scientific and technological domains, in order to ensure its adaptability and competitiveness in global discourse. It also highlights the importance of integrating the language into contemporary technological infrastructures, developing high-quality educational resources, and implementing targeted promotional strategies in multiple foreign languages to reach broader international audiences.

In sum, the internationalization of the Azerbaijani language is a multifaceted and long-term endeavor that requires coordinated efforts across governmental, academic, and cultural institutions. It demands not only strategic planning and resource allocation but also a vision that aligns linguistic development with global cultural and technological trends. As such, the process constitutes an essential component of Azerbaijan's broader cultural diplomacy and soft power initiatives in the 21st century.

Keywords: digital platforms, educational platforms, information platforms, social media platforms, automatic translation systems, chatbots, technological capabilities of the language, national corps

Introduction

Language is the leading intercultural tool and the carrier of some culture. A person realizes his national identity within the framework of belonging to one culture or another. This understanding is fixed in the linguistic consciousness of the individual and is reflected in the process of communication.

Language is one of the main factors ensuring the national unity of the nation. Speaking about caring for our mother tongue, the President Ilham Aliyev said: "There must always be respect and care for our mother tongue. We must protect our mother tongue from foreign influence. Our mother tongue is our inviolable wealth. Our mother tongue - the Azerbaijani language - has played an exceptional role in the formation of the Azerbaijani people and the formation of independent Azerbaijan. We must ensure that we always preserve the purity of our language. This issue must be given very serious attention".

Today, the development and protection of the Azerbaijani language is one of the state's priorities. Prof. Nizami Khudiyev groups the principles of the language policy of Great leader Heydar Aliyev as follows: "As in all fields, in language policy, he takes global goals as the basis and decides to solve any issue, taking into account all its aspects, past, present and future" [4].

Internationalizing the native language means promoting the use and learning of a language by more people worldwide. This is one of the most important steps taken to increase the reputation of the language, spread its culture and create various opportunities for its users. Although this process requires long-term and multi-faceted efforts, every citizen of the country who cares for the language should take responsibility for this work and do everything in his power to promote and promote the native language.

We consider it more appropriate to systematize the directions for internationalizing the native language as follows:

1. To promote language teaching and learning;
2. To increase the reputation of the language in the scientific and cultural fields;
3. Increasing the technological capabilities of the language;
4. Strengthening political and economic relations;
5. Using the potential of the diaspora.

With the support of the Ministry of Culture of the Republic of Azerbaijan, Azerbaijani cultural centers in foreign countries implement important projects in the direction of promoting and teaching the Azerbaijani language, along with our national culture. The centers opened for the teaching of our mother tongue in different countries create wide opportunities for foreigners who are interested in learning our language. Since 2017, the "Azerbaijani Language and Culture" Center has been operating at the State University of Xuzhou, which has a wide infrastructure, located near the city of Shanghai, People's Republic of China. In the created center, the state attributes of Azerbaijan, the history, geography, ethnography, literature, culture, history of statehood of Azerbaijan, its current position in the world community, books reflecting the Armenia-Azerbaijan, Nagorno-Karabakh conflict, collections of paintings by our prominent artists, folk and composer music.

In 2025, on February 7, online and full-time courses on the Azerbaijani language were launched at the "Azerbaijan Studies Center" reserved for the Azerbaijan Cultural Center at the Central Campus of Gazi University in Turkey.

The work done in the direction of teaching the Azerbaijani language includes the organization of language courses, the training of leading teachers, the compilation of teaching aids, and the development of online teaching platforms. Thus, language courses, interactive lessons and other teaching materials are provided over the internet, allowing the language to reach a wider audience. As a joint project of the Heydar Aliyev Foundation and the State Committee on work with Diaspora, Azerbaijani language teaching aids have been prepared for pupils aged 6-10 at weekend schools operating in the Azerbaijani language in foreign countries. The book, published with the financial support of the Fund for support to the Azerbaijani Diaspora, was written by Sabina Aliyeva, associate professor of the Department of "Azerbaijani linguistics" of the Azerbaijan University of languages. In the preparation of the book, the children's age level, outlook, interests, and the necessary needs for communicating in Azerbaijani language were taken into account. The book, which consists of 37 sections, includes various tasks that develop grammar rules, reading materials, writing skills and oral speech [2].

Offering scholarship programs for foreign students to study in the native language in our country in the direction of teaching and promoting the Azerbaijani language can also contribute to increasing the use of the language in the academic environment. At the same time, the study of local students in foreign countries and the participation of foreign students in exchange programs in our country give useful results in the direction of internationalization.

The publication of scientific works in the international indexes in the native language strengthens the use of the language in the scientific environment. In addition, holding international scientific and cultural events in the native language also ensures participation in academic and cultural dialogue. Translation of works written in the native language into other languages, demonstration of films, theatrical performances and other works of art at international festivals serve to increase the cultural value of the language.

The use of the language in digital platforms, programs and artificial intelligence systems is ensured by technological capabilities. The use of the Azerbaijani language on digital platforms is rapidly expanding. This is of paramount importance for the development and dissemination of the language. We can mainly group digital platforms using the Azerbaijani language as follows:

- Educational platforms;
- Cultural and literary platforms;
- Information platforms;
- Social media platforms (Scheme 1).

Educational platforms include the "Digital School" platform (provides students with interactive lessons, tasks and tests on the Azerbaijani language, mathematics and other subjects), the "Virtual School" project (online resources, textbook materials and methodical recommendations are prepared for teachers in Azerbaijani as part of the project), the "Khan Academy" platform (free video lessons and training materials are available in Azerbaijani language on mathematics, informatics and other subjects).

Among the culture and literature platforms, "Azerbaijan National Library" (works of Azerbaijani literature classics, books by modern writers and other examples of cultural heritage are presented in electronic format), "Azerbaijan Culture" portal (information, photos and videos about Azerbaijani culture, history, art and traditions), YouTube (videos on various topics in Azerbaijani, including lessons, programs, films and music videos are broadcast) is distinguished by a greater degree of functionality.

The information platforms include Azerbaijan State Information Agency (AZERTAC broadcasts operational and accurate news in Azerbaijan and the world in Azerbaijani language), "Trend" Information Agency (presents political, economic and social news in Azerbaijan and the region in Azerbaijani language), "Sputnik Azerbaijan" Information Agency (publishes news, analytical articles and interviews on various topics in Azerbaijan and the world), etc. we can draw an example.

We can give examples of widely used social media platforms: "Facebook" (numerous groups, pages, channels and communities operate in Azerbaijani language), "Instagram" (shares, photos and videos are published in Azerbaijani language), "Twitter" (short messages and news are shared in Azerbaijani language).

These are only a part of the digital platforms where the Azerbaijani language is used, and the number of these platforms is increasing and strengthening the presence of the Azerbaijani language in the digital space. The use of the Azerbaijani language on digital

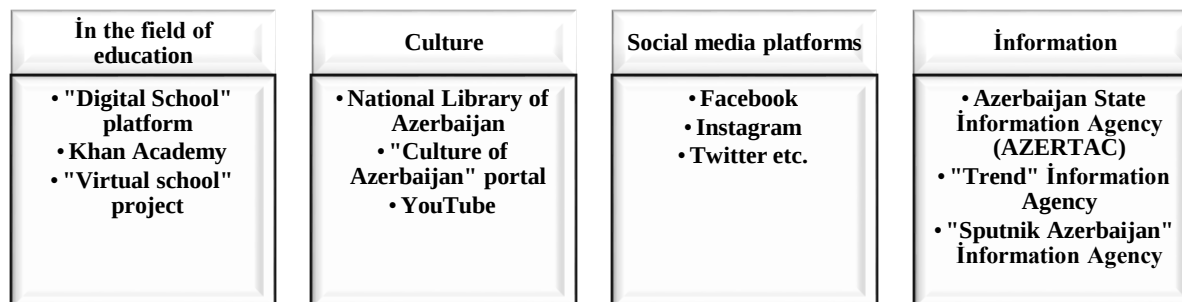
platforms is of great importance for the development, preservation and transmission of the language to future generations. These platforms are opening up new avenues for language learning, teaching, dissemination and use.

Digital platforms widely used around the world include Duolingo (one of the most popular language learning platforms, known for its gamified interface and various language courses), Babbel (operates on a subscription basis, offers high-quality language courses and live lessons with professional teachers), Memrise

(focuses on word learning and offers various techniques and games that help memorization), Rosetta Stone (focuses on language learning in a natural environment), Italki (offers the opportunity to take private lessons with teachers who speak different languages).

Expanding the use of our language on the Internet and in the digital environment to create interesting and useful online content (articles, videos, podcasts, etc.) in various fields; provides the native language interfaces of popular programs, websites and mobile applications, improves automatic translation systems.

Scheme 1.



It is well known that translation is a complex process that requires a deep understanding of both the source and target languages. Language translation is a tool for building bridges between cultures and people. It can help build understanding and strengthen communication, promote economic development, preserve culture and history, improve education, and promote peace and understanding. In the digital age, automatic translation systems (ATS) play an important role in overcoming the language barrier and facilitating communication between people who speak different languages. Automatic translation systems of the Azerbaijani language are also taking important steps in this direction.

Many platforms and software currently use machine learning and artificial intelligence technologies to convert text or voice speech from one language to another. However, the specific features of the Azerbaijani language, including its rich lexicon, grammatical structure and dialect diversity, create certain difficulties for automatic translation systems. Nevertheless, the researches and developments in this field lead to an increase in the translation quality and further improvement of the systems. There are several popular platforms and programs that offer automatic translation services in Azerbaijani:

- Google Translate: Google's free translation service, supports the Azerbaijani language, can be used for both text and voice translation.
- Yandex Translate: Yandex's translation service also provides translation in Azerbaijani language.
- Microsoft Translator: Microsoft's translation platform supports the Azerbaijani language and can be used on various platforms. In addition to these, many other platforms and software also offer automatic translation services in the Azerbaijani language.

Automatic translation systems of the Azerbaijani language play an important role in the development and dissemination of the language. These systems facilitate communication between people who speak different

languages, accelerate the exchange of information and promote intercultural dialogue.

The use of language in artificial intelligence systems is also a process that occurs due to the increase of technological capabilities. This allows artificial intelligence systems to understand and use human language and opens the way for the application of language in various fields. For example, there are chatbots that can communicate with people in a certain language, answer questions and help solve various problems. The most widely used of such chatbots are Gemini, ChatGPT, AI Chat, etc. we can give an example.

One of the main goals to increase the technological capabilities of the Azerbaijani language is to create its digital dictionaries and Corps. The purpose of creating the corpus is the use of various types of linguistic issues, for example, in the graphic and grammatical analysis of texts. The linguistic corpus is a collection of texts in electronic form, in which, with the help of a certain search engine, it is possible to find grammatical forms and meaning of words, word combinations. And the national corpus is a collection of texts reflecting various genres, styles, regional and social status. The purpose of creating this corpus is to study the lexicon and grammar of the language, to solve various problems (lexicon, language history, etc.) the survey is to free specialists from examining large volumes of material, which takes a lot of time in collecting information, selecting (collecting) samples.

Through the casing:

- changes in the frequency of words and phrases in connection with changes in the cultural and social life of society;
- morphological and grammatical changes in the language;
- changes in constructions;
- during the twentieth century, it is possible to trace and study the changes of words [5].

The establishment of the national corpus of the Azerbaijani language is one of the most important prob-

lems posed to computer linguistics. The considered national corps should include classical fiction, memoirs, journalistic articles, scientific and religious literature, press materials, media, oral speech, scientific and public speech, prose and verse works, correspondence, dialects.

Electronic dictionaries are dictionaries of various types that are included in the computer's memory. Electronic dictionaries differ from computer dictionaries depending on the goal set. Computer dictionaries are created in order for users to benefit from computer software. Internet sites include dictionaries of various types, for example, ABBYY Lingvo, polyglot (Azeri dictionaries), Lingvo, thesaurus, ontological, explanatory, spelling, reverse dictionaries, etc. [1]

Automatic translation systems of the Azerbaijani language play an important role in the development and dissemination of the language. These systems facilitate communication between people who speak different languages, accelerate the exchange of information and promote intercultural dialogue. With the development of technologies, the quality and capabilities of automatic translation systems will further increase, which will lead to a wider use of the Azerbaijani language on a global scale.

Efforts are being made in international organizations to make the native language one of the working languages, the development of economic relations with other countries stimulates the use of the native language in the business sphere, and the growth of the country's authority in the international arena also increases interest in the native language from a political point of view. The main burden in this direction falls on the State Committee for Work with Foreign Affairs of the Republic of Azerbaijan [3].

Supporting language and cultural events organized by compatriots living abroad, organizing native language schools and language courses, preparing cultural events, festivals, concerts and theater performances, using native language media (newspapers, magazines, radio, television, websites), distributing books and other publications abroad, increasing the accessibility of the language at the international level through online classes, language exchange platforms and social media, strengthening the scientific foundations of the language in cooperation with international academic groups. and to help its recognition in the international world, to raise the issues of teaching, use and protection of the Azerbaijani language before the governments, ministries of education and international organizations of the countries where they operate, to support the creation of dual language education programs, to promote the use of the language in business and tourism, the potential of the diaspora is extremely high, and using this potential effectively can contribute to the greater recognition, study and use of the Azerbaijani language in the world.

Diaspora organizations organize events such as days of Azerbaijani culture, Novruz Bayram festivities, national dance and music evenings, cinema screenings, theater performances and present the Azerbaijani language as part of these events. Thus, the international

audience perceives the richness and melodiousness of the Azerbaijani language over time.

It should not be forgotten that Azerbaijani scientists can support increasing interest in the Azerbaijani language in international academic circles by making reports in the Azerbaijani language at international conferences, cooperating with foreign universities and transmitting information about the Azerbaijani language and culture, conducting research in the field of history, grammar, dialects and comparative linguistics of the Azerbaijani language.

Scientific conclusion. As a result of the internationalization of a native language, its sphere of influence significantly expands, leading to broader recognition and usage beyond national borders. The increased visibility of the language contributes to its integration into a wide range of global domains, including culture, international trade, tourism, education, and media. This expansion facilitates greater cultural exchange and enhances the visibility of national heritage on the world stage. Furthermore, the international use of the language creates favorable conditions for the growth of economic opportunities by fostering access to new markets and enhancing cross-border commercial interactions.

In addition to economic benefits, the internationalization of the native language plays a vital role in promoting international scientific and technical collaboration. A language that is recognized and utilized within global academic and professional networks allows for more effective knowledge transfer, joint research initiatives, and innovation sharing. This, in turn, contributes to the nation's competitiveness in scientific and technological advancement.

Moreover, linguistic internationalization supports the development of closer political and diplomatic relations among countries. A shared or familiar language can act as a bridge in intercultural dialogue, reducing communicative barriers and fostering mutual understanding. Thus, the global promotion and adoption of a native language not only enhance its functional scope but also serve as a strategic tool for strengthening international partnerships and asserting cultural presence in global discourse.

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PHYSICAL SCIENCES

THE INFLUENCE OF SURFACE RECOMBINATION VELOCITY ON THE EXCLUSION OF MINORITY CHARGE CARRIERS IN CDXHG1-XTE MONOCRYSTALS

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<https://doi.org/10.5281/zenodo.15298397>

Abstract

This study experimentally investigates the effect of surface recombination velocity on the parameters of photoconductors based on $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ with $0.18 \leq x \leq 0.30$ under conditions of carrier extraction due to a longitudinal electric field. The analysis of the obtained experimental results established that for samples with a ground surface, the specific detectivity $D\lambda_{\text{max}}$ is almost independent of U_{bias} , whereas for samples with a polished surface, $D\lambda_{\text{max}}$ decreases with increasing U_{bias} . It was determined that the surface recombination velocity significantly affects the exclusion effect and its mechanism in $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ monocrystals.

The obtained dependencies indicate a significant influence of surface recombination on the parameters of photodetectors operating in the mode of minority carrier extraction in $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ -based devices.

Keywords: recombination, exclusion, minority carriers, voltage sensitivity, specific detectivity, bias voltage.

Introduction

One of the specific non-uniform electronic phenomena in semiconductors is the exclusion of minority charge carriers. The physical essence of this effect is as follows. In semiconductors, minority charge carriers play a significant role in conductivity. If the externally applied electric field to the sample is sufficiently high, specifically when the condition $L/\mu E \leq \tau$ is met (where L is the sample length, E is the electric field intensity, and μ is the mobility of minority charge carriers), the minority charge carriers are extracted from the sample through the contacts during the transit time $t_{\text{tr}} = L/\mu E$, leading to a decrease in conductivity.

There have been relatively few studies on the exclusion effect in various semiconductors to date [1-5]. However, prior to our research, information on this phenomenon in $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ was almost nonexistent, despite the fact that $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ monocrystals, due to the significantly high mobility of minority charge carriers (electrons), could be among the most suitable materials for studying this effect.

Theoretical Section

Semiconductor solid solutions with a variable bandgap width attract the attention of physicists and engineers worldwide as promising materials for semiconductor optoelectronics and as interesting objects for fundamental research in solid-state physics.

One of the unique representatives of this class of semiconductors is the material $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$, whose bandgap width increases from -0.3 eV to 1.6 eV as x (the CdTe content in the solid solution) increases from

zero to one. Today, $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ monocrystals have already found widespread application in various fields of technology, primarily in the production of infrared radiation detectors operating over a wide spectral range based on intrinsic photoconductivity. The results obtained from a comprehensive study of the electronic properties of $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ with different compositions and the influence of various external factors on them are valuable not only from a practical standpoint but also for understanding the mechanisms of physical phenomena in this material, discovering new properties, and identifying its unique characteristics. These studies may also help resolve many controversial issues in the physics of complex semiconductor compounds. Based on the results obtained, there is a possibility of developing fundamentally new devices and improving the parameters and characteristics of existing ones.

In strong pulling electric fields, the transit time of excess minority charge carriers (t_{tr}) through the sample may become shorter than their lifetime in the studied material. Under such conditions, these carriers can be extracted from the sample by the field before they have time to recombine. As a result, a nonuniform charge carrier distribution is established along the sample.

To clarify the mechanism of this process, let us consider a p-type semiconductor sample in the form of a parallelepiped with length L and cross-sectional area S (Figure 1a). Assume that the generation of non-equilibrium charge carriers by light occurs uniformly throughout the entire volume of the sample, the carrier concentration varies only in one direction parallel to the

excitation surface, and the electric field E is directed along the "x" axis. Then, in the case of a low excitation level, i.e., when $\Delta\sigma \ll \sigma_0$ (where $\Delta\sigma$ is the photoconductivity and σ_0 is the dark conductivity), the expression for the photocurrent at any point in the sample can be written as follows [1,5]:

$$\Delta J = \frac{e(1+b)\mu_p E S}{L} \int_0^L \Delta n(x) dx \quad (1)$$

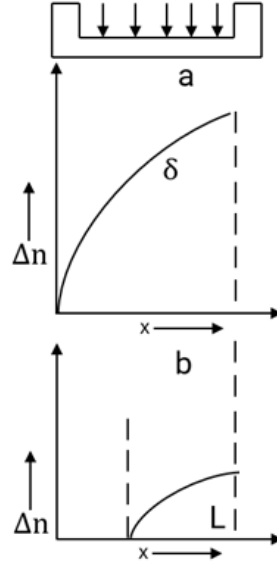


Figure 1. Sample schematic (a) and distribution of nonequilibrium charge carrier concentration along the sample in a strong electric field (b and c). (b) At the initial moment (c) After a time interval Δt following illumination

Where $\Delta n(x)$ represents the concentration of excess minority charge carriers in the studied sample.

The distribution of the minority carrier concentration $\Delta n(x)$ in general form is determined by solving the continuity equation.

$$\frac{d\Delta n}{dt} = g_s - \frac{\Delta n}{\tau} + \mu_0 E \frac{v\Delta n}{vx} + D_a \frac{v^2 \Delta n}{vx^2} \quad (2)$$

where g_s is the carrier generation rate per unit time, τ is the carrier lifetime, D_a is the ambipolar diffusion coefficient, and $\mu_a = \frac{(p-n)\mu_n\mu_p}{n\mu_n+p\mu_p}$ is the ambipolar drift mobility, which characterizes the drift velocity of the induced perturbation.

First, we determine the charge carrier distribution $\Delta n(x)$ along the sample length under steady-state conditions. In the case of a sufficiently strong electric field (where diffusion effects can be neglected), equation (2) can be rewritten as:

$$\frac{d\Delta n}{dx} = \frac{g_s}{\mu_a E} - \frac{\Delta n}{\mu_a E \tau} \quad (3)$$

The solution of this equation under the boundary condition $\Delta n(0) = 0$ has the following form:

$$\Delta n(x) = g_s \tau \left[1 - \exp\left(-\frac{x}{\mu_a E \tau}\right) \right] \quad (4)$$

If expression (4) for $\Delta n(x)$ is substituted into equation (3) and integrated, we obtain:

$$\Delta J_a = e(1+b) \frac{\mu_p \tau}{L} E \eta \Phi_s \left\{ 1 - \frac{\mu_a E \tau}{L} \left[1 - \exp\left(-\frac{x}{\mu_a E \tau}\right) \right] \right\} \quad (5)$$

where η is the quantum yield of the internal coefficient, and Φ_s is the photon flux of the signal. The resulting formula is: $g_s = \frac{\eta \Phi_s}{SL}$.

Formula (5) defines the stationary photocurrent in a semiconductor under exclusion conditions.

In the case of weak fields, when $\mu_0 E \tau \ll L$, expression (5) simplifies to:

$$\Delta J_{cm} = \eta \Phi_s e(1+b) \frac{\mu_p \tau}{L^2} U_{ct} \quad (6)$$

Where $U = E \cdot L$ is the voltage applied to the sample.

The distribution of minority carriers Δn after a time interval t following the cessation of excitation is shown in Figure 1(b).

As can be seen from equation (6), in this case, the stationary photocurrent increases proportionally to the applied bias voltage and depends on the carrier lifetime.

In the other limiting case, when the field is strong, i.e., $E \gg L/\mu_a \tau$, the transit time of charge carriers (t_{tr}) becomes shorter than their lifetime (flight mode). The stationary photocurrent reaches saturation and does not depend on the bias voltage [6]. Under the condition $\mu_a E \tau \gg L$, from equation (5) we obtain:

$$\Delta J_{max} = \frac{1}{2} \eta \Phi_s e(1+b) \frac{\mu_p}{\mu_a} \quad (7)$$

The dependence of the stationary photocurrent on the bias voltage, plotted based on expression (5), is shown in Figure 2. Thus, the photocurrent increases proportionally to the applied voltage at low biases and, at sufficiently strong electric fields, reaches saturation, which is determined by formula (7).

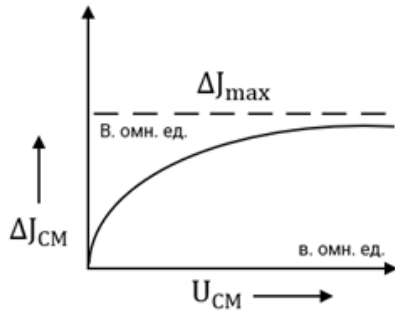


Figure 2. Dependence of the stationary photocurrent on the bias voltage.

This operating mode of the sample is called the flight mode. The bias voltage U_0 , at which the flight mode occurs, can be conditionally defined as the bias at which the length of the bipolar drift equals the distance between the electrodes. From there, we have:

$$U_0 = L^2 / \mu_a \tau \quad (8)$$

Now, let us consider the dynamic characteristics of the semiconductor sample. To determine the transient photocurrent from equation (1), it is necessary to

$$\Delta J(t) = f(x) = \begin{cases} \frac{1}{2} \eta \Phi_s e(1+b) \frac{\mu_n}{\mu_a} (1 - \frac{\mu_n E}{L} t)^2, & 0 \leq t \leq \frac{L}{\mu_a E} \\ 0, & t \geq \frac{L}{\mu_a E} \end{cases} \quad (10)$$

In the flight mode, the transit time $t_{np} = L^2 / \mu_a E$, as mentioned earlier, determines the total decay time of the photocurrent. This allows for estimating the ambipolar drift mobility μ_a based on the measured value of t_{np} . As shown by the corresponding calculations, the photocurrent curves are symmetric with respect to the decay curves.

It should be noted that the expressions derived above for the transient photocurrent (9) and (10) describe the relaxation process when the sample is excited by a long rectangular excitation pulse, i.e., it is assumed that the duration Δt of the light pulse is much greater than the time required to reach the steady-state photoreponse. In this case, during the action of the light pulse, a certain distribution of the concentration of minority carriers is established in the semiconductor, as described by equation (4).

Now, let's briefly consider the processes when the sample is excited by a short radiation pulse ($\Delta t \ll \tau$). In this case, the concentration of nonequilibrium carriers does not have time to change significantly during the light pulse. In weak fields (when $\mu_a E \tau \ll L$), the concentration of nonequilibrium carriers decreases due to their recombination according to the law:

$$\Delta n = \Delta n_0 \exp(-t/\tau)$$

In this case, both Δn and Δn_0 do not depend on x . Then, from equation (10) for the transient photocurrent, we obtain:

$$\Delta J(t) = \frac{e(1+b)\mu_p E S}{L} \int_0^L \Delta n e^{-t/\tau} dx = \delta I_{max} e^{-t/\tau} \quad (11)$$

The photocurrent, as in the case of long rectangular pulses, decays according to an exponential law. In the case of strong fields (in the flight mode, i.e., when $t_{tr} < \tau$), the photoresponse time becomes equal to the transit time:

$$\tau_0 = t_{np} = L^2 / \mu_a \cdot U_{sm}$$

know the distribution $\Delta n(x, t)$, which takes the following form (considering the recombination of charge carriers) [7-10]:

$$\Delta n(x, t) = \begin{cases} 0, & 0 \leq x \leq x_1 \\ g_s \tau \left[1 - \exp\left(-\frac{x-x_1}{\mu_a E \tau}\right) \exp\left(-\frac{t}{\tau}\right) \right], & x_1 < x < L \end{cases} \quad (9)$$

Where $x_1 = \mu_a E \tau$ is the distance by which the charge carrier is pulled away from the negative contact.

The total photocurrent decay time under exclusion conditions is determined by the transit time in weak fields (when $\mu_a E \tau \ll L$). In this case, equation (9) takes the form:

$$\begin{aligned} \Delta J(t) &= \eta \Phi_s e(1+b) \frac{\mu_a \tau}{L^2} I_{cr} \exp\left(-\frac{t}{\tau}\right) \\ &= \Delta J_{cm} \exp\left(-\frac{t}{\tau}\right) \end{aligned}$$

In this case, the relaxation of the photocurrent is determined solely by the recombination of charge carriers and follows an exponential decay law.

In the other limiting case of a strong field (in the flight mode), the photocurrent relaxation is influenced by different factors.

Neglecting the decrease of Δn due to recombination, we obtain the following expression for the transient photocurrent:

$$\Delta J(t) = \frac{e(1+b)\mu_p S}{L} \int_{x_1(t)}^L \Delta n(x) dx \quad (12)$$

The lower limit of integration $x_1(t)$ represents the distance by which the charge carrier is pulled away from the negative contact.

$$x_1(t) = \mu_n E t = \mu_n t / L \cdot U_{sm}$$

By performing the integration in equation (12), we obtain:

$$\Delta J(t) = \frac{e(1+b)}{L^2} \mu_p S \cdot I_{cr} \Delta n_0 [L - x_1(t)]$$

или

$$\Delta J(t) = \delta I_{max} \left(1 - \frac{\mu_a \cdot I_{cr}}{L^2} t\right) \quad (13)$$

где

$$\delta I_{max} = \frac{e(1+b)\mu_a \Delta n_0 S}{L^2} \cdot I_{cr} \quad (14)$$

From equations (13) and (14), it follows that in the case of short light pulses, i.e., when $\Delta t < \tau_0$, the decay of the photocurrent in the flight mode follows a linear law, and the amplitude of the photocurrent I_{max} does not reach saturation or offset. However, with an increase in the bias voltage, τ_0 decreases, violating the above condition, leading to saturation of the photocurrent amplitude.

Experimental Part

In previous measurements, it was assumed that the generation of nonequilibrium charge carriers in the studied samples is homogeneous, and that they do not recombine at the surface, i.e., the role of generation-recombination processes of charge carriers at the crystal edges could be neglected, and the influence of the sample's transverse dimensions was not considered.

However, our studies, as well as those by other authors, show that this assumption is not correct. In real samples, the generation of minority nonequilibrium carriers is inhomogeneous, and recombination at the surfaces cannot be neglected. These effects can significantly alter photodetector parameters, such as voltage sensitivity and detectivity under exclusion conditions. Since the mode of extracting nonequilibrium charge carriers provides the maximum value of the photomultiplier coefficient, it is of interest to conduct a detailed study of the influence of surface recombination rates on the parameters of photodetectors operating in this mode.

To this end, we experimentally investigated the impact of surface recombination rates on the parameters of photodetectors made of $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ with $0.18 \leq x \leq 0.30$ under conditions of charge carrier extraction by a longitudinal electric field. To achieve different surface recombination rates, the surfaces of the studied photodetectors were subjected to various types of processing. We investigated samples whose surfaces were subjected to mechanical polishing with fine-grained

powder, diamond paste polishing, and mechanical processing followed by chemical etching. In the first two cases, the samples were then rinsed only in a boiling HCl_4 solution, and induced current contacts were applied to them.

It should be noted that in the samples subjected to different surface treatments, the surface recombination rate varied within the range of $10^5 - 10^2 \text{ cm/s}$. After each operation, the photoelectric parameters of the fabricated photodetectors were measured.

Experimental results obtained during the study of relative spectral characteristics of the studied photodetectors (Figure 3 for $x = 0.19$ and $x = 0.30$) after three types of surface treatment showed that, unlike the conventional photoresistive mode (where additional peaks were observed in the wavelength range corresponding to surface absorption), in the extraction mode, the photo-sensitivity in the short-wavelength region of the spectrum stabilizes. That is, at high electric field values, the "peaks" in the short-wavelength region of the spectrum seem to be absent. The photo-sensitivity increases at high E compared to the values at low E .

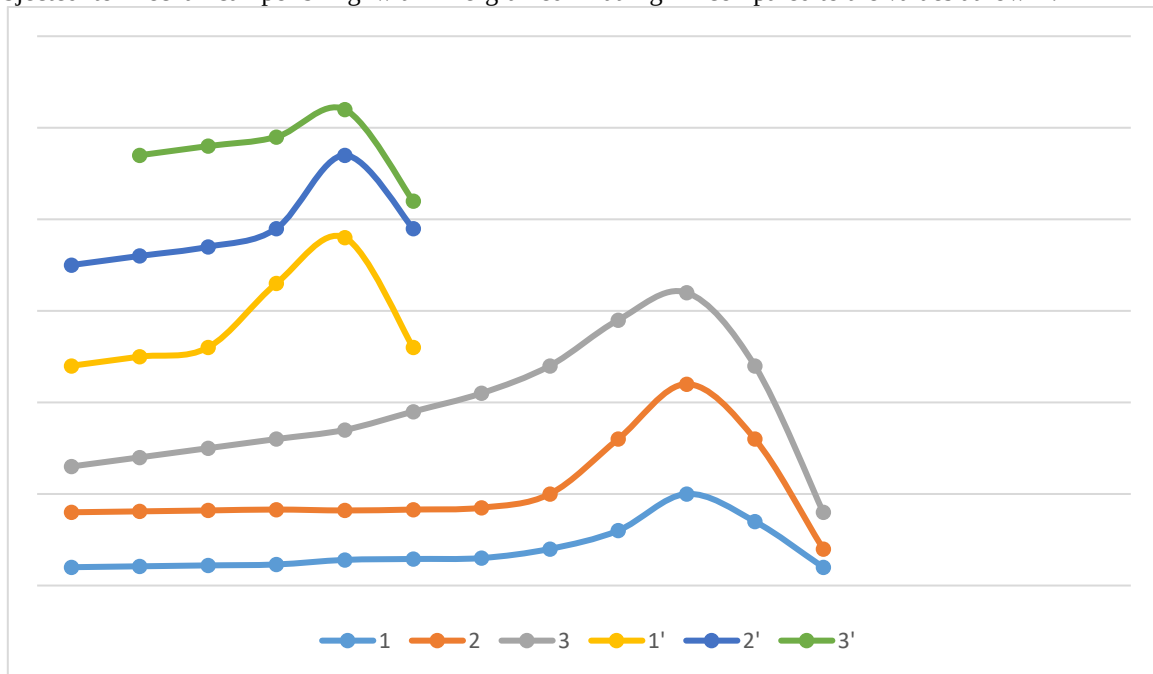


Figure 3. Spectral dependence of the photosensitivity of $\text{P-Cd}_x\text{Hg}_{1-x}\text{Te}$ samples with $x = 0.19$ and $x = 0.30$ under exclusion conditions.

1 – after grinding, 2 – after polishing, 3 – after etching. $T = 80 \text{ K}$, $U_{sm} \geq 3.0 \text{ V}$.

It should be noted that the increase in photosensitivity with the field strength does not follow a linear law.

In the setup based on an ABS (absolute black body) at $T = 300 \text{ K}$, the dependence of the photocurrent signal U_s on the type of surface treatment of the samples was studied. The results showed that with an increase in U_{sm} , the photocurrent signal initially (at low U_{sm}) increases linearly, and then (at higher U_{sm}) reaches saturation. It was found that the bias voltage corresponding to the beginning of the saturation region of the photocurrent signal differs in samples subjected to different surface treatments, even under otherwise identical conditions [11, 12, 13].

These obtained dependencies again demonstrate the significant impact of surface recombination on the parameters of photodetectors operating in the mode of extracting minority charge carriers based on $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$.

The joint study of the dependencies of the photocurrent signal and noise in photodetectors on the type of surface treatment of the semiconductor allowed us to determine key parameters such as voltage sensitivity and specific detectivity. In order to investigate the impact of these factors on the inertia of the photodetector, measurements were conducted on samples with various surface treatments (Figures 4 and 5).

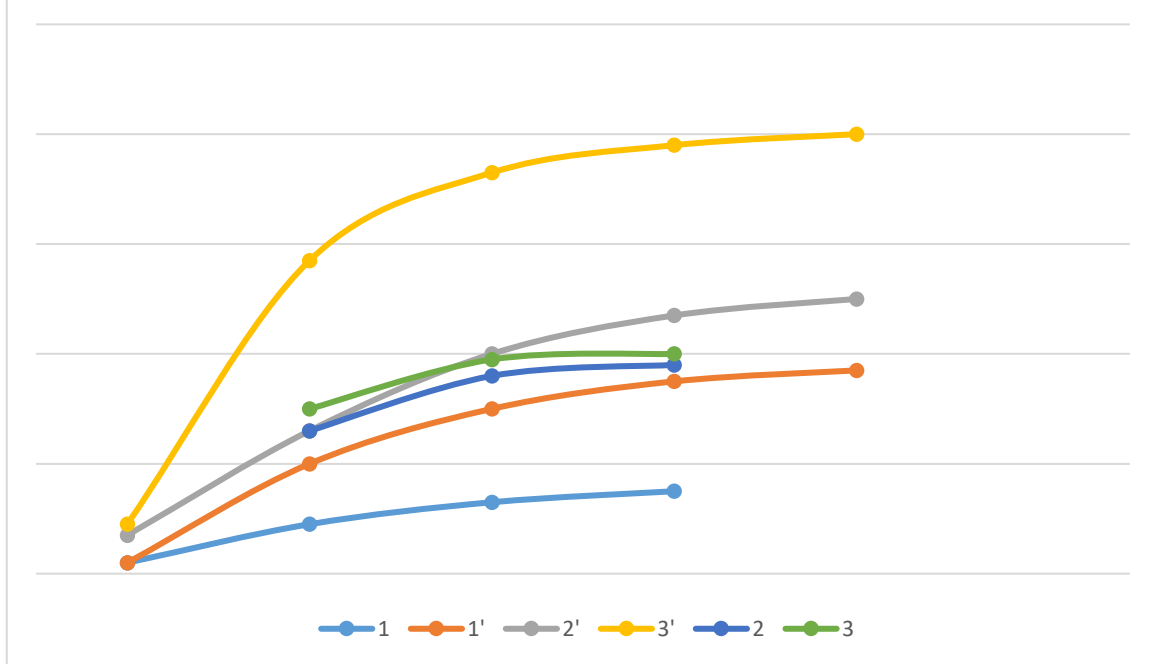


Figure 4. Dependence of $S_{\lambda_{\max}} U_{sm}$ in $P\text{-Cd}_x\text{Hg}_{1-x}\text{Te}$ crystals with $x = 0.19$ (curves 1-3) and $x = 0.25$ (curves 1'-3') after grinding (curves 1, 1'), polishing (curves 2, 2'), and etching (curves 3, 3') of the surface.

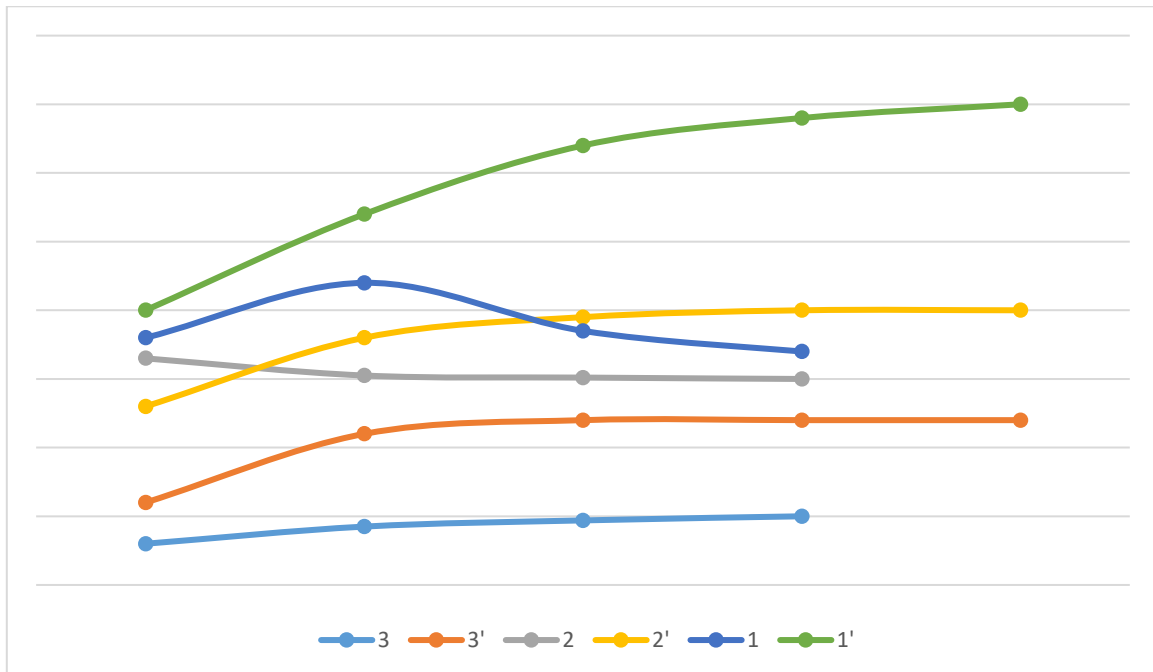


Figure 5. Dependence of $\Delta\lambda_{\max}$ on U_{sm} in $P\text{-Cd}_x\text{Hg}_{1-x}\text{Te}$ crystals with $x = 0.19$ (curves 1-3) and $x = 0.25$ (curves 1'-3') after grinding (curves 1, 1'), polishing (curves 2, 2'), and etching (curves 3, 3') of the surface. $T = 80 \text{ K}$.

Analysis of the experimental results revealed that for samples with a ground surface, $\Delta\lambda_{\max}$ almost does not depend on U_{sm} , while for samples with a polished surface, $\Delta\lambda_{\max}^*$ decreases with increasing U_{sm} . For samples with an etched surface, the $\Delta\lambda_{\max}^*(U_{sm})$ dependence behaves similarly to the $U_s(U_{sm})$ dependence – initially, with an increase in the bias voltage, $\Delta\lambda_{\max}^*$ decreases, and then it reaches saturation. This behavior can be explained by the fact that for samples with ground and polished surfaces, with increasing bias voltage in the range $U_{sm} = 0.05 - 0.15 \text{ V}$, the noise increases sharply. After further increasing U_{sm} , the noise level passes through a minimum and then grows again.

For samples with an etched surface, a slow increase in noise was observed with increasing bias voltage.

To explain the experimental results obtained in this article, let's consider the continuity equation for the total disturbance $\Delta n + \Delta p$ in the two-dimensional case, which, according to [13], is expressed as:

$$\mu_a E \frac{d\Delta n(x,y)}{dx} = P_a \frac{d^2 \Delta n(x,y)}{dy^2} - \frac{\Delta n(x,y)}{\tau} + g_\phi S(y) \quad (15)$$

The boundary conditions for this are:

$$j(x, 0) = -S\Delta n(x, 0); j(x, t) = S\Delta n(x, t); \Delta n(0, y) = 0 \quad (16)$$

The first two equations correspond to the usual boundary conditions for surface recombination velocity

S [14], and the third corresponds to the ohmic contact. The solution of equation (15) with the boundary conditions (16) can be analytically solved for $S = 0$ and $S = \infty$. In the latter case, the boundary conditions (16) take the form:

$$\Delta n(x, 0) = 0;$$

$$\Delta n(x, t) = 0;$$

$$\Delta n(0, y) = 0.$$

The total number of nonequilibrium electron-hole pairs (Δn) in the sample in this case is equal to [13]:

$$\Delta n = \frac{4\eta K_{\lambda} \Phi \tau W}{t} (k^{-K_{\lambda} t} + 1) \left\{ \sum_{h=0}^{\infty} \frac{1}{K_{\lambda}^2 + \left[\frac{n(2n+1)}{t} \right]^2} \left[\frac{L}{1 + D_a \tau \left[\frac{n(2n+1)}{t} \right]^2} + \frac{\exp\left(-\frac{L}{\mu_a E \tau}\right)}{1 + D_a \tau \left[\frac{n(2n+1)}{t} \right]^2} \right] \frac{D_a E \left[\frac{n(2n+1)}{t} \right]^2 L - \frac{1}{\mu_a E \tau}}{1 + D_a \tau \left[\frac{n(2n+1)}{t} \right]^2} \right\}$$

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TECHNICAL SCIENCES

METHODOLOGICAL APPROACHES TO STUDYING THE CRUSHING OF MICROPROJECTIONS IN CONTACT BETWEEN DISSIMILAR MATERIALS UNDER THERMAL DEFORMATION IMPACT

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Abstract

A methodology has been developed to study the contact interaction between dissimilar materials subjected to thermomechanical deformation over time. Kinetic curves were constructed to analyze contact formation, plastic deformation of microprojections, changes in microprojection height, contact stresses on microprojection contact areas, and variations in mechanical properties at the surface and within the near-contact volume of microprojections. These analyses were conducted across temperature ranges from room temperature to pre-melting points and pressure intervals before and after threshold values. The study demonstrates that plastic deformation of microprojections is responsible for contact formation and activation processes on contact surfaces. Additionally, the level of second-kind microstresses on microprojection contact areas significantly exceeds the nominal stress values used in calculation formulas. The research establishes that temperature and pressure have distinct effects on the intensity of plastic deformation, contact formation, and changes in mechanical properties at the surface and within the near-contact volume. The proposed process scheme enables the production of high-purity flat metal surfaces with adjustable mechanical properties and precision joints (both detachable and non-detachable).

Keywords: research methodology, contact interaction, microprojection crushing, kinetics, actual and physical contact, plastic deformation, sapphire, second-kind microstresses, smoothing, bonding.

1. Introduction

Advancements in science and technology impose increased demands on the geometry, strength, and reliability of machines, equipment, instruments, and devices, while maintaining their original physicochemical and mechanical properties during prolonged operation, including under extreme conditions and in aggressive environments. This necessitates the use of new materials or previously known materials in novel combinations. Consequently, there is a need to achieve precision detachable or non-detachable joints of these materials without altering their inherent properties.

One approach to addressing this issue is the study of contact interactions between materials in the solid phase under deformation or thermomechanical effects, leading to the development of new technological processes (TPs) for obtaining high-purity surfaces and precision joints without changing their original physicochemical and mechanical properties. Notably, TPs based on plastic deformation of microprojections on contact surfaces (such as pressure welding with heating, pressing and sintering of ultradispersed powders, obtaining high-purity metal surfaces with adjustable properties and geometry, etc.) play a significant role. These processes ensure efficiency by maximizing the preservation of the original material properties and regulating the precision of contact.

On one hand, precision joining involves not only controlling and regulating the deformation of the microrelief in the contact zone but also conducting preliminary treatment of contact surfaces using methods based on plastic reshaping through smoothing with natural and synthetic superhard materials. On the other hand, achieving a non-detachable precision joint requires understanding the kinetics and nature of processes occurring on contact surfaces under thermomechanical effects. This implies the need for direct experimental data on the kinetics of individual process stages, enabling the development of methods to control and regulate TPs for obtaining precision joints.

In this context, the problem of contact interaction under deformation or thermomechanical effects, encompassing joint formation, can be considered from two aspects:

1. Establishing kinetic patterns of contact formation between surfaces through plastic deformation of microprojections, considering changes in mechanical and elastic properties of the metal and surface geometry. This addresses the precision of the joint.

2. Investigating the activation nature of the surface of a harder material in contact with a softer metal and establishing kinetic patterns of bonding (strength growth) between them. This addresses the formation of a non-detachable precision joint.

Considering the problem of contact interaction from these aspects leads to the development of new TPs for obtaining precision detachable and non-detachable joints of materials in various combinations, including at temperatures below 0.5 of the metal's melting point, while preserving the original physicochemical and mechanical properties and geometry of the products.

The aim of this work was to establish the influence of thermomechanical impact levels on the nature of microprojection crushing during contact formation, the kinetics of contact development through plastic deformation of microprojections, changes in mechanical properties at the surface of contact pads and within the near-contact volume, as well as to assess the levels of second-kind microstresses compensated within the grain volume of microprojections under pressure welding with heating of dissimilar materials with sharply differing resistance to plastic deformation and chemical bonding nature.

2. Materials and Methods

The formation of a non-detachable joint during contact interaction of materials under pressure with heating is the result of several interrelated elementary processes, which, according to modern concepts, proceed in three main stages [1–3]:

1. the formation of physical contact;
2. the activation of atoms on the joining surfaces that are in physical contact and the formation of strong chemical (metallic) bonds;
3. the relaxation stage (formation of common grains, volumetric interactions, diffusion processes, etc.).

Due to the simultaneous occurrence of these processes in microscopic contact spots, conventional technological tests do not allow for a differentiated evaluation of the contribution of each stage to the overall joint formation. Therefore, identifying the development patterns of each process stage requires the use and development of specialized techniques and analytical calculation methods.

A number of studies [4–9] have experimentally examined the characteristics of elastic, plastic, and elastoplastic contact formation under varying parameters. However, there is a notable absence of works focused on the systematic study of the kinetics of actual contact formation, and its transition into physical contact, via the plastic deformation of microprojections on the welded surfaces. The qualitative and quantitative kinetic patterns of microprojection crushing at the contact interface have not been established, nor have the changes in mechanical properties at the surface of contact areas and within the microprojections. Additionally, the magnitudes of contact stresses within the microprojections, their kinetic evolution, and their fundamental role in activating the contact surfaces remain undetermined.

Furthermore, a significant discrepancy exists between experimental results and those predicted by existing models for individual process stages [3,7,10]. A common limitation of these models is that they rely on parameters of bulk creep deformation, while actual and physical contact formation occurs primarily due to plastic deformation of the microrelief features. This

limitation has been compounded by the lack of a simple and objective methodology for systematically and accurately identifying the qualitative and quantitative patterns of contact formation, plastic deformation, microprojection crushing and reshaping—directly at the contact surfaces during pressure welding with heating and precision finishing treatments (smoothing) using synthetic superhard materials (SHMs).

Experimental investigations of the contact surfaces were performed using profilometry and fractography (optical and electron microscopy) on a fixed area [9]. The statistical processing of roughness parameter changes on the contact surfaces was conducted using a specialized computer program for the profilograph–profilometer model 201 with an integrated video computing system (IVK). The profilograph needle had a radius of 2 μm ; vertical (VU) and horizontal (HU) magnifications ranged from 1,000 to 100,000 times and from 200 to 4,000 times respectively, with data automatically recorded onto thermoelectric paper.

Changes in mechanical properties on the surface of the contact pads and within the near-contact volume of the microprojections were assessed via microhardness (H) measurements using a PMT–3 device under a load of $P = 0.5 \text{ N}$ (50 gf). A fixed area on the test surface was marked using the diamond pyramid indenter of the PMT–3 instrument (Fig. 1 a–d) both before and after the application of the load. Profilograms were taken from the marked area pre- and post-loading. Control measurements of the height and base width of the microprojections were conducted using a MIS–11 dual microscope. An optical head from a binocular MBS microscope was used for observing and positioning the profilograph needle. After each loading cycle, the fixed area was photographed through sapphire.

The experimental studies were conducted on sample pairs of copper (MB grade) and synthetic monocrystalline optically transparent sapphire (corundum) with 600-orientation relative to the growth axis and a working surface finish of $R_z = 0.03 \mu\text{m}$. Sapphire was selected due to its highly favorable combination of properties relevant to practical applications—high hardness (9 on the Mohs scale), melting point, creep resistance, zero water absorption, and relative cost-effectiveness of production—all of which account for its broad use as a structural material in engineering [11–14].

This paper presents experimental results for the copper–sapphire pair. After mechanical processing, the copper samples were annealed in a hydrogen atmosphere at $T = 650^\circ\text{C}$ for 45 minutes. Contact surfaces were machined by turning ($R_z = 3.2 \dots 6.3 \dots 10 \mu\text{m}$) and planing ($R_z = 40 \dots 80 \mu\text{m}$). Sample dimensions were: length – 25 mm, diameter – 12 mm. The support surfaces of the samples were ground, and end face non-parallelism was no more than 0.002 mm. Loading was conducted using a diffusion welding setup of type A306.08. The vacuum level ranged from $(1 \text{ to } 5) \times 10^{-5} \text{ mmHg}$. Temperature was measured with a chromel–alumel (CA) thermocouple, controlled by an MPShPr–54 device, and sealed beneath the base of the microprojection.

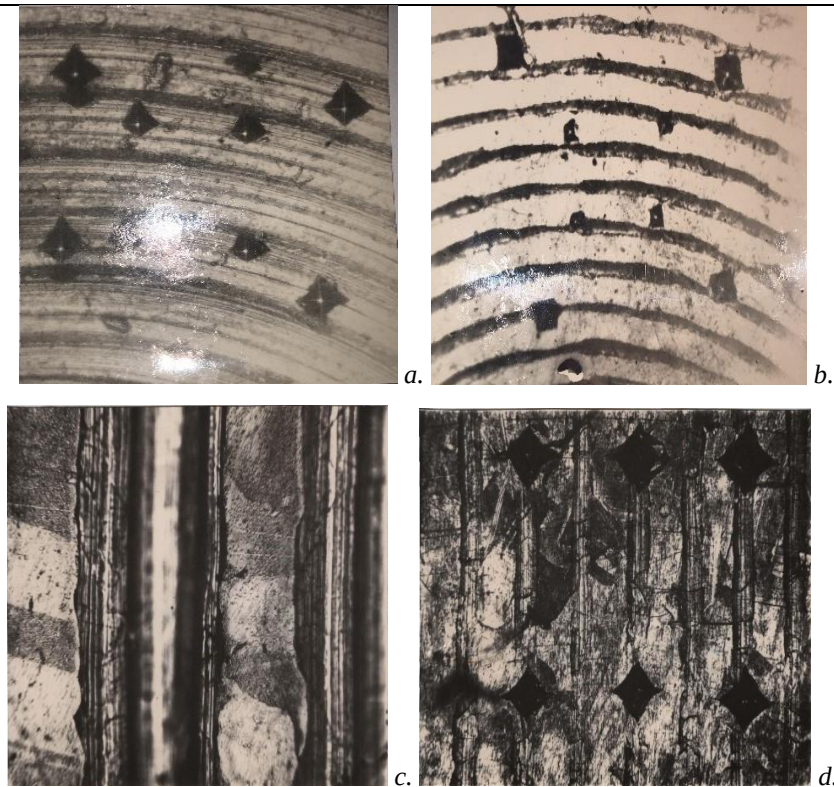


Fig. 1. Fractography of the contact surface before (a) and after (b, c, d) loading; surface treatment in (a, b) – turning, $R_z = 3.2 \dots 6.3 \dots 10 \mu\text{m}$; magnification $\times 110$; (c, d) – planing, $R_z = 40 \dots 80 \mu\text{m}$; (a, b, c) – Stage 1 of microprojection crushing; (d) – Stage 2 of microprojection crushing.

Loading of the contact (welded) surface was carried out as follows. The specimen, mounted in a fixture (Fig. 2a), was placed inside a chamber where a vacuum was created and the system was heated to the process temperature. External (welding) pressure (P) was applied to the contact surface through a sapphire disc. The

duration of the loading varied from 10...15...30 seconds to several tens of minutes, depending on the specific objectives of the smoothing or welding process. Thus, the process schemes for smoothing a metal surface with a flat sapphire disc and for welding under pressure with heating are similar, apart from certain technological differences [13–14].

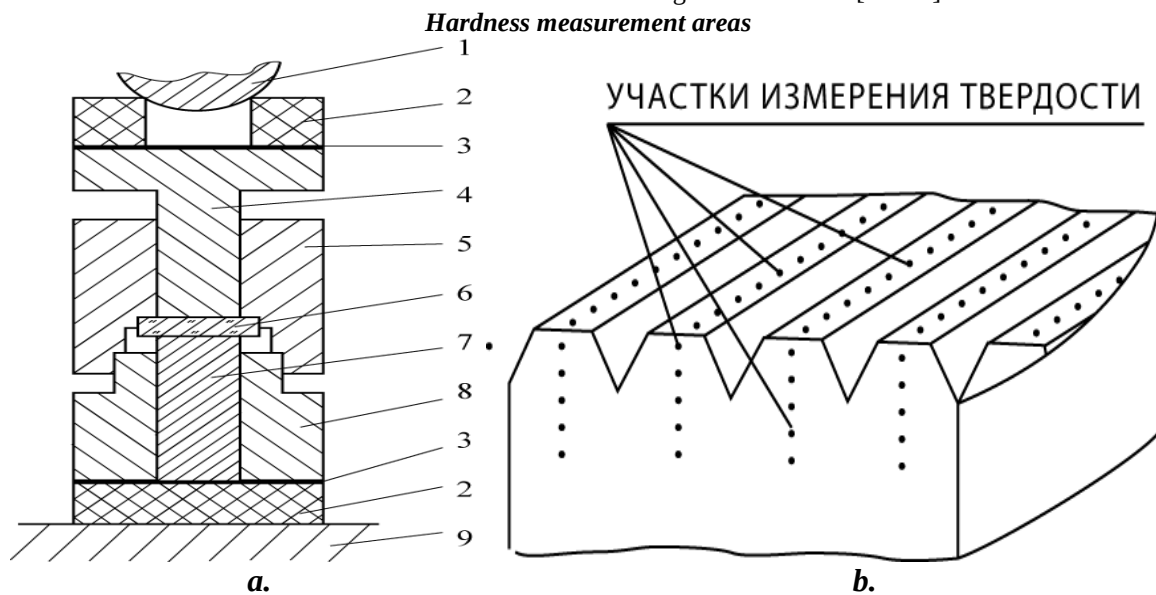


Fig. 2a, b.

Schematic diagram of the fixture for loading (a) and microhardness measurement (b) on the surface of the contact pads and into the depth of the microprojection.

Labels in Fig. 2a: 1 – ball, 2 – ceramic ring, 3 – mica, 4 – rod, 5 – sleeve, 6 – sapphire, 7 – test specimen, 8 – support sleeve, 9 – base support.

After holding the specimens in the fixture under specified temperature (T) and pressure (P), they were cooled to room temperature, and profilograms were again recorded from the fixed area using the same vertical (VU) and horizontal (HU) magnifications. By comparing the profilograms and processing them automatically with the IVK computer software, the relative amount of plastic deformation of the microprojections

can be determined based on changes in their height (Fig. 3a, b), though only during the 1st and 2nd stages of microprojection crushing (see Fig. 4a, b). Additionally, by calculating the relative lengths (l_1, l_2, l_3 — see Fig. 3) of the contact pads within the designated fixed section (L), it is possible to determine the relative or absolute area of actual contact [17].

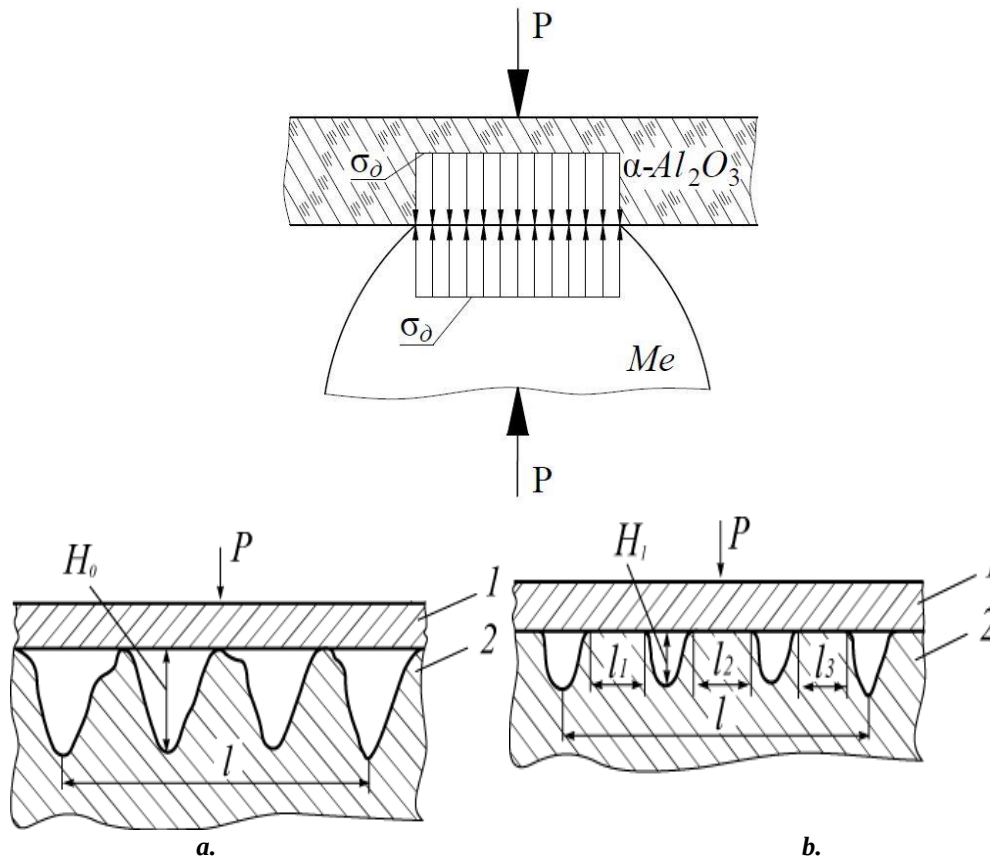


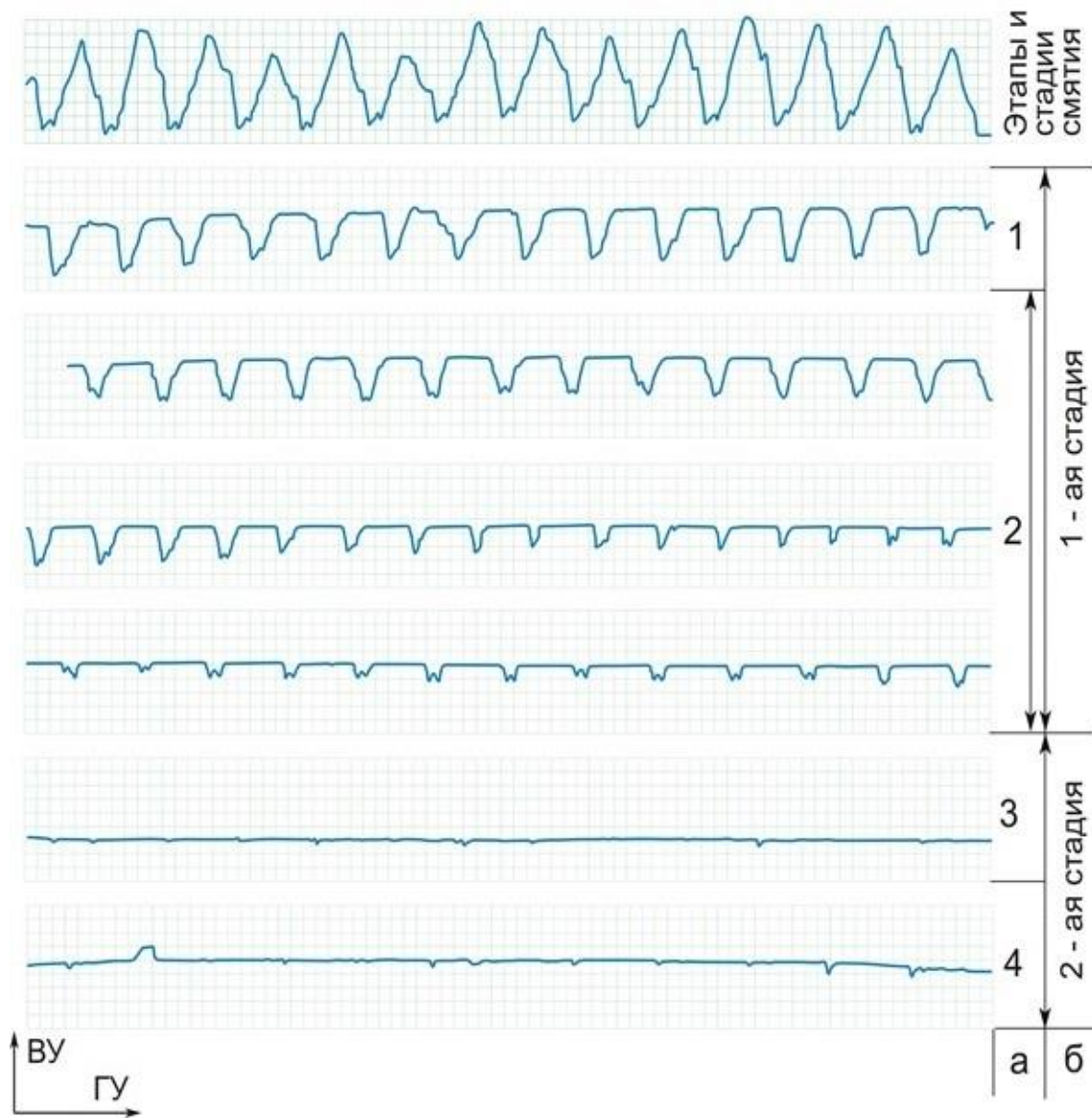
Fig. 3a, b.

Diagram of length (l) measurements on a designated section (L).

H_0 – initial height of microprojections; H_1 – height at a given moment in time;

$l_{1,2,3}$ – width of contact pads, mm;

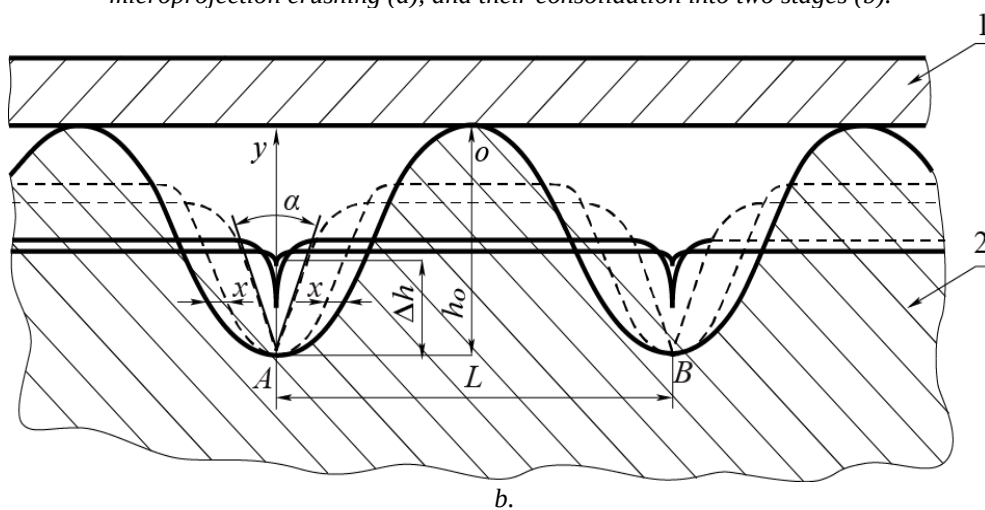
1 – corundum, 2 – metal.



a.

Fig. 4a.

Character of the profilograms of copper contact surfaces after interaction with sapphire, showing four stages of microprojection crushing (a), and their consolidation into two stages (b).



b.

Fig. 4b.

Diagram of the "apparent" rise of the lower point of the base of the microprojections on the flat surface during their crushing: 1 – sapphire; 2 – metal.

Mathematical processing of the obtained experimental results to assess the influence of (P, T, Rz) and time on the shape change of the microprojections, plastic deformation, and contact formation allowed for the derivation of an expression for calculating the formed contact area (F, mm²), namely:

$$F = \pi \cdot R^2 \cdot SF \quad (1)$$

Where:

- **R** – radius of the sample in mm,
- **S** – relative width of the contact areas (see Fig. 4), taking values ($0 < S < 1$).

Expression (1) allows for the calculation of the area of the formed contact at any stage of microprojection crushing during the finishing process of smoothing flat metal surfaces and their welding under pressure with heating, provided the relative width of the contact areas (determined experimentally via kinetics, i.e., this

value is taken from the experimental graph of the functional dependence $S = f(T, P, Rz)$) and the sample radius (R) are known.

In our experiments, when processing contact surfaces by turning, the number of ring-shaped microprojections (n) ranged from 130 to 132, while by planing, $n = 30$ to 32. After simple transformations, we find that the calculated error in determining the shaded contact area (F) (see Fig. 5a, b) is approximately 1%. Using expression (1), the normal stresses (σ_d) in the contact between the microprojection and sapphire were calculated over the entire range of temperatures and pressures using the well-known expression:

$$\sigma_d = \frac{P}{F} \quad (2)$$

Kinetic curves showing the changes in normal (σ_d) and tangential (τ_d) stresses were constructed for each fixed moment of time.

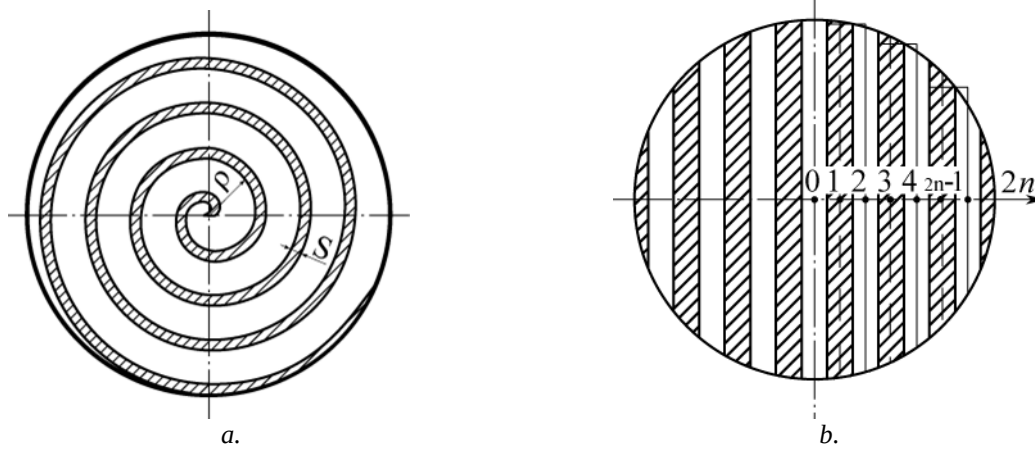


Fig. 5a, b.

Diagrams for calculating the contact area F: (A – turning; B – planing)

3. Main Content of the Work

The use of profilographs and profilometers for obtaining information on changes in surface topography is limited by the physical capabilities of the method used. The key metrological characteristics of roughness measurement techniques are [15]:

- Δz – lower limit of measurement for the height of microprojections;
- $\Delta x, \Delta y$ – spatial resolution of the field;
- **vmin** and **vmax** – frequency range limits of micron irregularities.

For profilographs, as well as for optical devices and methods for roughness control, the value of Δz is measured in hundredths of a micrometer, whereas the resolution in the field, $\Delta x, y$, is typically several times worse. This discrepancy can create the illusion of higher precision in measuring the "Z" coordinate of the real profile compared to the "X" and "Y" coordinates. In reality, this is not always the case, due to differences

in the conditions for measuring microprojections during their crushing at different stages of the kinetic curve of contact formation and the presence of a correlation between Δz and $\Delta x, y$, which is established by the Ingelstam relationship [16]. Furthermore, the value $\Delta x, y \neq 0$ defines not only the upper limit of the measured frequencies of micron irregularities (**vmax** = $\Delta^{-1}x, y$), but also introduces an additional systematic measurement error. This error depends not only on the class of accuracy of the profilograph but also on the surface relief characteristics and its temporal changes, which occur during solid-state welding under pressure with heating and during finishing smoothing [13, 14]. This component of the error is most significant in cases where the angle α at the apex of the microprojections (see Fig. 6a, b) is less than 90°. We will estimate the possible magnitude of this error and demonstrate that, in some cases, it can be excluded by a special method of processing the profilograms.

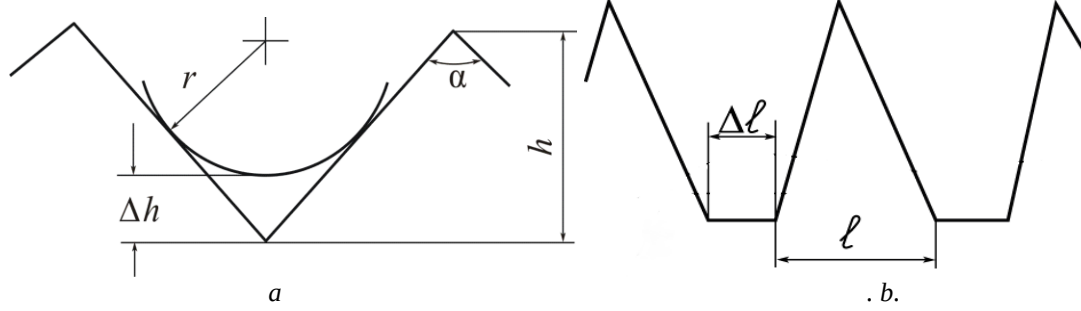


Fig. 6. Scheme of the profile of microprojections on the contact surface.

Let's consider linear homogeneous micron irregularities created on the studied contact surface during its treatment with a triangular-section cutting tool with a sharpening angle α . The profile of such a surface can be approximated by the model shown in Fig. 6a. From geometric constructions, it is easy to see that the relative systematic error of profilograph measurement $\Delta h/h$ is:

$$\frac{\Delta h}{h} = \frac{r \cdot (1 - \sin \frac{\alpha}{2})}{h \cdot \sin \frac{\alpha}{2}} = \frac{4 \cdot r \cdot \sin \frac{\alpha}{2} \cdot (1 - \sin \frac{\alpha}{2})}{l \cdot \sin \alpha}$$

where: r – radius of the profilograph needle tip ($r = 2 \mu\text{m}$ in our case).

As seen from the relationship (3), the measurement error is proportional to the ratio of r/h or r/l , and as the angle α decreases (while $h = \text{const}$), the error increases without bound. The relation (3) also shows the frequency dependence of the error $\Delta h/h$, since the value l^{-1} is the number of micron irregularities per unit length (the frequency of micron irregularities).

Numerical values of the measurement error, according to expression (3), for the specific case $r = 2 \mu\text{m}$ and microprojection height $h = 10 \mu\text{m}$, reach 3%, 8.5%, and 20%, respectively, for $\alpha = 120^\circ$, 90° , and 60° . The actual measurement accuracy can be higher due to rounding of the bottom of the pits between microprojections, but in all cases, these estimates are valid for micron irregularities spaced at a distance of about $\Delta x, y$ or with small values of the angle α .

This error can be excluded by a special method of profilogram processing. This possibility is embedded in the methodology for determining the area of actual contact and the magnitude of plastic deformation of microprojections, based on comparing profilograms.

Typically, the relative deformation of microprojections E_m is found by comparing (see Fig. 3 or 4) the average initial height (h_0) of the microprojections with their average height (h_t) at the current moment in time (t) using the formula:

$$E_m = \left\{ \frac{(h_0 - h_t)}{h_0} \right\} \cdot 100\%$$

However, the calculation of relative deformation of microprojections of welded surfaces during their group constrained settling does not account for the fact that, as the crushing process progresses, their side surfaces change (see Fig. 4), the angle between them decreases, and they weld together [8, 9, 12, 17]. To avoid the corresponding increase in the error of determining E_m using formula (4), we can use the relationship be-

tween the magnitude of E_m and the bearing part coefficient of the profile, which is numerically equal to the relative area of actual contact S , experimentally determined from profilograms by measuring the lengths of contact areas. The accuracy of measuring S is not significantly affected by the angle α at the apex of the microprojections.

Indeed, within the framework of the considered model of linear microprojections with triangular cross-sections, which become trapezoidal and rectangular as a result of their settlement, we will use the condition of mass and volume conservation of the microprojections.

This means that at all stages of microprojection compression, the cross-sectional area of the microprojections in the profilographing plane remains constant. Therefore, it follows that:

$$E_m = \frac{S}{(1+S)} \text{ or } \frac{\Delta l}{h_0} = \frac{1}{(1+S)}$$

Thus, the procedure for measuring h_t to find E_m can be replaced with the procedure for measuring S with high accuracy, thereby avoiding the inaccuracies in the measurement of the pit depth, which depends on the angle α and the established features and nature of the microprojection compression during their group settlement on the contact surfaces during pressure welding with heating and finish machining of metal surfaces with a flat sapphire tool [9, 12–14]. For the profile model that accounts for the “flatness” of the pit bottoms (Fig. 6b), expression (5) takes the form:

$$E_m = \frac{S \cdot \left(1 + \frac{\Delta l}{l}\right)}{\left[1 + S \left(1 + \frac{\Delta l}{l}\right)\right]}$$

As can be seen from the analysis of expressions (5) and (7), S is always greater than E_m , and as S approaches 1, E_m approaches 0.5. Whereas direct measurements of h_t of the microprojections and the estimation of the magnitude of plastic deformation E_m according to expression (4) lead to the conclusion that E_m is greater than S .

Therefore, comparing and analyzing the kinetics of the strength (bonding) of material joints with the kinetics of plastic deformation of microprojections during pressure welding with heating is incorrect and does not allow for an objective assessment of the process. Differentiating relations (5) and (7) allows us to find the rate ($\dot{E}_m$) of plastic deformation of microprojections:

For the model (Fig. 5a):

$$\dot{E}_m = \frac{\dot{S}}{(1+S)^2}$$

For the model (Fig. 5b):

$$\dot{E}_m = \frac{\dot{S} \cdot \left(1 + \frac{\Delta l}{l}\right)}{\left[1 + S \left(1 + \frac{\Delta l}{l}\right)\right]^2}$$

Expressions (8) and (9) show that the relative area of actual contact (S) always increases significantly faster than the change in the magnitude of plastic deformation (E_m) of the microprojections on the contact

surfaces. As an example, in Fig. 7a, b, the relationship between E_m and S is shown, and the kinetic curves of plastic deformation of microprojections during welding with heating of copper MB with sapphire and the formation of physical contact, calculated using formula (4), are compared with the features of compression (Fig. 7b) using formula (6) under the same welding and finishing parameters.

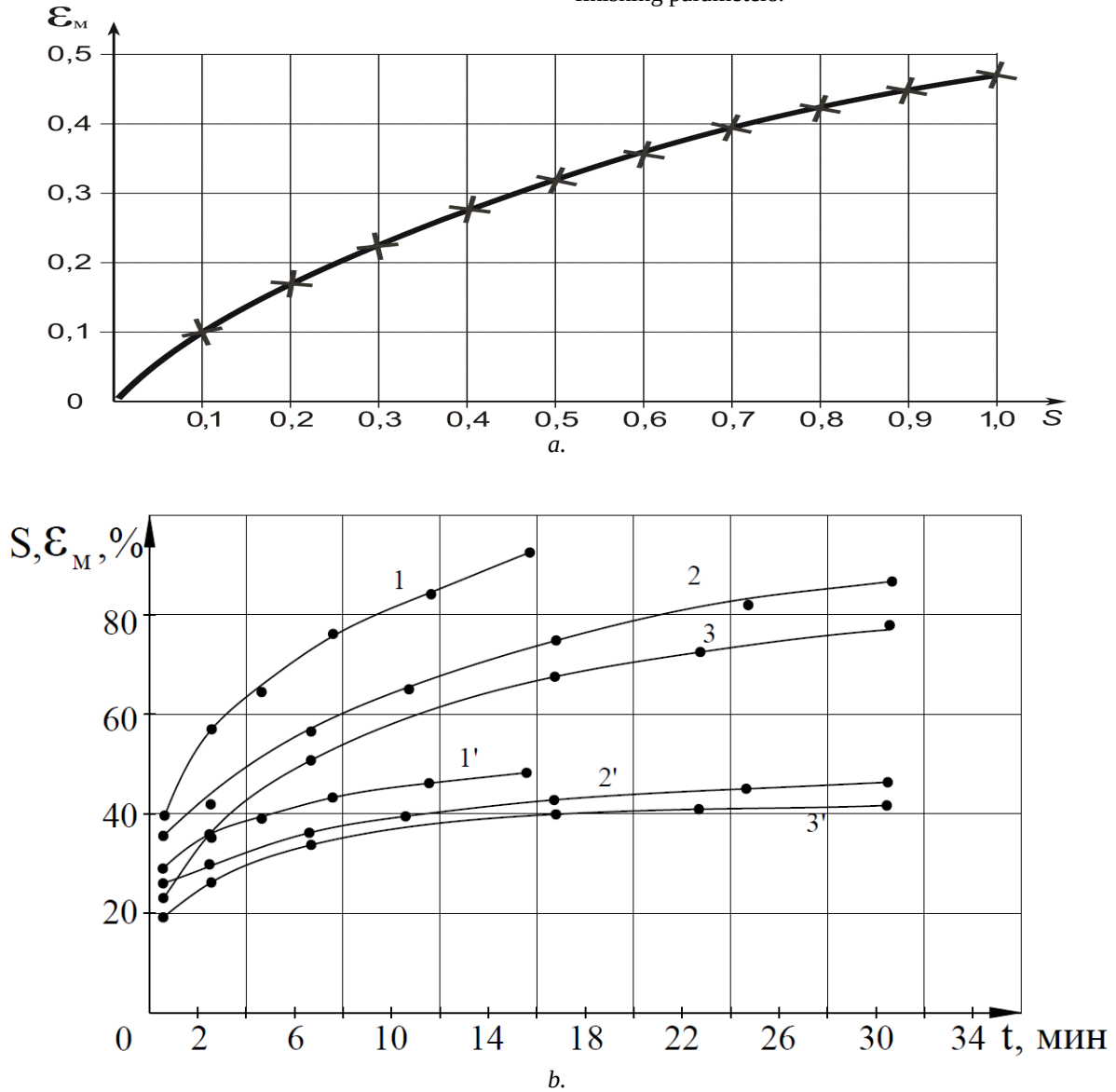


Fig. 7.

a - Graphical relationship between the actual contact area (S) and the magnitude of relative plastic deformation (E_m) of the microprojections;

b - Comparison of the kinetic curves of the formation of physical contact S (1, 2, 3) and plastic deformation of the copper microprojections E_m (1', 2', 3') constructed using formula (5) accounting for the features of the compression of the microprojections; $T_{sv} = 1173$ K;

Curves:

1, 1' - 20 MPa; 2, 2' - 15 MPa; 3, 3' - 10 MPa; $R_z = 40...80 \mu m$.

This means that the kinetic curve of plastic deformation of microprojections should always lie below the kinetic curve of the formation of the actual contact as it reaches 0.6 of the nominal transition into physical contact during the second stage of the compression of microprojections [12,17]. Comparing and analyzing the kinetics of the strength growth (bonding) should be done with the kinetics of the development of contact

areas (Fig. 8a, b, c) on plastically deforming microprojections, taking into account and based on the four stages of the compression of the microprojections, the developing micro-stresses of the second kind (normal σ_k and tangential τ_k), as well as the ongoing physical, chemical, and mechanical processes of the transfer of deformation from the "soft" metal to the harder body (sapphire) [19].

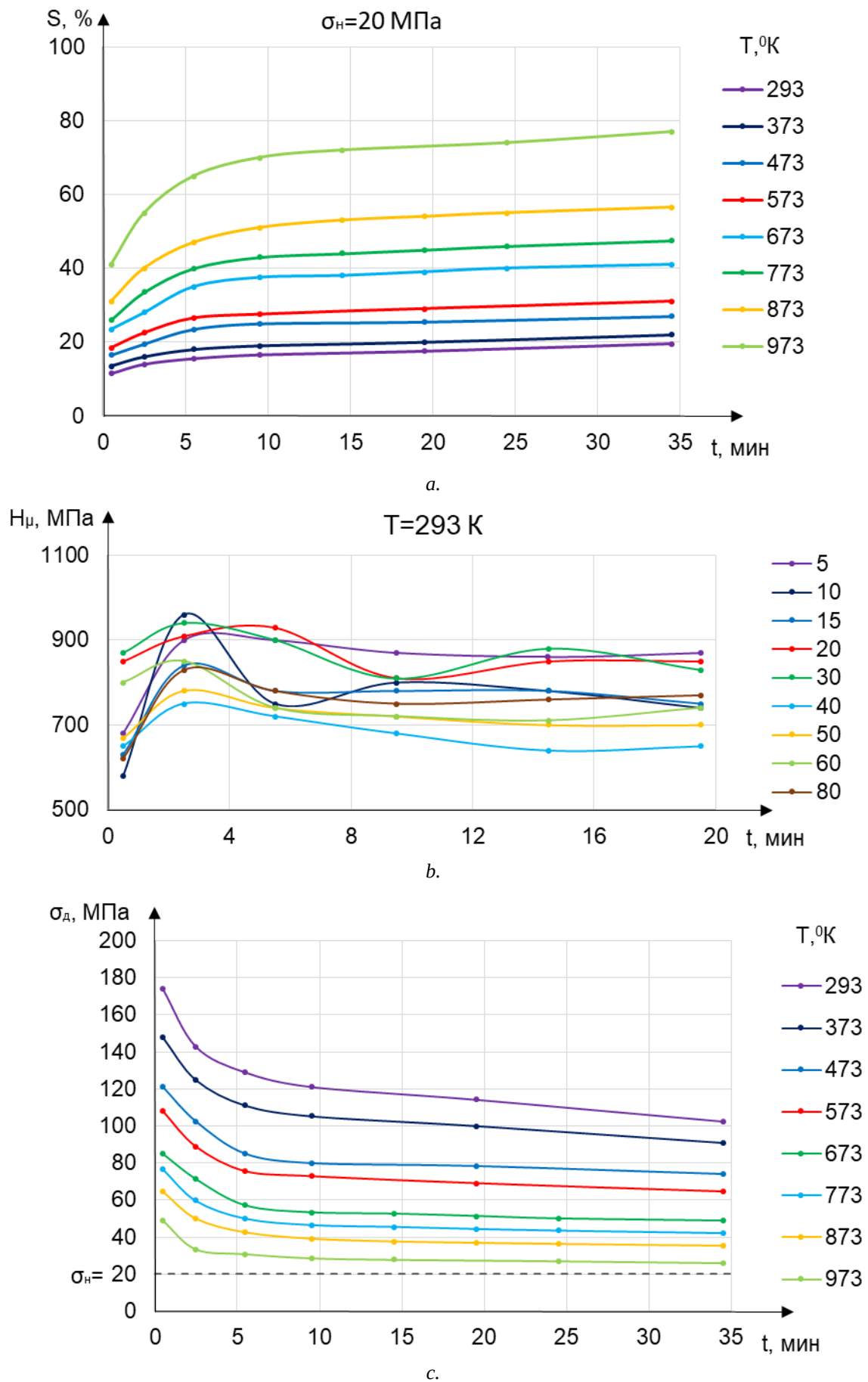


Fig. 8 a, b, c. Kinetic curves of the formation of actual contact (a), changes in hardness on the surface of the contact areas (b), and changes in the acting normal stresses σ_k of second-kind microstresses (c).

It is important to consider that the size of a microasperity corresponds to the size of a single metal grain. This means that when calculating σ_d on each contact area of a microasperity, we determine the stresses compensated within the grain volume—i.e., second-kind microstresses. By recalculating them using known formulas, we determine the magnitude of the shear stresses of the second kind, also compensated within the grain volume [21,22]. By obtaining experimental values of S and substituting them into equation (8), the value of the relative plastic deformation (E_m) of the microasperities on the welded surfaces can be calculated.

Figure 7a shows the graphical relationship between the real contact area (S) and the relative plastic deformation (E_m) of the microasperities during pressure welding with heating and during fine finishing with a sapphire tool on flat surfaces.

4. Conclusions

The developed method for determining E_m and S was used to establish quantitative and qualitative patterns and the nature of microasperity deformation on contact surfaces of metals during fine finishing and the creation of surfaces with regulated and controlled mechanical properties, as well as during pressure welding with heating of dissimilar materials with sharply differing creep resistance.

This methodology also allows the calculation of the level of second-kind microstresses on the contact areas of microasperities and within their volume.

The conducted research explains the nature of the shift of the kinetic curve of strength growth (bond development) relative to the curve of physical contact formation between dissimilar materials. It also proposes a mechanism of relay-like deformation transfer from the “soft” metal grain to the harder one (sapphire), and the role of second-kind stresses in the initiation of submicroscopic cracks within the metal grain.

Additionally, this allowed an evaluation of the accuracy of previously published data by other authors concerning E_m as calculated using formula (4), which did not take into account the nature of microasperity deformation on the welded surfaces. It was confirmed that E_m is significantly overestimated when calculated using formula (4) based on direct measurements of h , with the error reaching up to 100% as $S \rightarrow 1$.

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DECODING DATA: TYPES, SOURCES, AND LIFECYCLE MANAGEMENT**Ziyadkhanli S.***Azerbaijan State Oil and Industry University*<https://doi.org/10.5281/zenodo.15298401>**Abstract**

Decoding data involves interpreting information from its encoded or compressed form back into a usable format. This process is crucial in communication, data storage, and various digital interactions where data is often transmitted in a form that needs to be decoded for understanding or processing. There are several types of data that can be decoded. Structured data is organized in a defined format, such as rows and columns in databases, making it easier to process. Unstructured data, on the other hand, is raw and not organized in a predefined way, such as text documents or multimedia content. Semi-structured data falls in between, often seen in formats like XML or JSON, which are not fully structured but have some organizational elements. The sources of data can vary widely. Internal sources are data generated within an organization, such as customer interactions, sales data, or internal reports. External sources include information gathered from outside the organization, such as social media content, market reports, or public databases. Sensor data is another type, originating from devices like IoT sensors or environmental monitors that collect real-time data. Managing the lifecycle of data is a key aspect of handling it effectively. The data lifecycle starts with its creation or acquisition, followed by storage in databases, cloud services, or physical mediums. Once stored, the data is used for analysis or other purposes. As it becomes less active, it is archived to more cost-effective storage solutions, while older, irrelevant data may be destroyed to ensure compliance with privacy regulations or to optimize storage resources.

Keywords: data integrity, data validation, metadata, big data, data acquisition.

Introduction

Decoding data, understanding its types, managing its sources, and overseeing its lifecycle are essential aspects of effective data handling in the digital age. Decoding refers to the process of interpreting encoded or compressed information and converting it back into a usable form. This process plays a significant role in communication systems and data transmission, where information is often encoded for security or efficiency reasons. Data itself can be classified into different types: structured, unstructured, and semi-structured. Structured data is organized in a well-defined format, such as tables in relational databases, which makes it easy to store and analyze [1,p.33]. Unstructured data, such as text files or multimedia content, lacks this organization and requires more complex methods for analysis. Semi-structured data, which includes formats like XML and JSON, sits between these two extremes, having some organizational elements but not being fully structured. The sources of data are varied and play a crucial role in how it is collected and used. Internal sources come from within an organization, such as customer data, sales information, or operational metrics. External data might be sourced from third-party providers, social media platforms, or public databases. Additionally, sensor data is collected from physical devices or Internet of Things (IoT) systems, contributing real-time, dynamic information [12,p.13]. The lifecycle of data begins with its creation or acquisition, followed by storage, use, and eventual archiving. As data ages or becomes less relevant, it may be archived to reduce storage costs. In some cases, outdated data is destroyed to ensure compliance with privacy regulations or to maintain efficiency. Effective lifecycle management helps ensure that data is secure, accessible, and used responsibly.

"Understanding Data Management: From Collection to Disposal"

Understanding Data Management: From Collection to Disposal" covers the entire journey of data, from the moment it is first collected to its final disposal. Effective data management is essential for organizations to ensure that they can extract valuable insights while maintaining security and compliance. The process begins with the collection of data, which can come from various sources such as internal systems, external partners, or sensors. Once collected, data needs to be properly stored, organized, and processed for later use. This stage involves defining data structures and ensuring that the information is easily accessible for analysis. Depending on its nature, data may be classified as structured, semi-structured, or unstructured, each requiring different handling and storage methods. As the data is used, it contributes to decision-making, insights, and business operations. Over time, however, not all data remains relevant [6,p.18]. Older or unused data is either archived for long-term storage or destroyed to free up resources, ensure privacy, and maintain compliance with regulations like GDPR. The data management lifecycle requires careful planning and the right tools to ensure data is handled efficiently, securely, and in line with organizational needs. It also involves understanding data governance, security, and privacy concerns, ensuring that the information is kept safe from unauthorized access and is disposed of properly when no longer needed. The next step in the data management process is data usage, where the stored information is actively used for analysis, decision-making, and other business functions. At this stage, data plays a pivotal role in gaining insights that drive strategies, improve processes, and enhance customer experiences. The effectiveness of data usage largely depends on how well it has been organized, stored, and made accessible to those who need it, whether through reports, dashboards, or advanced analytics.

However, not all data will be in active use indefinitely. Over time, some data becomes less relevant or outdated. This leads to the need for data archiving. Archiving refers to the process of moving data that is no longer frequently accessed to long-term storage systems. Archived data remains stored but is less costly to maintain compared to active data, making it a cost-effective solution for preserving valuable historical information without consuming excessive resources. As part of the data lifecycle, data destruction is a critical step for ensuring that unnecessary or outdated data is completely removed. This is particularly important when the data is sensitive or personally identifiable. Adhering to data privacy regulations, such as GDPR or CCPA,

ensures that data is destroyed safely and responsibly. By deleting data when it is no longer needed, organizations mitigate the risks of potential breaches or misuse [2,p.10]. Throughout this lifecycle, organizations must also ensure that they have solid data governance in place. Data governance refers to the policies, procedures, and controls that ensure the proper management of data across its entire lifecycle. This includes setting clear data quality standards, ensuring compliance with legal regulations, defining access controls, and establishing accountability for data stewardship. Proper governance ensures that data remains accurate, consistent, and secure, supporting the overall integrity of the organization's data ecosystem.

Table 1.

Data Management Phases: Completion, Importance, and Efficiency Indicators

No.	Phase	Completion (%)	Importance (%)	Efficiency (%)
1	DataCollection	80	75	85
2	DataStorage	90	90	80
3	DataProcessing	70	80	75
4	DataUsage	85	95	90
5	DataArchiving	60	70	65

Source:Si, Y., Xiao, Q., Su, J., Zeng, S., & Hong, X. (2020). Research on data product quality evaluation model based on AHP and TOPSIS. In Proceedings of the 4th International Conference on Computer Science and Application Engineering (pp. 1–5). Sanya, China: ACM. <https://doi.org/10.1145/3424978.3425087>

The table outlines three key performance indicators for each phase of the data management process: completion, importance, and efficiency. These indicators help assess the effectiveness of data management from data collection to archiving. In the Data Collection phase, 80% of the necessary data has been gathered, indicating solid progress. However, the phase is considered somewhat less important (75%) in the broader context of data management [11,p.23]. Despite this, data collection is highly efficient (85%), meaning that the process is effective in capturing and organizing the data. For Data Storage, the process is almost complete, with 90% of data successfully stored. This phase holds a high importance score of 90% due to its critical role in ensuring that data is securely and properly organized for future use. The efficiency score is 80%, indicating that while the storage process is functioning well, there is still room for improvement, possibly in terms of optimizing cost or speed. In Data Processing, 70% of the data has been processed. The phase is of moderate importance (80%) as it is essential for transforming raw

data into useful information. Efficiency in processing is slightly lower at 75%, suggesting that some challenges or inefficiencies exist in organizing and preparing data. For Data Usage, 85% of the data has been actively used for analysis and decision-making, showing significant progress in leveraging the data. [9,p.18]. This phase is extremely important (95%) because it directly influences business decisions. Efficiency is also high (90%), meaning that data usage is effectively supporting decision-making and insights generation. Finally, in Data Archiving, only 60% of the data has been archived, which indicates that this phase is still in progress. Archiving is moderately important (70%), ensuring that historical data is preserved for future reference. However, efficiency is lower (65%), suggesting potential improvements in the archival process, such as better organization or more cost-effective storage solutions. This analysis highlights the strengths and areas for improvement across different stages of data management, providing valuable insights into where efforts are most successful and where further attention may be required.

Table 2.

Data Management Phases: Methodologies and Tools/Technologies

No.	Phase	Methodology	Tools/Technologies
1	DataCollection	Manual Input, Automated Systems, IoT Devices	Data Capture Software, Sensors, APIs
2	DataStorage	Relational Databases, Cloud Storage, Data Lakes	SQL Databases, NoSQL Databases, Cloud Solutions
3	DataProcessing	ETL Processes, Data Mining, Machine Learning Models	Data Warehouses, Hadoop, Data Processing Frameworks
4	DataUsage	Data Analytics, Dashboards, Reporting Tools	BI Tools (Power BI, Tableau), Statistical Tools
5	DataArchiving	Cold Storage, Tape Backup, Cloud Archiving	AWS S3, Glacier, Tape Backup Systems
6	DataDestruction	Shredding, DataDeletion, Encryption	Data Wiping Tools, Encryption Software

Source:Truong, H.-L., Comerio, M., De Paoli, F., Gangadharan, G. R., & Dustdar, S. (2012). Data contracts for cloud-based data marketplaces. *International Journal of Computational Science and Engineering*, 7(4), 280–295. <https://doi.org/10.1504/IJCSE.2012.049749>

The table provides an overview of the methodologies and tools/technologies used in different phases of data management. Each phase in the lifecycle of data is associated with specific approaches and technologies that support effective data handling. In the Data Collection phase, manual input, automated systems, and IoT devices are commonly used methodologies to gather data. Tools such as data capture software, sensors, and APIs facilitate this process by enabling automated and real-time data collection. For Data Storage, relational databases, cloud storage, and data lakes are the primary methodologies used to store data in an organized and scalable manner [7,p.14]. Technologies like SQL and NoSQL databases, as well as cloud solutions, are leveraged to ensure data is stored efficiently and is easily accessible. The Data Processing phase involves methodologies such as ETL (Extract, Transform, Load) processes, data mining, and machine learning models to clean, analyze, and process raw data. Data warehouses, Hadoop, and various data processing frameworks are used as tools to support these methodologies and transform data into valuable insights. In the Data Usage

phase, data analytics, dashboards, and reporting tools are employed to analyze and present data in meaningful ways [12,p.21]. Technologies like Power BI, Tableau, and statistical tools are used for visualization, reporting, and decision-making based on the data. For Data Archiving, methodologies like cold storage, tape backup, and cloud archiving are used to preserve data that is no longer actively in use. Tools such as AWS S3, Glacier, and tape backup systems are implemented to store archived data securely and cost-effectively. Finally, in the Data Destruction phase, methodologies like shredding, data deletion, and encryption are used to securely eliminate data when it is no longer needed. Technologies such as data wiping tools and encryption software are critical in ensuring that deleted data cannot be recovered and remains private. Each of these phases utilizes specific tools and methodologies designed to optimize data management, ensuring data is collected, stored, processed, used, archived, and destroyed securely and efficiently.

Table 3.

Data Management Phases: Quality, Security, and Accessibility Indicators

No.	Phase	DataQuality (%)	DataSecurity (%)	DataAccessibility (%)
1	DataCollection	85	90	80
2	DataStorage	90	95	90
3	DataProcessing	75	85	70
4	DataUsage	95	80	85
5	DataArchiving	80	85	75

Source:Stadelmann, T., Klamt, T., &Merkt, P. H. (2022). Data centrism and the core of data science as a scientific discipline.Archives of Data Science, Series A, 8(2), 1–16.KIT Scientific Publishing. <https://doi.org/10.5445/IR/1000143637>

The table outlines three key performance indicators for different phases of data management: Data Quality, Data Security, and Data Accessibility. These indicators provide insight into how well each phase performs in terms of the quality of data, its security level, and how easily it can be accessed. In the Data Collection phase, data quality is rated at 85%, indicating a good level of accuracy and relevance in the data collected. The security of the collected data is very high at 90%, reflecting strong protective measures. However, accessibility is slightly lower at 80%, suggesting that there might be some barriers to accessing the data efficiently during collection [10,p.45].For Data Storage, the quality of the stored data is rated at 90%, showing excellent organization and integrity. The security of the data is also very high (95%), reflecting strong encryption and access controls in place. Data accessibility is rated at 90%, indicating that the stored data is easily accessible when needed. In the Data Processing phase, data quality drops slightly to 75%, which could indicate some loss or transformation of data during processing. The security of the processed data remains strong at

85%, but accessibility is lower at 70%, suggesting potential challenges in accessing processed data due to complexity or organizational factors. For Data Usage, the data quality is at its highest, 95%, indicating that the data used for decision-making and analysis is of excellent quality. Security is somewhat lower at 80%, reflecting that data usage might involve certain vulnerabilities, while accessibility is rated at 85%, indicating good access to the data for business purposes. Finally, in the Data Archiving phase, data quality is rated at 80%, showing that archived data is still of good quality but might not be as actively managed. Security is rated at 85%, reflecting the protection measures in place for long-term storage. Accessibility is lower at 75%, indicating that archived data is harder to access compared to more active data. These percentage indicators provide valuable insights into the performance of data management in key areas, highlighting strengths and areas that may require further attention to improve data quality, security, and accessibility across different stages.

Table 4.

Data Management Phases: Retention and Compliance Indicators

No.	Phase	RetentionPeriod (Years)	Compliance (%)	AuditFrequency (Months)
1	DataCollection	5	95	12
2	DataStorage	10	98	24
3	DataProcessing	7	90	18
4	DataUsage	5	80	12
5	DataArchiving	20	85	36
6	DataDestruction	0	100	6

Source: Sukur, A., & Lind, M. L. (2022). Enterprise architecture to achieve information technology flexibility and enterprise agility. *International Journal of Information Systems and Social Change (IJISSC)*, 13(2), 1–20. IGI Global. <https://doi.org/10.4018/IJISSC.298337>

The table provides insights into the retention periods, compliance levels, and audit frequency for different phases of data management. Each phase is evaluated based on how long data is retained, how compliant the processes are with regulations, and how often audits are conducted. In the Data Collection phase, data is retained for five years, ensuring it remains available for immediate analysis and reporting. Compliance is rated at 95%, reflecting strong adherence to regulatory standards [3,p.27]. Audits are conducted every 12 months to ensure the processes remain in line with organizational and legal requirements. For Data Storage, the retention period extends to ten years, allowing for long-term access and use of stored data. Compliance is exceptionally high at 98%, indicating robust measures to meet legal and operational standards. Audits are conducted every 24 months to maintain the integrity and security of storage systems. In the Data Processing phase, data is retained for seven years, providing ample time for transformation and usage. Compliance is at 90%, slightly lower than storage, likely due to the complexity of processing tasks. Audits are conducted every 18

months to monitor the accuracy and efficiency of processing workflows. For Data Usage, the retention period is five years, matching the duration for data collection. Compliance is rated at 80%, suggesting the need for improved controls during data usage. Audits are conducted every 12 months to ensure proper usage and decision-making based on the data. In Data Archiving, data is retained for 20 years, reflecting the need for long-term preservation of historical data. Compliance is at 85%, with room for improvement in managing archived data in line with regulations. Audits occur every 36 months due to the less active nature of archived data [8,p.55]. Finally, in the Data Destruction phase, data is not retained, as this phase focuses on secure deletion. Compliance is rated at 100%, ensuring that data destruction fully adheres to legal and organizational standards. Audits are conducted every six months to ensure that all data is destroyed securely and in compliance with regulations. This information highlights the retention and compliance practices across various phases, emphasizing the importance of regular audits and adherence to regulatory standards in managing data throughout its lifecycle.

Table 5.

Data Management Phases: Performance and Cost Indicators

No.	Phase	PerformanceEfficiency (%)	OperationalCost (%)	TimeEfficiency (%)
1	DataCollection	85	20	90
2	DataStorage	90	25	85
3	DataProcessing	80	30	75
4	DataUsage	95	15	95
5	DataArchiving	75	10	70
6	DataDestruction	85	5	80

Source: Legner, C., Pentek, T., & Otto, B. (2020). Accumulating design knowledge with reference models: Insights from 12 years' research into data management. *Journal of the Association for Information Systems*, 21(3), 735–770.

The table provides an analysis of performance efficiency, operational cost, and time efficiency across various phases of data management. Each phase is evaluated based on how effectively it performs, the percentage of operational costs it consumes, and how efficiently time is utilized. In the Data Collection phase, performance efficiency is rated at 85%, indicating a high level of effectiveness in gathering data. Operational costs are relatively low at 20%, showing that data collection is cost-efficient. Time efficiency is very high at 90%, reflecting the speed and effectiveness of the data collection processes. For Data Storage, performance efficiency is higher at 90%, showcasing strong systems for storing data securely and accessibly [6,p.54]. Operational costs are slightly higher at 25%,

as storage infrastructure often requires significant investment. Time efficiency is rated at 85%, indicating good but not optimal speed in storing and retrieving data. The Data Processing phase has a performance efficiency of 80%, suggesting some room for improvement in organizing and analyzing data. Operational costs are the highest among all phases at 30%, due to the computational resources and tools required for processing. Time efficiency is moderate at 75%, reflecting potential delays or complexities in transforming raw data into usable formats. In the Data Usage phase, performance efficiency is the highest at 95%, indicating that data is being used very effectively for decision-making and insights. Operational costs are the lowest for active phases at 15%, showing that leveraging data

is relatively inexpensive. Time efficiency is also very high at 95%, reflecting the ability to use data quickly and effectively. For Data Archiving, performance efficiency is rated at 75%, as archiving systems may not always prioritize optimization. Operational costs are minimal at 10%, reflecting the cost-effectiveness of long-term storage solutions. Time efficiency is lower at 70%, as accessing archived data can take more time compared to active data. Finally, in the Data Destruction phase, performance efficiency is high at 85%, indicating effective and secure methods for data deletion. Operational costs are the lowest at 5%, due to the simplicity of the destruction process. Time efficiency is also strong at 80%, reflecting the swift execution of data destruction activities. This analysis highlights the strengths and areas for improvement in performance, cost management, and time utilization across the lifecycle of data management.

Effective data management involves optimizing each phase to ensure seamless operations, reduced costs, and high performance. While some phases, such as data usage, excel in performance and time efficiency, others, like data processing, require more attention to enhance operational outcomes. Balancing these factors is crucial for organizations aiming to extract maximum value from their data. One key area of focus is improving the data processing phase, which often involves complex operations like data cleaning, transformation, and analysis. Investing in advanced tools such as artificial intelligence or machine learning can help streamline these activities, reducing both time and costs. Similarly, adopting scalable cloud solutions for data storage can improve efficiency while lowering expenses related to physical infrastructure [11,p.65]. Another critical aspect is ensuring data security throughout its lifecycle. From collection to destruction, robust encryption methods, access controls, and regular audits are essential. This not only protects sensitive information but also ensures compliance with regulations like GDPR or CCPA, which can have significant legal and financial implications for non-compliance. Data accessibility is equally important, particularly for phases like storage, processing, and usage. Implementing systems that allow quick access to relevant information while maintaining security protocols can significantly improve decision-making and operational agility. Long-term considerations such as data archiving also play a pivotal role in effective management. While this phase typically involves lower costs, ensuring that archived data remains accessible and retrievable when needed is vital. Using metadata tagging and implementing intelligent archival systems can enhance both organization and retrieval speed [9,p.41].

A critical component of modern data management is the ability to leverage data for strategic insights and innovation. This requires not only effective processes but also a cultural shift within organizations to view data as a key asset. Decision-makers must prioritize investments in data-driven technologies and foster a data-centric mindset across teams to maximize the benefits. One area of growing importance is real-time data processing. With the rise of IoT devices, social media, and other dynamic data sources, organizations must handle and analyze data as it is generated. This enables

timely decision-making, improved customer experiences, and better operational efficiency. Implementing streaming analytics platforms and edge computing solutions can significantly enhance real-time data processing capabilities. Another transformative trend is the integration of artificial intelligence (AI) and machine learning (ML) into data management systems. AI-powered tools can automate data categorization, detect anomalies, and predict future trends, reducing manual intervention and enabling more accurate decision-making. Machine learning algorithms, for instance, can uncover patterns in vast datasets that would otherwise go unnoticed, opening new opportunities for innovation. At the same time, organizations must address the challenges of data governance. Establishing clear policies for data usage, ownership, and accountability ensures that data is handled responsibly and ethically. This includes defining roles for data stewards, creating standardized processes, and implementing regular compliance checks. Strong governance frameworks also help in resolving disputes related to data accuracy, access, or security. Another key focus is sustainability in data management. As organizations store and process increasing volumes of data, the environmental impact of data centers and IT infrastructure becomes a concern. Adopting energy-efficient technologies, optimizing resource utilization, and utilizing green data centers are steps toward minimizing the carbon footprint associated with data operations. Collaboration across departments is also essential to break down silos and enable a unified approach to data management. By integrating data from marketing, finance, operations, and other departments, organizations can gain a holistic view of their performance and make informed decisions that benefit the entire enterprise. Looking ahead, the evolution of technologies such as quantum computing and blockchain is set to redefine data management [10,p.19]. Quantum computing promises unparalleled processing power for handling complex datasets, while blockchain offers a transparent and secure way to manage data ownership and transactions. Ultimately, the future of data management lies in adaptability. Organizations that embrace change, invest in cutting-edge technologies, and continuously refine their strategies will be best positioned to thrive in a data-driven world. The ability to balance efficiency, innovation, and compliance will determine their success in harnessing the power of data.

CONCLUSION

Effective data management is the backbone of modern organizations, enabling them to harness the full potential of their data while maintaining efficiency, security, and compliance. By addressing each phase of the data lifecycle—collection, storage, processing, usage, archiving, and destruction—organizations can ensure that their data remains a valuable asset. The integration of advanced technologies like artificial intelligence, machine learning, and real-time analytics has revolutionized data management, making it more efficient and insightful. At the same time, robust governance frameworks and compliance practices ensure that data is handled ethically and securely, mitigating risks and protecting sensitive information. Sustainability and adaptability are emerging as critical considerations in

data management. Organizations must focus on reducing their environmental impact while preparing for future advancements in technologies like quantum computing and blockchain. Collaboration across departments and a unified approach to data management further enhance decision-making and operational agility. In conclusion, the organizations that prioritize strategic data management will not only drive innovation and improve productivity but also maintain a competitive edge in an increasingly data-driven world. The key to success lies in continuously refining processes, embracing technological advancements, and fostering a culture that values data as a core asset.

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№155/2025

Norwegian Journal of development of the International Science

ISSN 3453-9875

It was established in November 2016 with support from the Norwegian Academy of Science.

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