TEACHING AMINO ACIDS THROUGH VIRTUAL EXPERIMENTS AND SIMULATIONS IN A DIGITAL LABORATORY ENVIRONMENT

Orujov Y.
Baku State University, Master's student
Nagiyev K.
Chemistry faculty, chemistry teaching methodology, head of the department, doctor of chemical sciences, professor
Baku State University,
Abishov N.
Doctor of Pedagogical Sciences, Professor
Baku State University
Baku/Azerbaijan
https://doi.org/10.5281/zenodo.19573207

Abstract

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

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

INTRODUCTION

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

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

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

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

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

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

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

LITERATURE REVIEW

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

The existing literature shows that virtual experiments contribute not only to knowledge acquisition but also to the development of scientific thinking. Many authors argue that simulation-based learning supports conceptual understanding by allowing students to manipulate variables, test predictions, observe model-based outcomes, and repeat experimental procedures without material limitations. Such opportunities are highly valuable in chemistry, where learners often encounter difficulties in connecting symbolic representations, microscopic processes, and macroscopic observations. Digital laboratory environments therefore help bridge the gap between theory and practice by making invisible processes more accessible to learners. A number of studies in chemical education have also shown that simulations improve students' motivation and engagement. When students participate in interactive digital tasks, they tend to demonstrate greater curiosity, stronger concentration, and higher willingness to investigate chemical relationships independently. This is particularly important in topics that require spatial imagination and structural analysis. The teaching of amino acids belongs to this category because it involves the study of molecular structure, functional groups, acid-base behavior, stereochemistry, and biological significance. These aspects can be difficult for students to understand when instruction relies only on textbook explanation and memorization [5, p., 2244]

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

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

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

METHODOLOGY

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

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

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

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

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

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

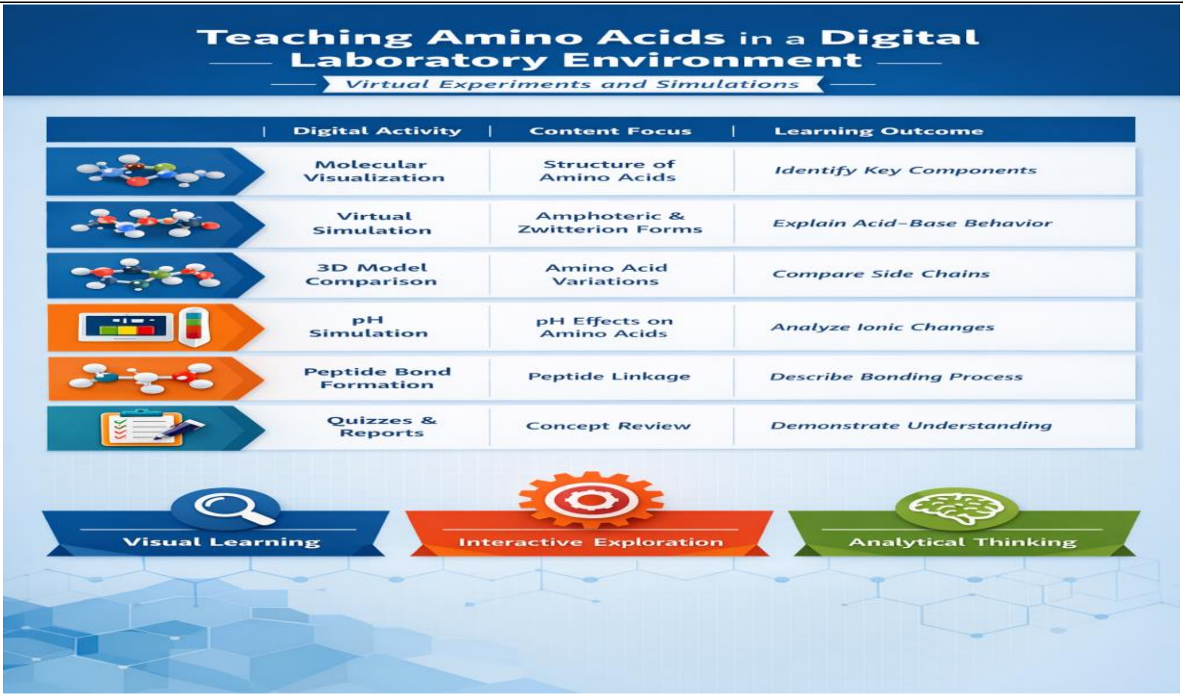

Figure 1. A digital laboratory framework for teaching amino acids through virtual experiments and simulations.

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

EXPERIMENTAL

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

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

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

Table 1.

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

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

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

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

RESULTS AND DISCUSSION

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

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

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

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

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

Table 2.

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

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

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

The table also demonstrates that digital laboratory tools create more favorable conditions for active student participation. Unlike traditional instruction, which often depends on verbal explanation and static representations, the digital environment enables learners to interact with visual models, observe simulated processes, and repeat activities when necessary. This contributes to greater conceptual clarity and a deeper understanding of the relationship between structure and function.

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

CONCLUSION

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

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

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

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

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