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PEDAGOGICAL EFFECTIVENESS OF VIRTUAL LABORATORIES IN CHEMISTRY EDUCATION AT HIGHER EDUCATION INSTITUTIONS

Abstract

The rapid digital transformation of higher education has significantly influenced the methodology of teaching natural sciences, particularly chemistry, where experimental learning plays a central role. In this context, virtual laboratories have emerged as an innovative pedagogical tool that simulates real chemical experiments through interactive digital environments. This study investigates the pedagogical effectiveness of virtual laboratories in higher education chemistry courses and evaluates their impact on students' academic performance, cognitive development, and engagement in learning processes. The research employed a mixed-method design, including a longitudinal survey of instructors and students conducted over three consecutive academic years, as well as a quasi-experimental approach comparing traditional laboratory instruction, video-assisted learning, and virtual laboratory-based teaching. Each academic year involved 30 instructors and 15 students participating in structured questionnaires and instructional analysis.

The findings reveal that virtual laboratories significantly enhance the accessibility, flexibility, and safety of experimental learning. They allow students to visualize complex chemical processes, repeat experiments multiple times without material constraints, and develop deeper conceptual understanding. The results also demonstrate a measurable improvement in student performance, with the experimental group achieving up to 97% academic success compared to the control group.

However, the study confirms that virtual laboratories are most effective when integrated with traditional hands-on laboratory work rather than used as a replacement. The blended learning approach provides a balanced development of theoretical knowledge and practical laboratory skills.

The study concludes that virtual laboratories represent a powerful pedagogical innovation that supports modern competency-based education, improves learning outcomes, and strengthens digital literacy in chemistry education.

Keywords: virtual laboratory, chemistry education, pedagogical effectiveness, digital learning, blended learning, higher education.

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ЖОҒАРЫ ОҚУ ОРЫНДАРЫНДА ХИМИЯНЫ ОҚЫТУДАҒЫ ВИРТУАЛДЫ ЗЕРТХАНАЛАРДЫҢ ПЕДАГОГИКАЛЫҚ ТИІМДІЛІГІ

Аңдатпа

Жоғары білім берудегі цифрлық трансформация жаратылыстану ғылымдарын, әсіресе химия пәнін оқыту әдістемесіне айтарлықтай әсер етті, мұнда тәжірибелік оқыту негізгі рөл атқарады. Осы тұрғыда виртуалды зертханалар интерактивті цифрлық орта арқылы нақты химиялық тәжірибелерді модельдейтін инновациялық педагогикалық құрал ретінде пайда болды. Бұл зерттеу жоғары оқу орындарындағы химия курстарында виртуалды зертханалардың педагогикалық тиімділігін зерттеп, олардың студенттердің академиялық үлгеріміне, танымдық дамуына және оқу үдерісіне қатысу белсенділігіне әсерін бағалайды. Зерттеу аралас әдіснамаға негізделді: үш жыл бойы жүргізілген оқытушылар мен студенттерге арналған ұзақ мерзімді сауалнама және дәстүрлі зертханалық оқыту, бейне-негізделген оқыту және виртуалды зертханаға негізделген оқытуды салыстырған квази-эксперименттік тәсіл қолданылды. Әр оқу жылында 30 оқытушы мен 15 студент құрылымдалған сауалнамалар мен оқыту талдауларына қатысты.

Нәтижелер виртуалды зертханалардың тәжірибелік оқытудың қолжетімділігін, икемділігін және қауіпсіздігін айтарлықтай арттыратынын көрсетті. Олар студенттерге күрделі химиялық процестерді визуализациялауға, материалдық шектеусіз тәжірибелерді бірнеше рет қайталауға және тереңірек тұжырымдамалық түсінік қалыптастыруға мүмкіндік береді. Сонымен қатар, нәтижелер студенттердің үлгерімінің айтарлықтай артқанын көрсетті: эксперименттік топ бақылау тобымен салыстырғанда 97%-ға дейін академиялық жетістікке жетті.

Дегенмен, зерттеу виртуалды зертханалар дәстүрлі нақты тәжірибелік жұмыстармен бірге қолданылған жағдайда ғана ең тиімді болатынын дәлелдейді. Аралас оқыту тәсілі теориялық білім мен практикалық зертханалық дағдылардың теңгерімді дамуын қамтамасыз етеді.

Қорытындылай келе, виртуалды зертханалар қазіргі заманғы құзыреттілікке негізделген білім беруді қолдайтын, оқу нәтижелерін жақсартатын және химия біліміндегі цифрлық сауаттылықты арттыратын қуатты педагогикалық инновация болып табылады.

Түйін сөздер: виртуалды зертхана, химия білімі, педагогикалық тиімділік, цифрлық оқыту, аралас оқыту, жоғары білім.

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ПЕДАГОГИЧЕСКАЯ ЭФФЕКТИВНОСТЬ ВИРТУАЛЬНЫХ ЛАБОРАТОРИЙ В ОБУЧЕНИИ ХИМИИ В ВЫСШИХ УЧЕБНЫХ ЗАВЕДЕНИЯХ

Аннотация

Быстрая цифровая трансформация высшего образования существенно повлияла на методику преподавания естественных наук, особенно химии, где экспериментальное обучение играет ключевую роль. В этом контексте виртуальные лаборатории стали инновационным педагогическим инструментом, который моделирует реальные химические эксперименты с помощью интерактивной цифровой среды. Данное исследование изучает педагогическую эффективность виртуальных лабораторий в курсах химии в высшей школе и оценивает их влияние на академическую успеваемость студентов, когнитивное развитие и вовлечённость в учебный процесс. В исследовании использовался смешанный метод: лонгитюдный опрос преподавателей и студентов, проводившийся в течение трёх академических лет подряд, а также квазиэкспериментальный подход, сравнивающий традиционное лабораторное обучение, видео-обучение и обучение с использованием виртуальных лабораторий. Каждый учебный год в исследовании участвовали 30 преподавателей и 15 студентов, заполнявших структурированные анкеты и участвовавших в анализе обучения.

Результаты показали, что виртуальные лаборатории значительно повышают доступность, гибкость и безопасность экспериментального обучения. Они позволяют студентам визуализировать сложные химические процессы, многократно повторять эксперименты без материальных ограничений и формировать более глубокое концептуальное понимание. Также было выявлено значительное улучшение успеваемости: экспериментальная группа достигла до 97% академического успеха по сравнению с контрольной группой. Однако исследование подтверждает, что виртуальные лаборатории наиболее эффективны при их интеграции с традиционными лабораторными занятиями, а не при их полной замене. Смешанный подход обеспечивает сбалансированное развитие теоретических знаний и практических лабораторных навыков.

В заключение, виртуальные лаборатории представляют собой мощную педагогическую инновацию, которая поддерживает современное компетентностное образование, улучшает результаты обучения и укрепляет цифровую грамотность в химическом образовании.

Ключевые слова: виртуальная лаборатория, химическое образование, педагогическая эффективность, цифровое обучение, смешанное обучение, высшее образование.

Introduction. Chemistry, as an experimental science, involves various forms of instruction such as demonstration experiments, laboratory work, and practical activities designed to enhance students' understanding of theoretical concepts.

Currently, the use of virtual laboratories has become an important educational approach in science education. Recent studies emphasize that digital learning environments, particularly virtual laboratory systems, play a significant role in modernizing chemistry teaching and improving student engagement. Virtual laboratories are considered an effective complementary tool for simulating chemical experiments and enhancing students' engagement in practical learning processes.

Daaif et al. highlight that virtual laboratory environments function as pedagogical simulation platforms that enable students to interact with chemical phenomena in a safe, controlled, and cost-effective digital environment. These systems allow learners to reproduce experimental conditions and

analyze chemical processes without physical risk or material constraints, while also supporting the development of analytical thinking and experimental interpretation skills.

In chemistry education, virtual laboratories are particularly useful for demonstrating complex or hazardous reactions that cannot always be performed in real laboratory conditions. They allow students to visualize chemical structures, manipulate virtual equipment, and analyze experimental outcomes in real time, thereby strengthening scientific reasoning and bridging theoretical knowledge with practical application.

Another important aspect highlighted in the literature is that virtual laboratories are designed not to replace traditional laboratory work, but to complement it. They provide preparatory training, reinforce theoretical concepts, and enable repeated experimentation. The integration of virtual and physical laboratory environments improves learning efficiency and deepens conceptual understanding.

Virtual laboratory systems enhance student motivation and learning outcomes by providing interactive and visually rich environments. At the same time, they reduce costs, save time, and minimize the use of chemical reagents, making them an environmentally and economically sustainable educational tool. At the same time, they contribute to reducing costs, saving time, and minimizing the use of chemical reagents, which makes them an environmentally and economically sustainable solution for modern education. It is an essential tool in educational activities, corresponding to modern technological trends. Virtual laboratories greatly simplify the process of conducting chemical experiments and contain a number of advantages in comparison with traditional laboratories. In this article, we will look at how virtual labs can increase students' motivation to learn. A virtual laboratory is a modern educational environment based on digital technologies that allows students to perform the same laboratory remotely. Digital technologies used in higher education have various advantages, including students' access to information educational resources and the ability to build individual educational trajectories (Belousova, 2023; Daaif et al., 2019; Minina, 2020).

An important responsibility of every teacher is to provide high-quality education to the younger generation. Researchers in pedagogy emphasize that the quality of education largely depends on teaching methods and the professional competence of educators (Bulatbaeva et al., 2016).

Laboratory and practical work in chemistry plays a key role in developing students' cognitive activity. Through experiments, learners gain a deeper understanding of scientific principles. Such activities develop analytical thinking, data processing skills, and the ability to draw scientific conclusions. The results of performed laboratory and practical work stimulate their thinking, lead to discussion, introduce them to methods of measuring various quantities, allow them to study the operation of different instruments, teach them techniques for collecting and processing experimental data, develop concrete laboratory skills, and require them to draw conclusions. Currently, natural science education is student-centered and focuses on developing competencies through the acquisition and application of scientific knowledge. Effective use of these competencies requires future teachers to demonstrate flexibility, emotional resilience, and digital literacy, including ICT skills (Ionov & Kim, 2025). Virtual laboratory work in chemistry can be understood as a virtual chemical experiment comprising a set of experiments united by a common goal of studying a chemical object or process (Gavronskaya & Oksenchuk, 2015a, 2015b). Scientific research requires students' engagement in logical reasoning and an understanding of scientific knowledge and processes, which depend on cognitive structures related to scientific, intellectual, and social contexts. Mixed-type virtual laboratories, such as Crocodile Chemistry, make it possible to model the regularities, conditions, and observable characteristics of chemical processes.

Virtual experiments enable the simulation of chemical processes that cannot be performed in traditional laboratories due to safety, cost, or technical limitations. They also reduce the consumption of reagents and allow dynamic visualization of complex reactions, making invisible molecular processes observable and understandable. Moreover, they help conserve chemical reagents. Computer simulations allow the dynamic demonstration of complex and hazardous chemical experiments and reveal internal features that cannot be observed in conventional laboratory settings. Virtual laboratories also help

teachers monitor students' academic progress more easily and identify errors or gaps in their knowledge.

The relevance of virtual laboratories is driven by the limitations of traditional laboratory instruction, including resource constraints, safety requirements, and equipment availability. Virtual environments allow students to observe chemical reactions and analyze experimental data in a safe and flexible learning space.

The relevance of this topic is due to the fact that traditional laboratory work is not always available due to limited resources, equipment, or safety requirements. Virtual laboratories provide learners with the opportunity to interact with models of laboratory equipment, observe chemical reactions, and analyze their results in a safe and accessible environment.

The purpose of this study is to analyze the pedagogical advantages of virtual laboratory instruction in chemistry education and to evaluate its impact on student learning outcomes in higher education.

Methods and Materials. The research was conducted during the 2024–2025 academic period using a quasi-experimental design. The study compared three instructional approaches in chemistry education: traditional laboratory instruction, video-based learning, and virtual laboratory-assisted teaching. The aim of this study was to examine the pedagogical advantages of virtual laboratory practice in chemistry education and its effectiveness in supporting student learning outcomes.

Virtual laboratories enable the simulation of chemical reactions at both qualitative and quantitative levels. Qualitative simulation systems, such as ChemLab and Yenka, allow students to observe reaction processes and laboratory procedures in a visual format. Quantitative simulation platforms, such as VirtuLab and PhET Interactive Simulations (<https://phet.colorado.edu/en/simulations/category/chemistry>), present experimental results in the form of graphs, numerical data, and interactive models.

In the process of teaching chemistry, the virtual laboratory helps the teacher to visualize the educational material, in particular, to explain the basic concepts necessary for an accurate understanding of the microcosm.

Virtual laboratories can be integrated into different stages of the learning process. They are used for introducing new material through visual and interactive demonstrations, reinforcing previously studied topics through repeated virtual practice, and assessing students' understanding of chemical phenomena through independent tasks.

Chemical experimentation plays a central role in chemistry education, strengthening students' understanding of fundamental chemical concepts and processes. In modern education, the development of digital literacy, critical thinking, and information technology skills has become increasingly important, as these competencies are essential for future professional practice (Morgacheva&Sotnikova, 2020; Saksena&Zho, 2018). One of the major distinctions and achievements of our century is rapidly developing digital technology. Digital literacy, information technology, and critical thinking skills are considered the most important. Time does not stand still, and therefore abilities that align with progress moving forward are required. In the near future, individuals who possess these skills - programmers and IT specialists — will be in highest demand on the market. These competencies also play an important role in performing practical chemical tasks (Shvertsova, 2022).

Conducting chemical experiments in laboratories plays an important role in the natural science curriculum, enabling our young students to understand the natural world in which they live.

The development of virtual laboratory structures is particularly relevant due to the high cost and resource demands of traditional laboratory work. Virtual laboratories provide students with opportunities to review instructional videos before performing experiments, follow laboratory procedures more effectively, and develop a deeper understanding of chemical processes. These systems also contribute to safety, accessibility, and improved learning efficiency (Gang & Wu, 2021).

W.D.Sasongko and W. (2019) Indah consider virtual laboratories an important innovation in modern education systems. They emphasize that virtual laboratories provide practical learning opportunities while overcoming limitations such as lack of laboratory equipment and materials in universities. Some

virtual laboratories can be used on any device with internet access, including laptops, tablets, or smartphones (Guzman&Babu, 2020).

In recent years, global challenges have accelerated the transition from traditional laboratory teaching to technology-enhanced learning approaches. Virtual laboratories have significantly transformed the teaching of chemistry by providing interactive and simulation-based experimental environments. This study provides teachers with a clear picture of the role virtual chemistry laboratories play in achieving good results, thereby offering reliable outcomes for learning and teaching chemical processes. The study aimed to examine the following:

- Effectiveness in terms of the ability to produce good results.
- Effectiveness in terms of the ability to achieve specific/prescribed/instructional/educational objectives.

Laboratory practical work is an essential component of science education. It develops students' ability to formulate problems, design experiments, work with laboratory equipment, process data, and interpret results. However, during the pandemic period, access to physical laboratories was significantly limited, which increased the need for alternative instructional methods. In our work, various methods of substituting laboratory practical classes are discussed. One of these methods is the use of specially designed virtual analogs. Virtual laboratory simulations serve as an alternative method for conducting laboratory practice. They are particularly useful in situations where real experiments are dangerous, resource-intensive, or technically unavailable. In addition, they allow repeated experimentation and improve students' understanding of scientific concepts. The study also notes that the use of computer modeling in practical work improves students' understanding of the material. Nevertheless, despite all its advantages, virtual laboratories cannot replace real ones.

Several virtual laboratory platforms are used in chemistry education, including Model ChemLab and ClassIn. These systems provide interactive laboratory environments that simulate real experimental conditions and allow students to perform various chemical experiments in a digital format.

Virtual laboratories have become an integral part of modern education. They provide interactive, safe, and cost-effective environments for studying chemical processes and significantly enhance the accessibility and quality of laboratory-based learning.

Results. Our research involved instructors and students from Abai Kazakh National Pedagogical University in Almaty. In 2022, a survey was conducted among instructors teaching in the Department of Chemistry in connection with efforts to expand available computer-based learning tools. By the beginning of the study, thanks to studying the computer science curriculum, students already had theoretical knowledge about educational technologies such as simulators, educational games, online learning, audio and video materials.

We believe that the most effective way to use virtual chemistry laboratories is to support extracurricular independent work of a chemistry student. In extracurricular independent activities, virtual chemical laboratories can work as interactive tasks or simulations of field experiments in order to prepare for laboratory work in the classroom. This approach helps to increase motivation to study chemistry, expand opportunities for independent study and prepare for future professional activities in modern digital education.

The purpose of the survey was to determine teaching strategies most frequently used by instructors for conducting chemistry laboratory classes. The survey was conducted through an information usage portal for instructors at the Department of Chemistry, Abai Kazakh National Pedagogical University. The survey was administered using the Google Forms format with the Flubaroo add-on. Flubaroo is a free tool that helps quickly process and summarize survey results created in Google Forms. When creating the survey, it should be kept in mind that the first question must include the last name of the respondent; therefore, for the first question type, we select «Text» make the question mandatory and check the «Make this question required» box.

A quantitative assessment of each indicator studied is carried out according to the selected diagnostic methods and indications, revealing the main features of certain criteria. A total of 30

instructors participated in the survey. The results of the survey regarding instructors' use of virtual laboratories as an additional tool for conducting chemistry laboratory classes are shown in the table below (Table 1) and presented as a diagram (Figure 1).

Table 1— Survey results on identifying instructional approaches used by instructors in teaching chemistry laboratory work

Question	Virtual laboratory (Number of instructors and percentage share,)	Video presentation method (Number of instructors and percentage share, %)	Traditional laboratory work (Number of instructors and percentage share, %)
Which laboratory methods do you utilize in your lessens?	22(73%)	3(10%)	5(17%)

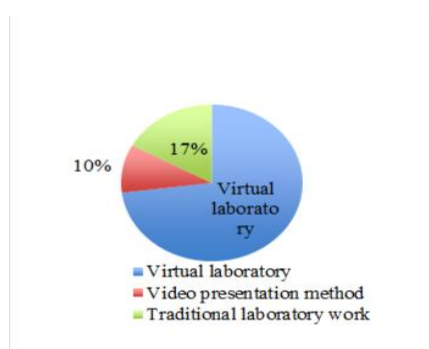


Figure 1. Percentage distribution of survey responses regarding instructional approaches to chemistry laboratory teaching

Through our research work, we pay attention to the development of students own cognitive skills when acquiring knowledge through a virtual laboratory, the critical development of cognitive processes, including the degree of perception, concentration on a particular though; the students motivation to study the subject is formed and develops.

The results of the survey showed that traditional chemistry laboratory work is still in the leading position among instructors. However, the fact that the percentage has already reached 73% indicates a growing interest in virtual laboratories. We observed an increase in interest in the subject of chemistry after conducting laboratory work. The survey to determine instructors' methods of teaching chemistry laboratory work was conducted from 2022 to 2025, beginning with the objectives set for the doctoral dissertation. One of our future goals is to examine the importance of students' research activities for effectively developing key competencies in prospective specialists in the field of chemistry, the importance of learned being able to solve experimental chemistry problems and the conditions for and processes of developing skills in the use of virtual chemical laboratories. In this research study, data were collected from instructors during the period 2022-2025 regarding how they conduct laboratory classes in chemistry. During this period, an increase in instructors' interest in virtual laboratories was recorded (Figure 2.)

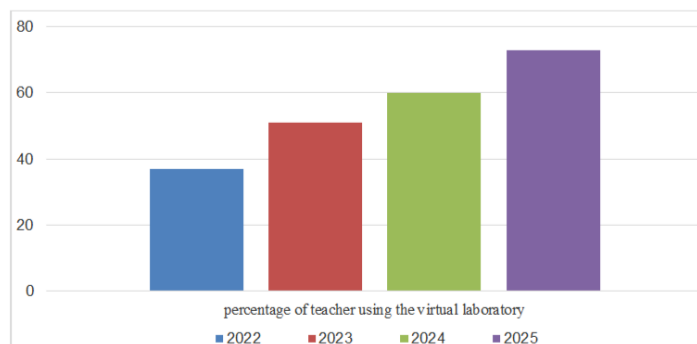


Figure 2. Growth dynamics of instructors' interest in virtual laboratory use between 2022 and 2025

To clarify the pedagogical experiment, scientific research was conducted. As the research object, students who studied between 2022 and 2025 were selected. In the first academic year, students enrolled in the specialty 6B01514 — Geography and biology participated (Zaurova et al., 2023). In the second academic year, students of the specialty 6B01513 — Biology were involved and in the third academic year, students of the specialty 6B01514 — Geography and biology participated. In each academic year, groups with the same number of students were selected for laboratory classes. The number of students was 15.

The pedagogical integration of virtual laboratories and artificial intelligence is an effective means of developing the research and digital competencies of future chemistry teachers.

In the first academic year, students of the specialty 6B01514 — Geography and biology carried out chemistry laboratory work independently using reagents. In the second academic year, students of the specialty 6B01513 — Biology watched a video before carrying out the laboratory work. In the third academic year, students of the specialty 6B01514 — Geography and biology watched a video clip and worked with a virtual laboratory as an additional tool before working with reagents. From these activities, we observed that students' interest in laboratory classes increased (Figure 3)

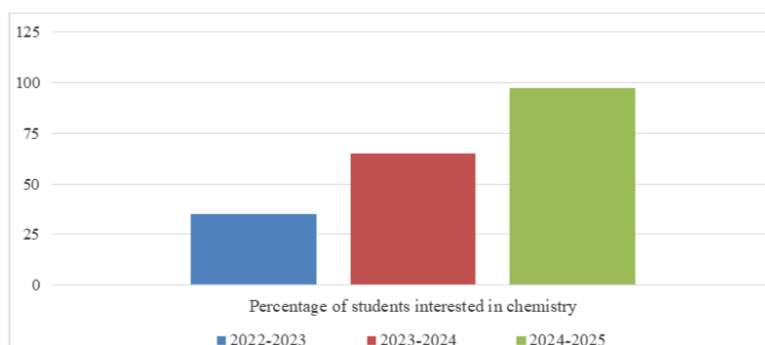


Figure 3. Measure of students' interest in the chemistry course

Based on the survey results, it was determined that laboratory work increased students' interest in the subject of chemistry. In addition, using virtual laboratories saved time and chemical reagents and it was found to be effective as an additional tool for students who were unable to attend class due to illness. When monitoring the experimental groups, we observed a 97% increase in students' interest in laboratory work.

In a changing world and modern progress, traditional pedagogical approaches require rethinking and supplementing with new practice-oriented methods aimed at developing students not only theoretical knowledge, but also practical skills and competencies necessary for their future professional activities (Galushina et al., 2025). Modern pedagogical technologies in chemical education are based on the principles of active learning, interdisciplinary interaction and a personality-oriented approach, which contributes to the development of critical thinking, independence and responsibility among students.

Scientific research was conducted to clarify the pedagogical experiment. As the research object, students enrolled in the 6B01514 – Geography and biology specialty during the 2024-2025 academic year were selected. The experimental group was monitored and comparisons were made with other groups. Topics for laboratory work in chemistry were selected, and virtual laboratory modules were prepared for these topics. During laboratory classes, students first watch a video and work with virtual laboratory simulations, completing the tasks provided, and then perform a laboratory experiment in practice (in practice). To ensure high-quality and mobile education in our setting work, information technology is being prepared for a virtual laboratory on 15 chemistry topics for innovative student training.

Laboratory Session 1. Safety precautions and operating techniques in the chemistry laboratory. Introduction to the inorganic chemistry laboratory and chemical glassware.

Laboratory Session 2. Main classes of inorganic compounds (oxides, acids, bases, salts).

Laboratory Session 3. Determination of the metal equivalent by the water displacement method (determination of the equivalent mass of magnesium).

Laboratory Session 4. Determination of the relative molar mass of carbon(IV) oxide.

Laboratory Session 5. Investigation of the effect of reactant concentration, temperature, and catalysts on the rate of a chemical reaction. Observation of the effect of initial substances and reaction products on the direction of chemical equilibrium shift.

Laboratory Session 6. Solving problems and performing exercises on reaction rates and chemical equilibrium.

Laboratory Session 7. Preparation of solutions with known mass fractions from anhydrous salts and water. Preparation of solutions with known mass fractions by diluting concentrated solutions.

Laboratory Session 8. Investigation of salt hydrolysis reactions; observation of changes in pH and the dependence of hydrolysis on temperature and dilution.

Laboratory Session 9. Balancing reactions using electron or ion–electron methods by determining oxidation states.

Laboratory Session 10. Determination of chemical properties of complex compounds, methods of obtaining complexes, and determining the stability of complexes.

Laboratory Session 11. Detection of elements in organic compounds.

Laboratory Session 12. Preparation of saturated and unsaturated hydrocarbons.

Laboratory Session 13. Oxidation and dehydrogenation of ethyl alcohol, oxidation with chromic mixture, preparation of ethyl acetate.

Laboratory Session 14. Derivatives of carboxylic acids. Fats and soap.

Laboratory Session 15. Preparation of high–molecular–weight compounds.

During the completion of 15 virtual laboratory experiments, key patterns of reactions, properties of substances and the influence of external factors on reaction rate and direction. The obtained results are generally consistent with theoretical concepts, which confirms the reliability of the models used in the virtual environment. One of the important observations was the influence of temperature, reactant concentration, and the presence of catalysts on the rate of chemical reactions. Virtual laboratories also made it possible to clearly demonstrate processes that are difficult to carry out in real conditions due to their danger or complexity. For example, reactions involving the release of toxic gases or those occurring at extreme temperatures can be safely studied in a digital environment. This significantly expands the possibilities for learning and analysis.

Despite this, virtual laboratory experiments have proven to be highly effective as a learning tool. They help practical skills, enhance analytical thinking and improve understanding of chemical processes. Thus the conducted studies confirm that virtual laboratories are a valuable supplement to traditional teaching methods, although they cannot fully replace real experiments.

In the 2024 - 2025 academic year, one group of students specializing in 6B01514 – Geography and Biology was selected. Subgroup 1.1 was designated as the experimental group, and subgroup 1.2 was selected as the control group. Each subgroup consisted of 15 students. Lessons in chemistry were

conducted using a virtual laboratory in the Kazakh language developed by the author. Particular attention was given to the quality of conducting laboratory work. That is, before performing the laboratory experiment in the actual laboratory, students first used a prepared virtual laboratory simulator and completed tasks related to the laboratory activity. A total of 15 virtual laboratory modules in chemistry were included. In addition, explanatory video materials on safety rules and laboratory equipment were provided. All of the laboratory topics mentioned above were covered.

Students' interest in the virtual laboratory was determined through midterms and session assessments. The indicators of students' knowledge levels after conducting the experiment aimed at improving their academic performance are presented in Table 3 and Figure 4.

Table 3 — Assessment of students learning outcomes for the 2024-2025 academic year

2024-2025 academic year	Knowledge quality indicator of Experimental group 1.1, %	Knowledge quality indicator of Control group 1.2, %
1st midterm assessment	90	80
2nd midterm assessment	96	81
Examination session	97	81

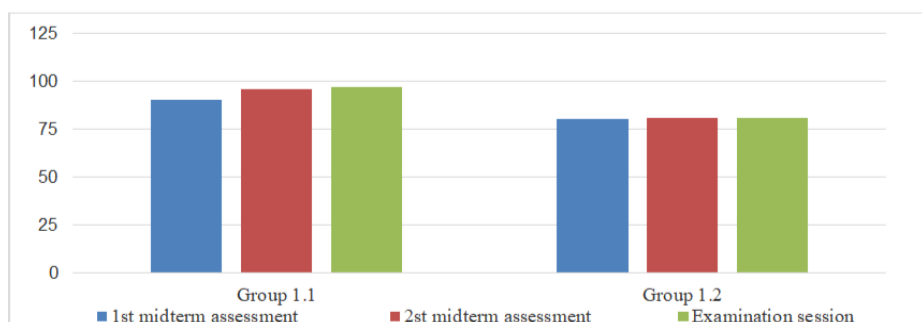


Figure 4. Assessment of students learning outcomes for the 2024-2025 academic year

As can be seen from Table 3 and Figure 4, the academic performance level of the experimental subgroup 1.1 increased from 90% to 97%. In contrast, there was no significant change in the academic performance of the control subgroup 1.2, which increased only from 80% to 81%. Thus, the use of virtual laboratories in teaching chemistry significantly increased students interest in chemistry and improved the quality of their learning.

The methodological conditions for the effective use of a virtual laboratory in a chemical laboratory are determined the dominance of a didactic goal, the expediency of application, the complexity of learning, the awareness of the actions performed and the knowledge gained, the brevity of the experiment, and the variability of application. It is shown that if students cognitive activity is organized as an independent educational study in small collaborative groups and ends with a stage of reflective assessment, the creation of a diverse laboratory using a virtual laboratory will be effective.

Virtual laboratories can be used by instructors during classroom sessions or independently, online or on a local computer, individual or in groups. In a virtual chemistry laboratory, it is possible to perform individual experiments to demonstrate a specific property or phenomenon, as well as laboratory work on particular topics. In this way, laboratory work enables students not only to apply theoretical knowledge in practice but also to develop interest in research activities. While performing experiments, students learn to think critically, analyze actions and results, and draw conclusions based on the data obtained.

Discussion. The results of this study confirm that the integration of virtual laboratories into chemistry education at the university level has a significant positive impact on students' academic

performance, motivation, and conceptual understanding of chemical processes. The experimental data obtained from both the survey and pedagogical experiment demonstrate a consistent improvement in learning outcomes when virtual laboratory tools are incorporated into traditional teaching methods.

In particular, the experimental group showed a noticeable increase in academic achievement, reaching up to 97% of students demonstrating improved knowledge quality, compared to the control group, where no significant progress was observed. The statistical difference between the groups confirms that the use of virtual laboratories contributes to more effective knowledge acquisition and skill development in chemistry.

These findings are consistent with previous research in the field of digital learning technologies, which emphasizes that virtual laboratories enhance cognitive engagement by providing interactive and visually enriched learning environments. As noted in the literature, simulation-based learning environments allow students to actively participate in experimental processes, repeat procedures, and observe chemical phenomena that may be difficult, dangerous, or costly to reproduce in real laboratory conditions.

The pedagogical effectiveness observed in this study can be explained by several factors. First, virtual laboratories provide immediate feedback, which helps students correct mistakes and better understand reaction mechanisms. Second, they allow repeated experimentation without material limitations, which strengthens procedural understanding and supports the development of analytical thinking. Third, the integration of multimedia elements such as animations, simulations, and graphical representations facilitates the visualization of abstract chemical concepts at the molecular level.

However, the results also confirm that virtual laboratories should not be considered a complete replacement for traditional laboratory work. Instead, they function most effectively as a complementary educational tool within a blended learning model. The combination of virtual simulations and hands-on experiments ensures a balance between theoretical understanding and practical skill acquisition. This approach allows students to first explore and predict experimental outcomes in a virtual environment and then validate their knowledge through real laboratory practice.

Comparative analysis with existing studies, including Daaif et al., supports the conclusion that virtual laboratories improve students' cognitive engagement and facilitate better comprehension of complex chemical processes. Nevertheless, while previous studies often emphasize simulation as a standalone learning environment, the present research highlights the superiority of an integrated approach combining both virtual and traditional laboratory methods. An additional important finding of this study is the improvement in time efficiency and resource management. The use of virtual laboratories significantly reduced the consumption of chemical reagents and laboratory time, allowing more opportunities for discussion, interpretation of results, and collaborative learning. This aspect is particularly relevant in modern higher education, where safety, cost-effectiveness, and accessibility are key priorities.

Despite the positive outcomes, several limitations should be acknowledged. The study was conducted within a limited sample size and focused on specific chemistry modules. Therefore, further research is required to validate the results across different disciplines, larger student populations, and diverse educational contexts. In addition, future studies should investigate long-term effects of virtual laboratory use on students' professional competencies and laboratory skills development.

Overall, the findings of this study suggest that virtual laboratories represent an effective pedagogical innovation in chemistry education. When properly integrated into the curriculum, they enhance students' understanding of chemical processes, increase engagement, and improve overall learning outcomes. These results support the further development and implementation of digital simulation tools in higher education institutions. The implementation of these pedagogical recommendations makes it possible to effectively integrate virtual laboratories, develop the research and digital competencies of future teachers and bring chemistry teaching to an innovative level.

Conclusion. In general, modeling and practical implementation of modern pedagogical technologies in chemical education is not a one-time process, but a continuous improvement based on scientific

research, pedagogical practice experience and openness to innovation. This is the only way to ensure the training of qualified specialists who are able to successfully solve modern professional and social problems.

This study examined the pedagogical effectiveness of virtual chemistry laboratories as a complementary instructional tool in higher education. A total of 15 laboratory topics were selected and implemented within an experimental group, allowing students to engage in simulated chemical experiments under controlled virtual conditions. The findings demonstrate that the integration of virtual laboratory environments significantly enhances students' engagement, conceptual understanding, and overall learning experience. The results indicate that virtual laboratories contribute to improved comprehension of theoretical material by providing visual and interactive representations of chemical processes, while also promoting the development of analytical thinking, experimental reasoning, and problem-solving skills. The experimental group demonstrated substantially higher academic performance, with 97% of students showing measurable improvement in learning outcomes, which confirms the effectiveness of virtual laboratory-assisted instruction. Moreover, virtual laboratories offer several practical advantages, including increased accessibility, reduced costs, and enhanced safety, particularly when dealing with complex or hazardous chemical reactions, making them a sustainable and flexible solution for modern chemistry education in contexts where traditional laboratory resources are limited.

The results of the study showed that the integration of virtual laboratories significantly increases students meta-cognitive activity, their digital skills and abilities for scientific analysis. At the same time, despite the existing technical and licensing restrictions in a global context, the use of pedagogical recommendations makes it possible to maximize the benefits of the platform.

However, despite these benefits, virtual laboratories cannot fully replace real laboratory experiences, especially in terms of hands-on skill development and physical interaction with equipment. Therefore, the most effective instructional approach is the integration of virtual and traditional laboratory methods, allowing students to benefit from both simulation-based learning and real experimental practice. The study also highlights several limitations and directions for future research, particularly the need for further investigation into the extent to which virtual laboratories contribute to the development of practical laboratory skills and their long-term impact on student competence, as well as the necessity of improving the realism of simulations and evaluating their effectiveness using more rigorous experimental designs and larger sample sizes. In conclusion, the integration of virtual laboratories into chemistry education represents a promising direction for enhancing teaching and learning processes, and their continued development and pedagogical implementation can significantly contribute to the modernization of science education and the formation of digitally competent learners.

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