METHODS OF UTILIZING VISUALIZATION AND VR/AR TECHNOLOGIES IN THE DEVELOPMENT OF CHEMISTRY PROJECTS FOR 8TH-GRADE STUDENTS

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Abstract

Visualization is crucial in chemistry education, particularly in mastering eighth-grade students' fundamental concepts and shaping a scientific worldview. Modern visualization technologies improve students' understanding and motivation. These technologies include 3D modeling, virtual (VR) and augmented reality (AR), animation, and interactive platforms. This study aims to explore effective methods for integrating these technologies into the development of chemistry learning projects. Special attention is paid to a comparative analysis of traditional and innovative methods of visualizing chemical phenomena, as well as to the evaluation of project-based learning in chemistry. A total of 120 eighth-grade students from Kazakhstani Secondary Schools, divided into the experimental and control groups, participated in a three-month study. During the pedagogical experiment, the experimental group received training integrating visualization and VR/AR technologies, while the control group received traditional training. This experiment consisted of three stages: preparatory, implementation, and final. The effectiveness of these technologies was assessed through pre-testing and post-testing. The results show that visualization and AR/VR technologies have a strong positive effect on learning chemistry in Grade 8.

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1. Introduction

Modern educational technologies play a crucial role in fostering project-based learning through the utilization of visualization techniques, virtual reality (VR), and augmented reality (AR) in chemistry

education. Visualization and VR/AR technologies are transforming traditional teaching methods. They create new opportunities for enhancing chemistry instruction and developing research competencies.

The integration of visualization and VR/AR technologies in chemistry education is especially relevant for 8th-grade students, as this stage marks their introduction to fundamental chemical principles, laws, and models. Visualization facilitates the comprehension of complex chemical processes and phenomena by making them more tangible, accessible, and comprehensible, thereby promoting deeper knowledge acquisition and the development of research skills. Researchers (Zavaltseva et al., 2023) argue that the incorporation of diverse visualization methods in chemistry lessons covers a wide range of technologies, from traditional diagrams and graphs to advanced digital solutions such as three-dimensional modeling, VR and AR, and interactive simulations. Their application of these technologies is particularly effective within project-based learning, as it not only enhances students' understanding of the subject matter but also fosters critical thinking, research skills, and a creative approach to problem-solving.

VR and AR technologies allow students to immerse in a virtual environment. In these environments, they can practice skills, conduct experiments, and solve problems creatively. A study conducted by Amirbekova, Shertayeva and Mironova (2024) demonstrates that incorporating visualization and VR/AR technologies into chemistry instruction enhances students' cognitive engagement, goal-setting abilities, and strategic planning in learning activities. Moreover, these technologies positively impact the assimilation of theoretical knowledge and the acquisition of practical skills, ultimately leading to improved academic performance compared to traditional teaching methods.

Fomenko (2023) emphasizes that visualization technologies, which are rapidly evolving in the era of widespread digital literacy, create new opportunities for presenting complex scientific concepts and patterns in an accessible intuitive understandable manner. Chemistry, as a natural science discipline, often involves highly abstract processes and phenomena, necessitating the use of specialized visualization tools for accurate interpretation and in-depth understanding.

Salykina (2021) highlights that project-based learning is one of the most effective teaching methods as it contributes to the development of key competencies of students, enhances students' research skills, and increases motivation for studying chemistry. According to Yakovleva (2014), the use of project-based learning becomes particularly significant during the study of chemistry in the 8th grade. This approach ensures not only a solid understanding of theoretical concepts but also their practical application through the modeling of real chemical processes and phenomena, aligning with the principles of activity-based learning in education.

The eighth grade is an essential stage in chemistry education, as it is when students develop foundational knowledge of substances, chemical reactions, chemical laws, and methods of scientific inquiry. At this stage, the implementation of project-based learning enables students to:

- Deepen their understanding of fundamental chemistry concepts;
- Apply acquired knowledge in practical contexts;
- Develop skills in handling chemical substances, laboratory equipment, and digital tools;
- Enhance independence, critical thinking, and teamwork abilities.

According to Yakovleva (2014), designing chemistry projects in the 8th grade serves as an effective tool for developing cognitive engagement, research skills, and interest in chemistry. The integration of visualization technologies further enhances learning by making it more interactive, accessible, and engaging, aligning with modern educational standards and requirements.

Dewey (2020), relying on the ideas of constructionism, emphasizes that project-based learning enables students to "construct knowledge" through hands-on engagement with the material. For instance, chemistry projects, such as modeling chemical reactions or developing environmental initiatives, activate analytical thinking and independent research, corresponding with Dewey's learning-by-doing approach.

The so-called "project method" and "productive learning", which were later elaborated upon by Dewey's followers, contribute to personal development and self-regulation while cultivating cultural awareness and social interaction.

According to Gardner's (2007) theory of multiple intelligences, differentiating educational methods based on students' cognitive profiles facilitated optimization of the educational process. In the context of chemistry education, project-based learning based on multi-modal approaches engages various forms of intelligence. For example, molecular structures visualization (spatial intelligence) facilitates the analysis of three-dimensional interactions, the creation of presentations (linguistic intelligence) develops skills in structuring and interpreting scientific data, and conducting laboratory experiments (kinesthetic intelligence) ensures theoretical concepts through sensorimotor consolidation.

Schwab, cited in Zagranichnaya et al. (2019), emphasizes the role of inquiry-based learning, which emphasizes the importance of scientific exploration. Chemistry projects that require students to formulate hypotheses (e.g., "How does pH affect reaction rate?"), conduct experiments, and analyze data to promote critical thinking and a deeper understanding of the scientific method.

The review by Budarina et al. (2022) examines the distinctive features of teacher training in Finland, a country that has consistently received high international rankings in student achievement for over 20 years. Finnish educators emphasize that educational projects should be closely connected to real-world applications. For instance, the development of the project "Chemistry in Food Production" not only explains theoretical concepts but also demonstrates the practical relevance of the discipline, thereby enhancing intrinsic motivation and curiosity. According to them, chemistry projects for 8th-grade students are considered a pedagogical tool that transforms abstract concepts into personal experiences, fostering both cognitive engagement and the development of essential 21st-century soft skills.

Researchers consider the integration of visualization technologies—such as VR, interactive simulations, and 3D modeling—particularly promising for expanding the potential of project-based learning (Iyamuremye et al., 2023; Saba et al., 2021; Nsabayezu et al., 2022). For instance, the use of computer programs to create molecular models or the visualization of chemical reactions in VR environments enhances students' understanding of chemical processes and reinforces learning through dynamic, visual representation (Tang et al., 2020; Shen et al., 2019; Amirbekova, Shertayeva, Korobeynikova & Aysina, 2024).

AR and VR technologies are becoming increasingly prevalent in chemistry education, expanding the possibilities for project-based learning by creating immersive scenarios and interactive learning environments (Oktay & Yüzer, 2023). Various visualization techniques are employed for processing experimental data within AR/VR applications, allowing real-time implementation of modeling and statistical analysis methods (Siwach et al., 2022). Research (Edwards et al., 2019) indicates that VR simulations enhance safety and accessibility, particularly when working with hazardous reactions, such as ammonia synthesis. These simulations enable students to "travel" inside molecules to examine their structure—for example, through platforms like Nanome. Additionally, applications such as Elements 4D and Merge Cube enable users to manipulate molecular models via smartphones, increasing interactivity (Yang et al., 2022).

Saba et al. (2021) identified key advantages of AR/VR in education, including increased student motivation, personalized learning experiences, and reduced risks associated with laboratory experiments. However, they also noted significant challenges, such as the high cost of equipment and the limited availability of ready-to-use educational programs. Further studies (Iyamuremye et al., 2023; Rodríguez et al., 2022; Gamito et al., 2023) confirm that visualization and AR/VR technologies significantly improve chemistry comprehension among eighth-grade students. Nevertheless, the successful implementation of these technologies requires careful consideration of technical and financial constraints, as well as adequate teacher training.

The relevance of this study is driven by the need to enhance the quality of chemical education through the integration of innovative teaching methodologies, particularly visualization and VR/AR technologies. The use of animations, virtual laboratories, 3D models, and interactive simulations offers new opportunities for organizing students' project-based learning activities. These tools not only facilitate the demonstration of chemical reactions and substance structure but also actively engage students in the learning process, fostering their practical skills and research abilities.

The aim of this study is to identify and substantiate effective methods of utilizing visualization and VR/AR technologies in the development of chemistry projects for 8th-grade students. Moreover, the study seeks to determine the impact of these technologies on the development of students' scientific research skills and their ability to create educational projects.

To achieve this aim, the study addresses the following research questions:

Q1. To what extent is the utilization of visualization and VR/AR technologies in the context of chemistry project development in schools represented in the scientific literature?

Q2. Can the impact of visualization and VR/AR technologies on students' acquisition of chemical knowledge and the development of research skills be determined, or is this an area for future investigation?

Q3. Do visualization and VR/AR technologies offer tangible advantages in fostering students' research competencies compared to traditional chemistry instruction?

Research hypothesis: It is hypothesized that the use of visualization technologies in project-based chemistry education for 8th-grade students contributes to a deeper understanding of the subject matter, enhances cognitive motivation, and promotes the development of research competencies. Additionally, it is expected that these technologies facilitate the comprehension of complex chemical concepts by providing visually structured information.

2. Materials and Methods

The study employed analytical, experimental, and statistical research methods to assess the effectiveness of visualization and VR/AR technologies in chemistry education.

2.1. Study Design and Participants

The research was conducted over three months at Secondary School No. 15 named after D. I. Mendeleyev and Secondary School No. 7 named after K. Spatayev in Shymkent, Kazakhstan. A total of 120 eighth-grade students participated in the study. A sample was divided into two groups:

- Experimental group (n=55): Chemistry lessons incorporated visualization and VR/AR technologies;
- Control group (n=65): Chemistry was taught using traditional methods in a physical laboratory without visualization technologies.

The experimental and control groups were comparable in knowledge, age, gender, and background. This ensured the validity of the findings.

2.2. Data Collection and Assessment Tools

To assess students' engagement and motivation, the study utilized the Self-Assessment Manikin (SAM) scale in conjunction with observation and questionnaire-based methods. Additionally, during the pedagogical experiment, a pre-test and post-test design was used to measure learning outcomes. These tests assessed:

Students completed pre-tests and post-tests. The tests measured understanding, problem-solving speed, and error rates. Tasks included recognizing structures and explaining reactions.

Additionally, a pre-test and post-test design was used to measure learning outcomes. The tests assessed:

- Conceptual understanding (e.g., tasks for recognizing molecular structures or explaining chemical reactions);
- Problem-solving speed;
- Error rates.

2.3. Implementation of Visualization and VR/AR Technologies

To evaluate the effectiveness of visualization methods in eighth-grade chemistry instruction, the study incorporated the following evidence-based approaches:

1. 3D molecular modeling:

- Software such as Avogadro, ChemDoodle, and PhET Interactive Simulations was used to examine the spatial structures of substances;
- Three-dimensional visualization enhanced students' comprehension of stereo-chemistry of molecules;
- Hands-on modeling using ball-and-stick kits, clay, and magnetic molecular constructors enabled students to understand valence and geometry, creating molecular models.

2. Animation of chemical reactions:

Tools like PowerPoint or Canva were used to create dynamic animations of molecular dissociation and bond formation. These animations facilitate explanations of topics such as "Types of Chemical Reactions".

3. Infographics and concept maps:

Visual structuring of information (e.g., classification of substances, periodic table organization) enabled consolidation of key concepts.

4. Gamification and creative assignments:

AR-based interactive activities, such as quests employing applications like Elements 4D and Merge Cube, increased student engagement and motivation. These methods aligned with the cognitive and developmental needs of eighth-graders integrating interactivity and gamified elements to foster research skills.

2.4. Experimental Design

The pedagogical experiment, aimed at studying the effectiveness of visualization in the educational process, adheres to methodological principles and comprises three stages. Each stage is grounded in evidence-based pedagogy and cognitive didactics to ensure the validity of the findings.

Recent experimental studies in the context of chemistry education demonstrate that integrating VR/AR technology into the instructional process improves both student engagement and academic performance (Amirbekova, Shertayeva & Mironova, 2024). These findings substantiate the necessity of adopting an empirical approach in our pedagogical experiment.

The selection of a pedagogical experiment as the research design is justified by its capacity to identify causal relationships between the implementation of innovative technologies and changes in learning outcomes. As Makransky and Mayer (2022) argue, immersive technologies yield statistically significant positive effects when introduced pedagogically grounded instructional frameworks.

Furthermore, research published in the Journal of Technology and Science Education confirms that the successful integration of AR technologies into chemistry instruction depends on the methodological structure of lessons and students' readiness to engage with digital tools (Mau-Duc et al., 2025).

1. The preparatory stage

This stage encompasses the design of the experimental tools and the selection of educational content tailored to the cognitive characteristics of eighth-grade students. The development of didactic materials includes:

- 3D molecular models (using an application such as Avogadro or Nanomaterials Simulator) to enhance stereo chemical visualization;
- Infographics with hierarchical structuring of information, involving the classification of substances and problem-solving algorithms;
- Tactile simulators, such as ball-and-stick molecular constructors and AR-enhanced flashcards.

2. The implementation stage

This stage comprises a series of instructional cycles that alternate between digital tools and tactile models. Data collection includes pre- and post-testing (assignments for identifying structures and predicting the properties of substances), and video analysis of group work.

The development of chemistry projects includes several key stages:

1. Topic selection

Project topics were carefully chosen to ensure relevance, aligned with students' cognitive and academic levels, and to arouse interest. For example, the study of the properties of water and solutions, the impact of acids and alkalis on the environment, synthesis, and properties of soap and detergents, effects of chemical substances on plant growth, and the creation of molecular models using 3D technology.

2. Research questions and methods.

Students determined the key questions they wanted to explore and identified the expected outcomes of their projects. Depending on the topic, the project conduction process involves laboratory experiments and chemical tests, analysis of literature and Internet sources, computer modeling of chemical processes, and extensive use of visualization technologies.

One of the most effective visualization methods was the use of physical molecular models, which helped students better understand atomic spatial arrangement and chemical bonding types. In addition, software programs such as ChemSketch and Avogadro enabled students to create and analyze molecular models and observe chemical reaction dynamics, contributing to a deeper conceptual understanding.

3. Project presentation and digital tools

Diverse digital tools were employed to present the project, such as interactive whiteboards, video materials and chemical reaction animations, flash animations, and video sketch noting.

Engaging in multimedia-based project work facilitates students' deeper understanding of chemical concepts while developing digital skills. For example, in the project "The Impact of Acids and Alkalis on the Environment," students examined the structure, properties, and application of inorganic compounds, creating various visual materials. The final projects were presented in the format of scientific reports, multimedia presentations, interactive videos, or 3D models.

4. The final stage

A comparative analysis of learning outcomes between the experimental and control groups is conducted using statistical methods to identify significant differences ($p \leq 0.05$):

- Student's t-test and ANOVA to assess variation in performance;
- Correlation analysis to examine the relationship between the type of visualization (independent variable) and academic performance indicators (dependent variable), using Pearson or Spearman correlation coefficients.

3. Results

A review of pedagogical literature highlights the advantages of incorporating visualization technologies in chemistry project-based learning for eighth-grade students. Visualization tools, such as 3D modeling, interactive simulations, and AR, enhance students' comprehension of complex chemical concepts. Learners who engage with visual models of molecular structures, chemical reactions, and laboratory processes manifest higher academic performance compared to those who are taught using traditional methods.

The results of students' academic performance dynamics in the experimental and control groups are presented in Table 1.

Visualization Methods	Performance, %		Student's t-test	p	Performance, %		Student's t-test	p
	A	A1			B	B1		
3D Molecular Modeling	78±2	88±1	-8,52	≤0,05	76±3	80±4	-1,04	≥0,05
Animation of Chemical Reactions	77±3	89±2	-6,73	≤0,05	79±1	81±2	-1,55	≥0,05
Infographics and Concept Maps	76±2	86,5±4	-4,26	≤0,05	72,5±3	77±1	-1,64	≥0,05
Gamification and creative assignments	79,5±2	81±3	-0,96	≥0,05	77±2	79,3±1	-1,55	≥0,05
Rxy (Correlation Coefficient)			0,7364	≤0,05			0,6294	≤0,05

Table 1. Dynamics of students' academic performance in the experimental group using the visualization and VR/AR technologies (A – pre-testing, A1 – post-testing) and in the control group (B – pre-testing, B1 – post-testing)

The initial performance levels in both groups were similar and at a medium level. However, after implementing visualization and VR/AR technologies, students in the experimental group demonstrated a significant improvement in academic performance, while changes in the control group were not statistically significant.

A statistically significant increase in academic performance (from 78±2 to 88±1, p≤0.05) indicates the effectiveness of 3D molecular modeling in enhancing experimental group students' engagement. This method facilitates learners' transformation of abstract concepts into visual geometric models. Students can also interact with molecules using smartphones.

Similarly, a performance enhancement from 77±3 to 89±2 (p≤0.05) emphasizes the positive impact of animated chemical reactions among students in the experimental group. These animations enable them to visualize invisible chemical processes, such as electron movement, reaction mechanisms, changes in the structure of molecules, and phase transitions.

The utilization of infographics and concept maps also significantly improved performance (from 76±2 to 86.5±4, p≤0.05). These tools enhance cognitive and communicative competencies among students in the

experimental group by presenting data and processes in formats, such as diagrams, charts, and illustrations, making large volumes of information more accessible. Concept maps help students organize their thoughts and highlight the key concepts.

Finally, gamification and creative assignments led to a moderate performance increase (from 79.5±2 to 81±3, p≥0.05), indicating a boost in experimental group student motivation and engagement. These activities encourage creative problem-solving and experimentation.

The dynamics of research competence indicators among students in the experimental group are presented in Table 2.

Scale	Performance, %		Student's t-test	p	Performance, %		Student's t-test	p
	A	A1			B	B1		
Planning	15,1±0,6	16,4±0,4	-3,12	≤0,05	15,0±0,4	15,2±0,2	-0,77	≥0,05
Logical reasoning	28,2±0,3	30,7±0,2	-11,53	≤0,05	28,9±0,5	29,4±0,1	-1,70	≥0,05
Use of visual materials	16,8±0,3	18,2±0,5	-4,16	≤0,05	17,0±0,1	17,2±0,2	-1,55	≥0,05
Creativity	14,9±0,4	16,8±0,2	-7,36	≤0,05	14,7±0,5	15,4±0,3	-2,10	≥0,05
Independence	6,7±0,3	7,8±0,4	-3,81	≤0,05	6,6±0,2	6,6±0,1	-1,55	≥0,05
Use of interdisciplinary connections	5,6±0,2	6,6±0,2	-6,12	≤0,05	5,7±0,3	6,2±0,2	-2,40	≥0,05
Overall score	87,4±2,1	96,5±1,9	-5,57	≤0,05	87.9±2,9	90,4±0,9	-1,55	≥0,05

Table 2. Results of the study on the dynamics of research competence among students in the experimental group using visualization and AR/VR technologies (A – pre-testing, A1 – post-testing), and the control group (B – pre-testing, B1 – post-testing)

The pre-test revealed that research competence indicators in both the experimental and control groups were comparable and below the average level. However, upon post-testing, a significant positive trend was observed in the experimental group across all competence scales, reaching the statistical norm (overall score increased from 87.4±2.1 to 96.5±1.9, p≤0.05). This indicates a higher level of student engagement in project-based learning, enhancing their cognitive activity, developing creativity skills, and ability to integrate interdisciplinary connections and visual materials into their project planning.

In contrast, the control group did not show statistically significant changes in research competence indicators (overall score: 87.9±0.9 and 90.4±0.9, p ≥ 0.05).

To further assess the use of visualization techniques in education, a survey was conducted among 120 eighth-grade students. The survey aimed to identify the extent to which visualization methods were applied for educational purposes. According to the results, 74% of respondents reported the application of visualization in their studies, while 26% did not (Figure 1a).

According to the survey results, 60% indicated that 3D modeling is more effectively utilized for developing educational projects, while 40% preferred its use in presentations (Figure 1b).
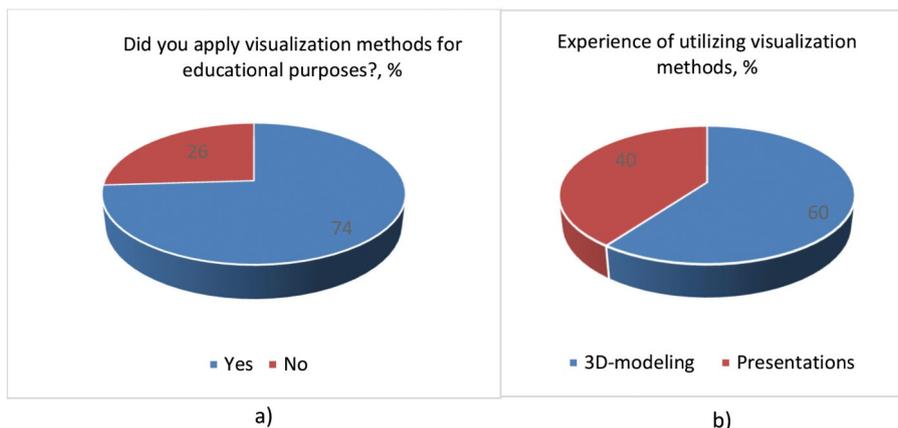
Figure 1. Results of the survey

When asked, "How has the use of visualization affected your learning experience (positively, negatively, neutrally)?" - 77% responded positively, 23% reported a neutral effect, and 0% indicated a negative impact (Figure 2).
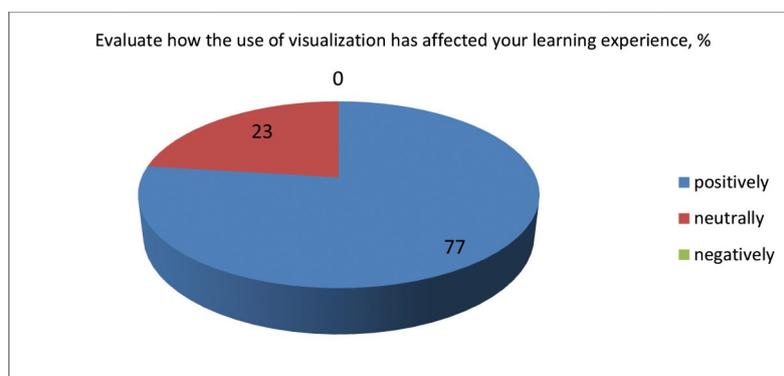

Figure 2. Results of the survey

Regarding the question "Have you encountered any challenges or difficulties in using visualization for educational purposes?", students identified the following issues:

- Difficulty accessing software or online platforms.
- Challenges in interpreting visualized data.
- Insufficient skills in working with graphs, charts, and diagrams.
- A preference for textual over graphic information among some students.
- Lack of methodological guidelines on how to effectively use visualization.
- Limited time allocated for explaining visual materials during lessons.

The survey results further revealed that over 80% of students reported a significant increase in their interest in the subject due to project-based learning incorporating visualization techniques.

Conducting a pedagogical experiment requires a systematic and methodical approach. The implementation of project-based learning necessitates the use of visualization techniques. Prior to the study, the majority of students had not employed visualization methods, due to a lack of prior experience. Only 15% of students had previously utilized this approach in their educational activities. However, following the experiment, these figures increased to 65% and 25%, respectively (Figure 3).
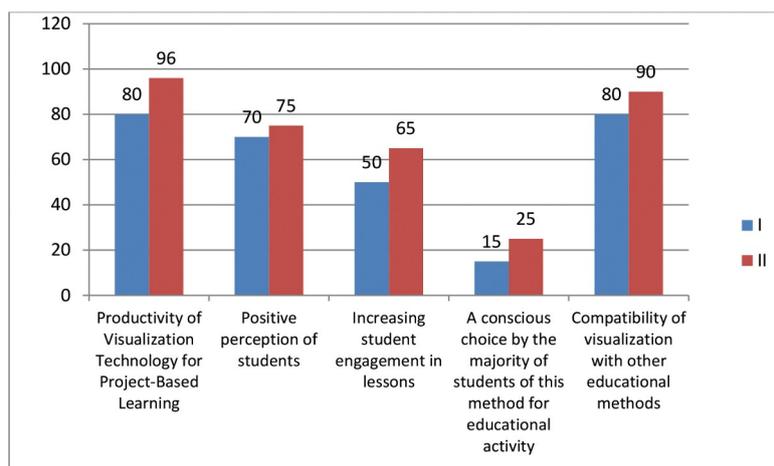
Figure 3. Results of the survey

The effectiveness of this method in developing students' ability to utilize visualization technologies reached 96% among those who consciously chose this approach for conducting their projects and were ready to devote more time to project development. Moreover, the number of students participating in the design and defense of projects incorporating visualization increased by 10%.

The experimental results manifested an increase in indicators across all key criteria, as depicted in Figure 3:

- A 16% increase in the productivity of visualization technology for project-based learning;
- A 5% improvement in students' positive perception of visualization;
- A 15% increase in student engagement in lessons;
- A 10% rise in students' conscious choice of this method for educational activities;
- A 10% improvement in the compatibility of visualization with other educational methods.

The integration of visualization techniques into the learning process has yielded valuable insights for assessing the effectiveness and success of this approach. Visualization and AR/VR technologies enable students to create more informative and visually compelling projects. The utilization of graphic models, interactive presentations, and animations enhances the clarity and validity of research findings, which is especially beneficial when presenting projects at scientific conferences and competitions.

4. Discussion

A review of the literature demonstrates that visualization and AR/VR technologies facilitates the development of research competencies. They improve students' spatial perception of learning content (Cadeado et al., 2022). The empirical data obtained in this study align with this study: standardized test results revealed a statistically significant increase in academic performance in chemistry within the experimental group, where visualization and AR/VR technologies were employed, compared to the control group, which followed traditional teaching methods ($p \leq 0.05$).

Recent research indicates that the use of visualization technologies, including AR/VR methods, as well as graphic tools such as infographics and concept maps, contributes to the development of students' cognitive and communicative competencies by optimizing information processing and structuring (Iyamuremye et al., 2023). The results of the present experimental study support these provisions: a quantitative analysis of academic performance in the experimental group revealed a statistically significant increase in the average score (from $M = 76 \pm 2$ to $M = 86.5 \pm 4$, $p \leq 0.05$), which correlates with enhanced abilities for data analysis, visual modeling of chemical processes and effective communication. The application of infographics for schematic representations of complex concepts (e.g., diagrams, illustrations) and concept maps for the hierarchizing organization of information contributed to reducing cognitive load, minimizing interpretation errors, and increasing the speed of material comprehension.

Contemporary international studies emphasize that the integration of 3D modeling into the educational process in chemistry helps to overcome cognitive barriers associated with the perception of abstract concepts such as molecular structures, spatial isometry, and reaction mechanisms. According to scholars (Horváth, 2021), three-dimensional models provide interactive interaction with microscopic objects, thereby stimulating visuospatial thinking and improving comprehension of chemical patterns. Experimental data demonstrate that the use of 3D models leads to higher test scores for recognizing structural isomers and predicting reactivity.

Furthermore, recent research in chemistry education highlights the potential of gamification as a tool for optimizing the learning process. Studies by Osman and Lay (2020) indicate that the implementation of the MyKimDG module, which incorporates game-based learning mechanisms, enhances students' cognitive engagement, systematizes theoretical knowledge, and develops applied skills through creative problem-solving. The findings of this experimental study confirm this hypothesis: in the experimental group, where game-based methods (e.g., non-standard problem-solving tasks, experimental simulations, and interactive quests) were applied, the average academic performance score increased from M = 79.5 ± 2 to M = 81 ± 3 (p ≥ 0.05). While the improvement in academic performance was not statistically significant, a qualitative analysis revealed an increase in motivation, creativity, and willingness to engage in experimental activities. Students demonstrated an increased interest in solving problems that required unconventional approaches, which aligns with the development of meta-subject competencies such as critical thinking, adaptability, and independent problem-solving.

5. Conclusions

The findings of the study support the hypothesis that visualization and AR/VR technologies have a positive impact on the development of students' research competencies and academic performance. The findings show that interactive visualization reduces the abstract nature of chemical concepts. It enhances motivation and supports deeper understanding.

The obtained results confirm that the integration of graphic visualization methods, such as infographics, and concept maps, into the chemistry education process fosters the development of meta-subject competencies, including cognitive flexibility and knowledge presentation skills. A well-designed combination of AR/VR technologies and traditional visualization tools helps students understand abstract concepts. It also promotes systemic thinking.

5.1. Research Limitations

International research emphasizes 3D modeling as a key tool in digital pedagogy, capable of transforming chemistry instruction by increasing both visual representation and interactivity. However, the effectiveness of this method depends on its didactic design: 3D models should complement, rather than replace, theoretical analysis. A promising direction includes a combination of 3D technologies with VR/AR platforms for creating immersive laboratory simulators and adaptive algorithms tailored to students' individual cognitive profiles.

The application of gamification through the MyKimDG module demonstrates a limited impact on academic performance but significantly enhances student engagement and creative activity. This suggests that game-based methods can serve as effective pedagogical tools for reducing the monotony of learning and stimulating inquiry-based interest. To achieve statistically significant improvements in learning outcomes, gamification should be combined with formative assessment methods and personalized assignments. A promising direction for future research is the integration of gamification into blended learning formats with an emphasis on project-based learning and digital simulations.

Moreover, the primary limitations of this study were related to the sample selection of respondents and time constraints. The experiment involved eighth-grade students, whose research competencies are still in the early stages of development. At this level, students have limited theoretical knowledge and practical

experience in conducting chemistry projects, enabling them to track the dynamics of change in the experimental and control groups more clearly.

The time factor was also significant. To maintain the integrity of the experimental conditions, students in the control group did not use visualization technologies and VR/AR approaches to develop research skills. This limitation affected their engagement in the learning environment. To prevent an imbalance in the curricula of the experimental and control groups, the duration of the experiment was restricted to one month.

5.2. Guidelines for Future Research

A key aspect of future research is the expansion of digital didactic technologies through the combined use of AR/VR and other interactive tools (e.g., 3D modeling, and gamification) to comprehensively analyze their impact on learning outcomes. To verify the effectiveness of immersive technologies, further research should assess the knowledge retention and adaptability of these methods across various STEM disciplines, including physics, biology, and ecology. Moreover, differentiated approaches should be developed to account for students' cognitive characteristics and the specifics of different subject areas.

Practical recommendations encompass:

- Integration of AR/VR into blended learning formats with a balanced use of immersive modules;
- Creation of open-access platforms to minimize resource constraints;
- Development of didactic algorithms that balance visualization and theoretical analysis.

Thus, this study manifests that using visualization and AR/VR technologies in chemistry education for 8th-grade students has a significant didactic effect. These technologies not only enhance the quality of knowledge acquisition but also foster the development of essential 21st-century competencies, such as critical thinking, digital literacy, and research skills.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Ethical Statement

The study was conducted following the Declaration of Helsinki and approved by the Ethical Committee Board for the Evaluation of Scientific Research of South Kazakhstan Pedagogical University named after O. Zhanibekov (Approval code: 05/370; approval date: 5 March 2025). Informed consent was obtained from all subjects involved in the study.

Authors' contributions

Nailya Shertayeva: writing – original draft, conceptualization, supervision.

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Ainur Zhorabekova: writing – review & editing, data processing, investigation.

Elmira Amirbekova: writing – original draft, acquisition of funds, research, visualization.

Akerke Kossauova: writing – original draft, data curation, software.

Yerman Shertayev: writing – review & editing, resources, validation.

Data availability

Data included in the article itself or supplementary material

Use of Artificial Intelligence

The authors declare that Artificial Intelligence software (Grammarly) was used for linguistic editing and grammar correction of the manuscript.

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