

Exploring the Role of Emerging Technologies in Chemistry Education: A Study on Student Engagement and Equity

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Abstract

In the century of digitalism, the use of technology in education is transforming traditional pedagogy in science subjects such as chemistry, which typically involve abstract concepts and complex molecular structures. The study explores how new digital technologies such as virtual labs, augmented reality (AR), virtual reality (VR) and artificial intelligence (AI) are enriching students' engagement, understanding and critical thinking in chemistry learning. A quantitative research project was conducted to survey 163 students in grades 7–11 to measure their perceptions of the effectiveness of technology in enhancing their learning experience. Results showed that 65% of students reported increased engagement in technology lessons, explaining that they enjoyed the lessons because the virtual labs were interactive and the AR/VR experiences were immersive. The equipment allowed students to visualize chemical reactions and molecular structures in three dimensions, bridging theory and practice. In addition, 53% of students agreed that virtual labs helped them think critically and solve problems more effectively by enabling safe experiments and manipulation of variables. The study identified some pressing issues such as device shortages, system malfunctions, and teacher readiness. These impacts represented a digital divide in education in under-resourced schools. To ensure equal access and effective use of computer-based chemistry learning materials, the study concluded with policy implications for legislators and educators.

Keywords: augmented reality (AR), virtual reality (VR), artificial intelligence (AI), chemistry education

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Introduction

Traditional chemistry instruction often relies on lectures, textbook diagrams, and limited laboratory access. These methods are insufficient to engage all learners, particularly when teaching concepts like molecular geometry, reaction mechanisms, and quantum chemistry. Many students struggle not due to a lack of intelligence, but due to the abstract nature of the content and a lack of visualization tools. Modern technology provides promising solutions, yet the integration of these tools into the classroom remains inconsistent. Issues such as limited access, lack of teacher training, and misalignment with curricula continue to hinder progress. This dissertation investigates how to close the gaps and capitalize on opportunities created by technology to transform chemistry education. We are living in an era of digital transformation that is affecting all aspects of life, including aspects of teaching and learning. Teaching now extends beyond four walls of a room and innovations in education are happening due to phenomena such as augmented reality, virtual labs and simulations, artificial intelligence (AI) tutors, and gamified learning. The unfortunate truth is that although new technologies and capabilities emerge, many chemistry courses at colleges and universities or high schools are taught using traditional means that are often teacher-centred. Physical processes based on chemical principles—such as the concept of atomic orbitals or distributions of an electron cloud or thermodynamic pathways—are developed using two-dimensional (2D) diagrams or static lectures – neither of which represent an effective way of allowing all learners, especially those who have difficulty overcoming chemical abstractions, to create conceptual understanding.

While there are advantages of teaching chemistry in these conventional ways, we have also noticed that the traditionally-used methods of chemistry education don't work for all modern students. The more complex the subject of chemistry, the more abstract it becomes for students—and concepts like molecular interactions, thermodynamics, and reaction mechanisms are difficult to absorb when they are only presented in lectures and textbooks. Laboratory work is essential to chemical education, but it can sometimes diminish when we do not have sufficient resource opportunities, or in the case of the lab, time or safety factors to consider. All these variable pressures show us that there is a need to reform and explore new non-standard teaching methods, in regards to reasonable solutions as well as designing fun, interesting, and how to include as effectively and easily as possible different learners, in order to make it captivating to learn.

This research is guided by the following key question: *How does the integration of technology impact students' ability to apply chemical knowledge in practical contexts, and how do these effects vary across different grades and school types?*

Literature Review

Use of technology in the teaching of chemistry rests upon a variety of theoretical models regarding how to best integrate digital tools into the teaching and learning processes.

TPACK Framework

In the context of chemistry education, when considering TPACK, teachers will choose technological tools that deliberately integrate into the curriculum they are delivering and deliver the intended teaching and learning objectives. For example, when teaching the shape of molecules teachers will use augmented reality apps like Elements 4D or MolecularAR, to

allow students to visualize and manipulate molecules in 3D space. Considering TPACK, CK is the understanding of chemical bonds and the structure of molecules, PK is the development of inquiry tasks that recognize the nature of student's research approach to learning, and TK is the effective use of AR to improve the quality of learning.

Chittleborough (2014) states the TPACK framework is useful in the science context to understand that abstract scientific concepts benefit from multimodal representation, and Dos Santos (2023) explains that teachers with TPACK knowledge and understanding can be more adaptable to the ever-changing educational technology environmental factors. Mishra and Koehler (2006) explain, continuous professional learning is necessary to develop and practice TPACK, particularly in Chemistry education because technology is constantly being refined.

SAMR Framework

The SAMR Model, developed by Dr. Ruben Puentedura (2006), has defined four stages in which technology can be integrated into teaching practice: substitution, augmentation, modification, and re-invention. As a framework, this hierarchical model enables educators to consider their level of technology use and how deep or transformational the learning task is.

Educational Software

The introduction of specifically designed educational software, such as CocoSoft is fundamentally changing the practice of teaching analytical chemistry. This software does not compete with online data, rather it makes it easier for students to engage in ways that do not burden them through unnecessary repetition, such as data collection and analysis of chromatograms or composing reports (Cocovi-Solberg & Miró, 2015). By simplifying the process, students are capable of engaging with the content in the most meaningful way, as well as developing skills, understanding how to interpret results and planning experiments.

Kazakhstani Researchers on Digital Chemistry Education

Increasingly, there is a focus on how digital technologies can enhance the professional competencies of future chemistry teachers in Kazakhstan. The researchers at O. Zhanibekov South Kazakhstan Pedagogical University, Karmanova et al. (2024), completed a study examining the impact of utilizing digital platforms (e.g., ZOOM) and gamified learning with pre-service teachers, in terms of pedagogical and technological preparedness in teaching chemistry.

Methodology

Research Design

This mixed-methods inquiry explicitly took a quantitative and qualitative stance on understanding the role of technology in chemistry education. We sought to investigate the role of technology in students' learning experiences and to understand teachers' views and actions regarding teachers' digital practices. We utilized three different methods: a survey for students, an experimental lesson measured using a pre- and post-test design, and a survey questionnaire for teachers. The approach provided a triangulated perspective of the research topic.

Participants

A total of 152 students from Grades 7 to 11 took part in the student survey. Participants were drawn from diverse school types across Kazakhstan, including public schools, private institutions, and specialized centers. This sample allowed for broad representation of students' digital learning experiences. An intact Grade 8 class of 26 students was selected to participate in an experimental technology-integrated chemistry lesson. The group was chosen based on accessibility, availability of technological infrastructure, and teacher cooperation. These students completed both pre- and post-tests related to the lesson.

Data Collection

Student Questionnaire

The questionnaire was distributed digitally via Google Forms. Responses were anonymous, and students completed it within 10 minutes during a designated class period. A pilot with 10 students was conducted to ensure clarity and reliability. The instrument achieved a Cronbach's alpha score above 0.80, indicating strong internal consistency.

Data were collected through a structured survey, administered via Google Forms. It consisted of 13 questions. These questions were designed to assess specific aspects of student experiences with technology in chemical education, including engagement, understanding, skill development, and cooperation.

The main features of the process of collecting data are as follows:

Survey Design

The items were framed to assess engagement, comprehension, and the perceived collaboration facilitated by technology in chemistry classrooms. Both positively and negatively worded items were included in order to provide a balanced view of the students' experience and avoid response bias.

Survey Distribution

The electronic format of the survey was chosen to ensure convenience and accessibility, allowing respondents to participate at any time convenient for them.

Measured Variables

Engagement: Items focus on how technology engages students' attention and fosters their interest in chemistry. For example, "How engaging are virtual labs for learning chemistry?"
Skills Development: Questions ask about how tools like virtual labs and augmented/virtual reality help develop problem-solving and critical thinking skills. For instance, "To what extent do virtual labs help understand complex chemical concepts?"

Experimental Lesson With Pre- and Post-test

An experimental lesson was designed to assess how digital tools affect learning outcomes. The topic was “Acids and Bases”, aligned with the national Grade 8 chemistry curriculum. Digital Tools Used:

- A virtual laboratory simulation platform
- An interactive quiz/game app (e.g., Kahoot, Quizizz)
- Multimedia content (animations and visuals)

Pre-test and Post-test

A 15-question multiple-choice test was administered before and after the lesson. The test was based on Bloom’s taxonomy and evaluated students’ knowledge and understanding of acids and bases. Each student completed both tests in 10–12 minutes.

Additional Observations

The classroom teacher recorded notes on student engagement, behavior, and digital interaction during the lesson to support qualitative analysis.

Data Analysis

Quantitative data from both the student survey and the experimental pre/post-test were analyzed using SPSS (version 26). Descriptive statistics (mean, standard deviation, frequency) were used to summarize survey results. Paired sample t-tests were conducted on the experimental group’s pre-test and post-test scores to evaluate the effectiveness of the technology-based lesson.

Results

The research question was addressed using a mixed-methods approach that combined experimental design, survey analysis, and advanced statistical testing. The focus was to understand whether the integration of technology improves students’ ability to apply chemistry knowledge in real-world scenarios and whether these outcomes differ depending on the student’s grade level or age group.

The main source of data came from a pre- and post-test comparison between a control group taught with traditional methods and an experimental group that experienced a lesson enhanced by modern technologies such as augmented reality (AR), virtual labs, simulations, and gamified tools. The results showed that the technology- enhanced group demonstrated a notable improvement in post-test scores, indicating an increase in their ability to apply chemical knowledge. For example, students were better able to connect atomic-level interactions with real-life chemical reactions after participating in immersive AR/VR experiences.

Table 1*Results of Pre and Post-tests in a Traditional Method Group*

Student	Pre-test	Post-test
Student 1	6	7
Student 2	6	7
Student 3	7	7
Student 4	7	7
Student 5	6	7
Student 6	7	7
Student 7	6	7
Student 8	7	7
Student 9	7	7
Student 10	7	7
Student 11	6	7
Student 12	6	7
Student 13	7	7
Student 14	7	7
Student 15	6	7

Table 2*Results of Pre and Post-tests in the Tech Method Group*

Student	Pre-test	Post-test
Student 1	6	8
Student 2	6	8
Student 3	7	8
Student 4	7	8
Student 5	7	8
Student 6	6	8
Student 7	6	8
Student 8	6	8
Student 9	7	8
Student 10	6	8
Student 11	6	8
Student 12	6	8
Student 13	6	8
Student 14	6	8
Student 15	7	8
Student 16	7	8
Student 17	6	8
Student 18	6	8

Pre- and post-test results revealed a statistically significant improvement in the performance of the technology-integrated group, supporting the positive impact of digital tools on students' ability to apply chemical concepts. As shown in Table 3, the mean post-test score of the experimental group increased substantially compared to the traditional group, with higher gains in both average and median values. These results provide clear quantitative evidence

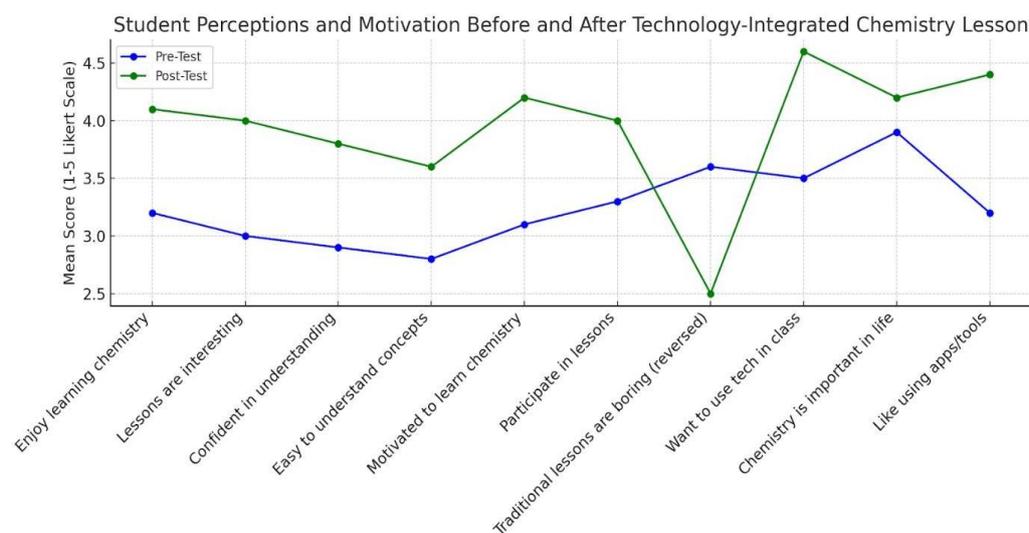
that technology-enhanced instruction contributed to deeper conceptual understanding and practical knowledge application.

Table 3
Descriptive Statistics

Item	N	Missing	Mean	Median	Std Dev	Min	Max
item 1	163	24	2.47	2	1.22	1	5
item 2	163	24	3.49	3	1.08	1	5
item 3	163	24	3.87	4	1.11	1	5
item 4	163	24	3.67	4	0.929	1	5
item 5	163	24	3.96	4	0.981	1	5
item 6	163	24	3.73	4	1.3	1	5
item 7	163	24	3.73	4	1.11	1	5
item 8	163	24	3.66	4	1.16	1	5
item 9	163	24	3.64	4	0.954	1	5
item 10	163	24	4.0	4	1.01	1	5
item 11	163	24	3.92	4	0.93	1	5
item 12	163	24	3.17	3	1.5	1	5
item 13	163	24	2.45	2	1.29	1	5

Supporting this finding, the student survey revealed that 67% of students indicated that their retention of knowledge improved through technology-enhanced lessons, and 70% reported that AR/VR simulators helped them apply chemical concepts in real-world contexts. One student expressed: “I used to try and understand how reactions happen at the atomic level—it was hard, but after seeing it in VR, my understanding was instant.” Another commented, “Using AR to explore molecules was so fun and different—I felt like I was actually inside the molecule!” These qualitative responses provide insight into the cognitive benefits of using interactive and visual learning environments, highlighting how technology fosters a deeper connection between theoretical knowledge and practical application.

Figure 1
Analysis of Student Questionnaire (A part)



In summary, the findings demonstrate that the integration of technology significantly enhances students' ability to apply chemical knowledge in practical contexts. These benefits

were observed across all grade levels, although the school type possibly reflecting differences in infrastructure, device availability, or teacher training influenced the extent of the benefit. The results validate the use of immersive technologies like AR/VR and simulations in chemistry education, offering strong support for continued integration of digital tools in science classrooms to promote applied learning and deeper conceptual understanding.

Discussion

The integration of AR tools in our study is in line with Abdinejad et al. (2021), who found that AR technologies not only increase students' engagement but also improve their ability to apply chemical knowledge to practical scenarios, such as understanding molecular processes. Sharma et al. (2021) discusses how AI and interactive bots can be used to improve student learning in chemistry by fostering problem-solving and active participation in experiments. Chiu and Linn (2012) investigate how visualizations in chemistry support knowledge integration, which can vary across different age groups. Methodological alignment:

1. The pre- and post-test assessed knowledge application before and after the intervention.
2. The survey collected student perceptions of how technology affected motivation and engagement.

Limitations

While this study provides valuable insights, there are several limitations that should be considered when interpreting the findings:

Sample Size and Scope

The investigation was conducted with small samples of students in the grades of 7 – 11 across few schools. The sample was adequate for the current exercise for preliminary understanding, but larger-scale studies across more diverse and greater populations would certainly provide evidence for generalizability. Future studies should incorporate schools from more varied areas and socio-economic demographic to better understand the impact of technology on chemistry education.

Short-Term Focus

This research studied technology's immediate impact on student engagement, cognition, and skill-building. In order to understand longer-term impacts of technology on learning outcomes and readiness to enter a career, longitudinal research is necessary to explore the long-term implications of using technology often. Future studies need to monitor students over longer periods of time to determine the ways technology affects academic performance, critical thinking, and skill development into the workplace.

Reliance on Self-Reported Data

This research relied upon student surveys heavily. Surveys can be distorted by personal biases or misunderstandings. While surveys can provide some insight into the perceptions of students, they do not always reflect real learning outcomes and behaviors. Future studies should combine self-reported data with other data types, such as classroom observations,

performance-based assessments, and/or interviews with teachers to gain a better understanding.

Technological Challenges

Some students expressed challenges with navigating the more complicated tools of the study, which may have affected their perceptions of the technology's value. Technical distractions, including lag on the software, complicated user interfaces, and limited pre-usage training, often interrupted learning. Therefore, better more intuitive designs, easier user interfaces, and training for students and teachers are critical technical barriers to removing when enhancing technology use in the classroom

Conclusions

This research investigated the integration of digital technology into chemistry education, with the goal of evaluating its impact on student learning, understanding teacher perceptions, and identifying practical barriers to implementation. The study used a mixed-methods design, combining pre- and post-tests, student and teacher questionnaires, and statistical analyses to provide a comprehensive understanding of technology use in chemistry classrooms.

The research question explored how technology affects students' ability to apply chemical knowledge, and whether these outcomes differ by grade level or age. The findings revealed that students who participated in technology-integrated lessons featuring tools such as AR/VR, simulations, gamification, and AI platforms demonstrated improved ability to apply chemical concepts in practical contexts. This was confirmed through pre- and post-test comparisons. However, the statistical analysis (MANCOVA) showed that grade level and age did not have a significant effect, while school type had a notable influence on engagement and skill development. This suggests that while technology benefits students broadly, its impact may be influenced by the resources and infrastructure available in different school environments.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors confirm that ChatGPT, an AI-assisted language model, was used only to edit and refine the words of the manuscript. Its use was limited to grammar and spelling checks and paraphrasing sentences for enhanced clarity and accuracy. The author also confirms that there was no use of AI or AI-based technologies in the development of content material for the manuscript. All work, ideas, procedures, findings, analyses, and discussions constitute original work by the author from the meticulous and systematic conduct of the research.

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