Faculty of Education and Humanities
Department of Pedagogy of Natural Sciences

"Admitted to defense":
Head of Department
Assoc. Prof. PhD Zhangyl Abilbek
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«06» наурыз 2025y

MASTER'S DEGREE DISSERTATION

Integration of Technology in Chemistry Education

7M01502 – Chemistry

Students: ____________ Lyazzat Daniyarkyzy
Scientific advisor: ____________ Assoc. Prof. PhD Zhangyl Abilbek
Format controller: ____________ M.Sc. Nazgul Otegenova

Kaskelen, 2025

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SDU UNIVERSITY

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Ministry of Education and Science of the Republic of Kazakhstan
SDU University
Faculty of Education and Humanities
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Lyazzat Daniyarkyzy

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MASTER'S DEGREE DISSERTATION

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7M01502 – Chemistry

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CONTENTS

ABSTRACT

This section details the research methods used to implement technology into chemical education research. The study adopts a quantitative methodology, specifically a survey method based on a systematic study of the impact and perceptions of the use of technology by students. The focus for this project was to obtain objective data in order to recognize trends, correlations and total impact of the technology use. The study included students from multiple levels of learning such as high school students, undergraduates completing a chemistry course, and possibly graduate students which allows the study to have more holistic picture of the chemistry learning experience. They were a broad array of students so we could consider an extensive range of experiences with respect to one's views on technology in educational settings. Data collection was primarily through a thorough and systematic survey tool specifically developed to derive both closed (for instance, on the Likert scale) and open responses. The survey tool has specific emphasis on the examination of students experiences, attitudes to learning, perceived benefits, drawbacks and frequencies of the use of diverse technological tools in chemistry learning environments. Key areas of research included their interaction with simulators, virtual labs, educational software, and online resources. The analytical methods were strictly based on a statistical analysis of the collected survey results. This included both descriptive statistics (e.g., frequencies, averages, standard deviations) to summarize the demographic data of participants and their overall responses, and logical statistics (e.g., t-tests, ANOVA, correlation analysis) to identify statistically significant patterns, correlations, and meaningful outcomes. The aim was to draw informed conclusions about the relationship between the integration of technology and the results of students, their perception and involvement in the process of studying chemistry.

Key words: *integrative chemistry teaching*, *ChatGPT, Artificial Intelligence (AI), chemistry education, Technology, hardware, software*

АҢДАТПА

Бұл бөлімде технологияны химиялық білімге интеграциялау үшін ғылыми зерттеулерде қолданылатын әдістеме егжей-тегжейлі сипатталған. Зерттеуде сандық тәсіл қолданылды, атап айтқанда студенттердің технологияны қолданудың әсері мен қабылдауын жүйелі түрде зерттеуге негізделген сауалнама әдісі қолданылды. Бұл жобаның мақсаты технологиялық интеграцияның тенденцияларын, байланыстарын және жалпы тиімділігін анықтау үшін өлшенетін деректерді жинау болды. Бұл зерттеуге әртүрлі білім деңгейлеріндегі студенттер, соның ішінде орта мектеп оқушылары, магистранттар және мүмкін аспиранттар қатысты, бұл химияны оқыту тәжірибесі туралы кең түсінік берді. Оларды іріктеудің мақсаты білім беруде технологияны қолдану бойынша кең ауқымды көзқарастарды ескеру болды. Деректерді жинау негізінен жабық (Мысалы, Ликерт шкаласы бойынша) және ашық жауаптарды жинауға арналған кешенді және құрылымдық сауалнама жүргізуге негізделген. Бұл құрал студенттердің тәжірибесін, оқуға деген көзқарасын, қабылданатын артықшылықтарын, қиындықтарын және химияны оқыту орталарында әртүрлі технологиялық құралдарды пайдалану жиілігін зерттеу үшін мұқият әзірленген. Зерттеудің негізгі бағыттары олардың тренажерлармен, виртуалды зертханалармен, білім беру бағдарламалық жасақтамасымен және интернет-ресурстармен өзара әрекеттесуін қамтыды. Аналитикалық әдістер қатаң түрде жиналған сауалнама нәтижелерін статистикалық талдауға негізделді. Бұған қатысушылардың демографиялық деректерін және олардың жалпы жауаптарын қорытындылау үшін сипаттамалық статистика (мысалы, жиіліктер, орташа мәндер, стандартты ауытқулар) және логикалық статистика (мысалы, t-тесттер, ANOVA, корреляциялық талдау) статистикалық маңызды заңдылықтарды, корреляцияларды және маңызды нәтижелерді анықтау. Мақсаты технология интеграциясы мен студенттердің нәтижелері, олардың химияны оқу процесіне қабылдауы мен қатысуы арасындағы байланыс туралы негізделген қорытынды жасау болды.

Түйінді сөздер: *интегративті химияны оқыту, ChatGPT, Жасанды Интеллект (AI), химия білімі, Технология, аппараттық құрал, бағдарламалық қамтамасыз ету*

АННОТАЦИЯ

В этом разделе подробно описывается методология, используемая в научных исследованиях для интеграции технологий в химическое образование. В исследовании использовался количественный подход, в частности, метод опроса, основанный на систематическом изучении влияния и восприятия использования технологий учащимися. Целью этого проекта был сбор поддающихся измерению данных для определения тенденций, взаимосвязей и общей эффективности технологической интеграции. В этом исследовании приняли участие учащиеся с разным уровнем образования, в том числе старшеклассники, магистранты и, возможно, аспиранты, что позволило получить широкое представление об опыте изучения химии. Целью их отбора было учесть широкий спектр точек зрения на использование технологий в образовании. Сбор данных в основном основывался на проведении всеобъемлющего и структурированного опроса, предназначенного для сбора как закрытых (например, по шкале Лайкерта), так и открытых ответов. Этот инструмент был тщательно разработан для изучения опыта учащихся, их отношения к обучению, предполагаемых преимуществ, проблем и частоты использования различных технологических инструментов в учебных средах по химии. Ключевыми областями исследований были их взаимодействие с симуляторами, виртуальными лабораториями, образовательным программным обеспечением и онлайн-ресурсами. Аналитические методы были строго основаны на статистическом анализе собранных результатов опроса. Это включало как описательную статистику (например, частоты, средние значения, стандартные отклонения) для обобщения демографических данных участников и их общих ответов, так и логическую статистику (например, t-тесты, ANOVA, корреляционный анализ) для выявления статистически значимых закономерностей, корреляций и значимых результатов. Цель состояла в том, чтобы сделать обоснованные выводы о взаимосвязи между интеграцией технологий и результатами учащихся, их восприятием и вовлеченностью в процесс изучения химии.

Ключевые слова: *интегративное обучение химии, ChatGPT, искусственный интеллект (ИИ), химическое образование, технология, аппаратное обеспечение, программное обеспечение.*

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LIST OF ABBREVIATIONS

AI – artificial intelligence
TPACK – technological pedagogical and content knowledge
SAMR – model replacement, addition, modification, reinterpretation
ICT – Information and Communication Technologies
ANCOVA – Analysis of covariance
STEM – Science, Technology, Engineering, and Mathematics
CK – Content Knowledge
PK – Pedagogical Knowledge
TK – Technological Knowledge
AR – augmented reality
VR – virtual reality
VL – Virtual laboratories

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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. This is the motivation for my doctoral research in examining the gap between what is available technologically and its use in chemistry education. In this era where technological advances occur quickly, transforming nearly all aspects of our lives, education is also changing dramatically. Digital innovations, such as interactive simulations, virtual labs, and augmented reality offer students fundamentally different ways to learn chemistry, which can lead to more engaging and effective learning experiences through reducing many of the limitations of formal learning. As structures in the abstract realm of chemistry can be complicated, learners are required to deal with not only abstract concepts, but they must also understand if they genuinely are made up of atoms (subatomic) and how the many types of models work. Learning chemistry via traditional methods is challenging, especially when students must deconstruct their understandings to comprehend a different perspective of familiar things. A traditional way of teaching chemistry can -among other challenges- fail to show molecular processes visually (e.g., molecular movements, such as those as they interact when reactants make products) through 2D diagrams, demonstrate clearly how to explain multi-stage chemical reactions, and facilitate pedagogically suitable, safe, and manageable laboratory work experience.

The advent and emergence of technologies have the potential to radically change chemistry education. Whether with an interactive simulation, a virtual lab, or an augmented reality learning resource, students may have to learn chemistry, but simultaneously offer a more engaging way to learn for those studying for careers in science or industry. Virtually adaptable labs can provide a safe and accessible way to investigate curricular material, ultimately addressing time issues, equipment issues, or safety issues one may encounter in a laboratory space. In addition, augmented reality and simulations can create and offer more visually descriptive and realistic representations of abstract processes, chemical reactions, structures, etc., that facilitate learning and deeper reflection on chemical processes (including microscopic interactions) and generate critical thinking for the problem-solving needed that represents real-world applications in science or industry, which relates to creating successful pathways for careers.

While the potential for technology use may promote potential benefits to education, the reality is that educational institutions often do not integrate effectively, and even with prior research, can lead to changing technology or lack of substantial and pervasive use across different educators and institutions. The utility of implementation is based on a number of matters related to interdependence and problems, such as the availability of expensive digital tools; technical resources; teacher training; or exclusive legitimate data regarding the use of the digital tools in other courses. There is, we noticed, a sluggishly progressing, tenuous and fragile evolution of technology implemented in curricula, despite all the productive technological advances, these figures reaffirm the disconnection between what is fundamentally available technologically, especially at the emerging or early adoption stage, and limited use of technology in education, as we noted previously. Technology is a malleable mechanism, but also is overall a phenomenological purpose that if used well it produces a distinctively different and productive experience with innovative but effective teaching of chemistry that grows understanding in science. This inspires scientific research to understand if technology use implemented into chemical education somehow benefits students by meeting their learning outcomes, and communicate what opportunities exist for adopting improved education.

Research Problems

While there are advantages of using 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.

Not only does modern technology provide us with a considerable opportunity of how we might solve many current problems in chemical education, the biggest impediment to using them currently, is not having the necessary skill level, or resources to leverage, digital technology, as a teacher while teaching in a learning process.

Secondly, the impact of specific technologies on the assimilation of material, interest and academic performance of students in chemistry has not been sufficiently studied. Despite a significant amount of research on the use of technology in education in general, there is clearly not enough research specifically on chemistry. This disadvantage highlights the need for a deeper study of how technologies can be adapted to meet the specific challenges facing chemical education.

Research aim and Objectives

The main intention of this research is to analyze the impact of digital tools on chemistry teaching and learning. We would like to understand the impact of technology on teaching practice, students' interest towards chemistry as well as the impact of technology on students' chemistry performance. The primary goals of the research are as follows:

1. Assess effectiveness of technological tools such as virtual labs and augmented reality to enhance students understanding of chemistry concepts.
2. To investigate chemistry teachers experiences and views regarding their use of technologies throughout the educational process.
3. Identify challenges and obstacles for implementing technologies into chemistry teaching and offer solutions regarding those obstacles.

The hope for this research is provide valuable information for teachers, educational program developers, and individuals involved in technology for education implementation. Therefore we wish to provide suggestions to educators to enhance their teaching utilizing technology to enhance the overall quality of chemistry education.

Research Questions

This research is guided by the following key questions:

1. 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 type?
2. What are the experiences and perceptions of educators regarding the use of technology in chemistry instruction?
3. What challenges and barriers exist in the implementation of technology in chemistry classrooms, and how can these be overcome?

Significance of the Study

This research is important because it will enhance chemistry teaching and broaden the comprehension of advancing education through technology. The research will provide data on how technology affects learning chemistry - student interest, understanding of chemistry and performance - all of which will be useful for teachers, scientists, and educational policy makers. The research findings provide a framework for developing new, more effective ways to implement technology into chemistry teaching that engages learners more effectively for different learners' needs.

The study hopes to assist teachers more effectively and ultimately provide teachers with specifics to increase the effectiveness of their work. Technology use in teaching enables teachers to provide more engaging, exciting and accessible lessons, which positively contributes to students' comprehension of chemistry. For students, technology use can help make chemistry easier, and more interesting, which should translate into engagement and performance in relation to chemistry. In essence, this research therefore hopes to help create a fairer and more effective education system, whereby technology serves as an effective tool for improving learning, and lifelong learning and development.

2. Literature Review

2.1 Theoretical Part

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. The TPACK model (technological pedagogical knowledge of a content area); SAMR (substitution, augmentation, modification, redefinition) model and constructivist learning theory provide important suggestions for allowing technology to be used in chemistry teaching. That is significant, because of the distinct challenges students face in learning chemistry: the abstract nature of the concepts; the representation of molecules, especially in three dimensions; the complexity of a chemical reaction which is typically viewed through a lens as opposed to a dynamic process which can be difficult to comprehend and therefore, learn from through texts or static images.

TPACK Framework

The TPACK framework (Technological Pedagogical Content Knowledge) developed by Mishra and Koehler (2006) is an integrated model of teacher knowledge, including Content Knowledge (CK), Pedagogical Knowledge (PK) and Technological Knowledge (TK), which shows that effective and quality teaching requires not only subject matter knowledge and knowledge of how to teach, but it also requires teachers to explore the use of technology at school using digital learning and teaching tools that are able to support student learning.

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 MoleculAR, 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 recognise 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. This emergent factor is particularly relevant in chemistry because educational tools used by teachers, such as simulations and virtual laboratories, are often updated and provide learning contexts that teachers might not be familiar with. To develop TPACK capacity or competency, teachers must engage in ongoing professional development to allow teachers the ability to make decisions, apply and demonstrate the most effective technological product or intervention.

Mishra and Koehler (2006) established the TPACK model which shows how three significant areas of knowledge - pedagogy, technology and discipline - are interrelated. This model indicates that teachers must have detailed knowledge of their discipline and how to teach it, as well as to see how the use of technology can be used to support teaching in that discipline. Chittleborough (2014) explains that TPACK is a useful tool for teachers who want to viably redevelop their current style of teaching and use technology to assist in improving student learning without the detriment of subject content.

In chemical education, TPACK is about the competent selection of appropriate technological solutions that are displayed harmoniously with a specific topic and the teaching method that has been selected. For example, when using augmented reality applications like Elements 4D to study the shape of molecules, students can visualize and manipulate the molecule in 3D space. Here CK is an understanding of the chemical bonds and the shape of the molecules, PK is developing research tasks around the chemistry purpose of students learning, and TK is the effective use of AR as a learning tool and not just distraction. In this scenario TPACK is effective across all of its story across subject knowledge and pedagogy.

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. Dos Santos (2023) also indicated teachers with TPACK skills will be more productive in the use of interactive tools, which will allow students to develop a better understanding of complex concepts on topic performance.

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.

For example, in chemistry teaching, at the substitution level, a digital periodic table replaces a printed one. At the augmentation level, we use an interactive periodic table that gives us dynamic information on element properties. At the modification level, we use tools like PhET simulations or ChemCollective virtual labs to allow students to do experiments prohibited in a traditional classroom because they are too dangerous, too expensive, or traditionally not easily replicated in everyday learning. The highest level, re-invention occurs when technology allows for the creation of entirely new learning tasks like developing a virtual reality-based tutorial in which students can "walk through" molecular structures or engage in chemical reactions in a 3-dimensional space.

The SAMR model is applicable to chemistry in particular because of the content complexity and the abstraction of many of the concepts we engage in chemistry. The SAMR model helps to guide teachers who want to integrate technology in ways that might be more transformational, and it supports the development of more interactive, student-centred learning environments that extend beyond simply bringing content (Al-Bataineh et al., 2022).

Ruben Puentedura developed the SAMR model in 2006 to describe the four stages of technology integration into the educational process: substitution, augmentation, modification, and re-invention. This model acts as a tool for educators to assess our efficiency in using technology in teaching and ultimately serves as a strategy to improve the educational experience.

In the first stage (substitution), the technology merely offers a replacement of existing tools while presenting no new function. The electronic periodic table replaces the paper periodic table but adds no new function.

In the second stage (augmentation), the technology offers new functions to existing methods of use. Example: the interactive periodic table allows students to visualize and study the properties of elements dynamically.

In the modification stage, the technology provides the learner with a significantly changed learning task. Example: Virtual labs allow students to conduct experiments in defined or controlled environments that are safe.

In the highest stage (re-invention), technology allows for a completely new learning experience. Example: augmented and virtual reality allows students to interact with molecules in a 3-dimensional space.

In context of chemistry teaching, the SAMR model helps teachers see whether we are replacing tradition with technology or changing the activity of learning. It helps articulate what we want students to learn and how they interact with those chemical concepts.

Constructivist Learning Theories

The constructivist perspectives of Piaget and Vygotsky stress the important role of the learner engaged in the learning process. In their approaches, the learner takes an active role instead of passively receiving information so they can construct their own knowledge through interaction with their surroundings and independent inquiry. This perspective would work well with the use of digital tools such as augmented (AR) and virtual (VR) reality because they provide students with hands-on learning opportunities. Vygotsky's zone of proximal development is the most critical aspect of constructivism. The zone of proximal development is the difference between what a learner can do individually and what they can do with the support of a mentor or more knowledgeable peer. Technologies such as AR create an environment that allows students to build expert like problem solving skills that help them overcome difficulties in understanding abstract ideas in chemistry. For example, by using AR applications to visualize electronic orbitals or chemical interactions, students can better conceptualize and visualize some of these abstract concepts using AR experiences instead of textbooks.

Piaget's stages of cognitive development are also applicable to the context of chemistry education. Topics such as molecular geometry and reaction mechanisms that require formal logical thinking suggest that a learner would need to think abstractly. It often requires visual support to understand these concepts. AR and VR allow learning about chemical concepts to focus on the visual representations of molecules and their interactions, and help students connect the practical and theoretical knowledge of what they are learning.

Applying Frameworks to AR/VR and AI Tools

The theoretical principles described earlier find direct application in chemistry education using modern technologies such as augmented reality (AR), virtual reality (VR) and artificial intelligence (AI). For example, AR applications like ChemCaper vividly demonstrate the TPACK concept by effectively combining chemical knowledge, pedagogical approaches, and technological tools. AR not only visualizes educational material, but also actively engages students in the study of molecular structures.

VR, in turn, provides an immersive experience corresponding to the stages of SAMR, as shown by the research of Weymouth and Reicher (2020). VR allows you to visualize complex quantum phenomena such as wave functions, making abstract concepts more understandable. Finally, AI tools such as ChatGPT support a constructivist approach to learning by providing personalized experiences, as a Dos Santos (2013) study has shown. AI applications increase student engagement by providing instant feedback, adapting learning paths, and offering personalized support tailored to each student's individual needs.

Reflections and Challenges

Even as the recommended strategies indicate that technology will be successfully used in education; there will still be barriers to the suggested strategies. To begin, these strategies recommend the successful use of, a qualified teacher education program centred on TPACK; it is the lack or possibly the limited degree of education available to educators focused on TPACK will delay the use of any of these strategies. Second, even with successful initial teacher education, also the limited access for educators to up-to-date technology (e.g. augmented and virtual reality) because of limited or no existing infrastructure limits implementation of any of the suggested strategies. Finally, although the use of technology is beneficial for students, a disinterest of technology can be equally harmful in supporting students' development of practical skills.

2.2 Technology Trends in Chemistry Education

Technological development has profoundly altered the manner in which chemistry is taught and learned. The advent of modern teaching tools and technologies such as virtual laboratory simulations, augmented and virtual reality, gaming platforms, artificial intelligence and specific software - has greatly altered the traditional ways of teaching and learning chemistry to make it much more comprehensible and exciting. These technologies allow for the alleviation of many of the challenges we face in learning about chemistry (an abstract field) and the confines of conducting real laboratory activities. In this article, we outline the use of these technologies within chemistry teaching and their advantages.

Virtual Laboratories

Virtual laboratories (VL) provide a valid alternative to traditional practical laboratories in educational sciences and better preparing students for the laboratory settings where they will eventually work. Within this digital environment, the simulated laboratory enables students to investigate science principles by varying and manipulating parameters, viewing outcomes and evaluating data without sacrificing physical space. The Labster platform has interactive modules that represent a wide variety of scientific fields from fundamental chemistry to reaction kinetics with explicit instructions and real-time feedback. An example of this is the virtual acid-base titration lab where students practice pipetting, track the rate of change in pH, and compute concentrations. VL not only reinforces concepts but also develops students' practice related skills that transfer into real laboratory settings. Finally, it is more preferable to use overhead lines for schools that do not have the budget for resources or where safety indicates they should avoid chemicals that can be dangerous, use expensive equipment and equipment set up time. Research has supported the premise that OL augments understanding of educational content. Smetana and Bell (2012) when comparing VL on an understanding of <science -> molecular interactions, reported that students who worked with VL had larger and significant changes in test score than students who worked in a traditional laboratory. OL has limitations. Kobayashi et al. (2021) note that even with the good news of positive cognitive outcomes, OL does not tap into the tactile input and hands-on collaboration found in a face-to-face experimental exploration. It appears the best way to capitalize on the pros of both face-to-face and OL is to use OL as an add-on, not in place of, practical activities.

Augmented and Virtual Reality (AR/VR)

Augmented (AR) and virtual (VR) realities provide new ways to examine chemistry by giving students a fuller understanding of processes. AR applications such as ChemCaper and Elements 4D are transforming smartphones and tablets into spaces for students to visualize molecular structures within the real world. AR is particularly motivating when teaching learners in chemistry topics such as the shape of molecules and hybridization, which are more difficult to teach in traditional ways. Conversely, VR affords an immersive experience by allowing students to be fully immersed in a virtual environment. These platforms, developed in 2020, provide students with the opportunity to examine and explore electron density maps, along with visualizing chemical processes at the molecular level. Specifically, a need exists to create simulations surrounding the interaction of enzymes and substrates in a VR format to allow students to "feel" the binding process and understand how biochemical processes work.

Research supports that AR and VR produce positive learning outcomes. Summary findings indicate that students who use AR show enhanced spatial thinking and improved memorization of information, while students who engage in VR simulations illustrate improved learning of the complex concept of wave functions in quantum chemistry, which are difficult to imagine with conventional images. Despite the potential for using AR and VR in educational practices, its widespread adoption in education is struggling to become commonplace. The costs associated with hardware, software, and training are obstacles to its adoption. Furthermore, some learners have difficulty using VR because of discomfort or nausea when in the environment; therefore, careful consideration needs to be undertaken to include this technology in the learning process.

Gamification

Gamification in education refers to adding game-oriented aspects (score, level, rewards and tasks) into the educational process. Therefore the objective is to enhance the interest and motivation of students. Gamification within chemistry education makes understanding difficult concepts easier and more engaging. An example of Gamification would be the ChemCaper Role Play Game, where students are given educational tasks related to chemical bonds and calculations.

Gamification has wider ranging benefits than motivating learners. Performance on tasks, participation, and learning deeper materials is also promoted. Research has shown that students using gamified chemistry applications in their study efforts retain the material better, exhibit increased interest in chemistry, and actively participate in the learning process, compared to students who learn with traditional methods/tasks. Gamification encourages students to participate actively and collaborative skills are developed, as many gamified applications offer multi-user or team-based tasks. Students can unlock content in an escape room format by solving chemical puzzles and related tasks. These activities provide avenues for knowledge consolidation and promotes critical thinking and teamwork skills.

The balance is important to avoid. If students become focused on game elements for otherwise intrinsic rewards, they may start focusing on readings for "cash" rather than for comprehension. Teachers must be selective in gamification and make certain is serves as an adjunct to, rather than supplant, their learning goals.

Artificial Intelligence (AI)

Artificial intelligence (AI) is revolutionizing the teaching of chemistry, as it has become an effective way to learn on their own. With ChatGPT and other platforms, students can receive nearly immediate answers to their questions, help solving problems, and programming support which is personalized for each student, taking into mind the different ways that students see and comprehend information, as well as knowledge gaps. AI is becoming more effective as a modern educational component. The advantages of AI in chemistry education include:

- Instant Help: AI tools such as ChatGPT analyze student responses, identify errors, and suggest fixes. For example, if a student has difficulty building Lewis structures, the AI can provide specific recommendations.
- Adaptive learning: AI adjusts the complexity of tasks to the student's level of knowledge, helping them master complex topics such as thermodynamics and increase self-confidence (Dos Santos, 2023).
- Round-the-clock access: AI platforms are available at any time of the day, providing reliable resources for self-study, which makes studying chemistry more accessible and flexible.

However, the use of AI in education has its drawbacks. Excessive reliance on AI can negatively affect the development of critical thinking and independent problem solving skills, as students may become accustomed to automated responses. In addition, the accuracy of AI responses depends on the quality of the data entered, so teachers need to teach students how to use these tools effectively.

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 and Miró, 2015). By simplifying 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.

The collaborative online domain offers another benefit to learning as it allows students to work collaboratively with their peers by working as a team that reciprocally interacts. Students are able to complete experiments together; they can share data; they can compare results; and they can conclude as a group. It creates a collaborative spirit and is consistent with modern learning typologies that utilize projects or group engagement.

The use of educational instruments can present considerations for education practitioners. There is a need for instructor training in relation to new teaching instruments. Also importantly, educational software cannot interfere with the curriculum. Other issues also need to be considered such as the access to the tools is limited in schools (due to funding restrictions) and therefore the overall quality of education, as students will not have the same access to support tools.

2.3 Chemistry-Specific Studies

Technological advancements in chemistry education have gained greater focus, which has led to an elevation in interest for this pedagogical method. There is research evidence that, if used effectively, these methods can not only engage students in chemistry lessons but can also improve student conceptual understanding and retention of material. The experiential learning from virtual laboratories, augmented and virtual reality, gaming platforms, and artificial intelligence, regarding the use of these tools to teach chemistry, has shifted the focus for both educators and students. While these technologies, as described previously, are promising, they are also often challenging. This indicates the challenges of moving from notion to implementation. The goal of this article is to analyze some of the existing practical examples on the impact these technologies have on student academic performance, and to reflect on the difficulties educators have when integrating these technologies.

Enhancing Student Outcomes through Technology Integration

Benefits of contemporary technology in chemistry education are limitless and have yielded great benefits in educating students with difficult topics that are often quite abstract. A useful application of technology in education is with virtual labs, which has been shown to provide value by mitigating many of the disadvantages faced by traditional laboratories. Smetana and Bell (2012) provided an example of such an experiment, with a group of high school students who learned about chemical reactions in a virtual environment. Upon comparing these students to students who had access to real laboratories, it was found that the virtual environment students performed better in tests that assessed their understanding of the material. The two researchers identified factors that contributed to improved academic performance: ability to manipulate the parameters of the experiment, ability to observe the outcomes, and the ability to repeat experiment. Augmented reality (AR) applications, such as Elements 4D and

ChemCaper have furthered the level of learning by enabling students to turn complicated ideas into something visual/understandable. A study by Abdinejad and co-authors (2021) assessed the learning of undergraduate students studying molecular interactions with AR applications and found improvement approximating 25% in understanding of the material over students who only studied with traditional textbooks. With AR, students interact with 3D models of real and imagined concepts that provide for deeper learning and allow students to develop better understanding of concepts that are originally abstract and difficult for students. Therefore, AR helps students develop a more meaningful connection of their theoretical knowledge with their perception, allowing for much better learning experiences and making learning more interesting. Similarly, gamified learning platforms have proven to improve learning outcomes both in academic performance and interest in complex topics. For example, Francisco's (2023) study looked at the impact of the AR role playing game ChemCaper, developed to teach chemistry, on the motivation and interest of schoolchildren. The study found that schoolchildren who played the game experienced increased motivation and engagement in their learning process which benefited their results as well. The interactive format of the game facilitated active learning and better learning of difficult concepts.

Improvements in Engagement, Comprehension, and Knowledge Retention

The successful study of chemistry is heavily dependent on student interest. Certain complex and theoretical concepts can leave students feeling disengaged. However, newer technologies such as augmented and virtual reality (VR) have created effective means of maintaining students attention through an interactive learning environment. For example, in a study by Weymouth & Reicher, their study provided students in quantum chemistry with the opportunity to visualize electronic maps, manipulate and collide molecules in 3D, and scan longer distances with no added effort from a location with great accuracy. Using VR the researchers achieved a significant increase in student engagement in the subject. The students not only found VR more interesting, they reported a better understanding of the abstract quantum concepts being taught. Interacting with electronic maps in 3D expanded their engagement and understanding of the content. However, interactive simulations are also improving understanding in science education. Using interactive simulations allows students to complete experiments and observe, in real time, the results of their actions. For example, PhET simulations allow students to study chemical equilibrium by changing concentrations of reagents, applying the stoichiometric calculations and observing the physical changes. For example, research has shown students that studied dynamic equilibrium and studied the empirical observations using interactive simulations achieved a better understanding of the multi-faceted or dynamic nature of equilibrium than students that studied it using a static scheme or understanding the static nature of equilibrium. The students developed a better conceptual understanding of equilibrium because they were able to manipulate the variables and observe the outcomes. The ability to manipulate variables of study and observe the outcomes improves learning and helps with improvement of memorization.

Even virtual labs have proven themselves, with an emphasis to support repeated practice. In a study conducted by Smith & Bell (2012), the researchers found that students working in virtual laboratories can memorize 30% more information about reaction kinetics as compared to students who worked solely in traditional laboratories. This evidence points to the importance of providing subsequent accessible and repeatable “hands-on” opportunities to explore complex material in a chemistry education course.

AI and Gamified Platforms Improving Critical Thinking

In the current setting of chemistry education, we are observing the increasing trends of artificial intelligence (AI) and gaming platforms focused on fostering students' capacity for critical thinking. AI-based platforms such as ChatGPT offer an increasingly individualized learning experience, allowing for personalization by developing students in the way they need to be developed and offering personalized feedback. In the study by Dos Santos (2023), the study concluded that students who have access to AI as a learning tool exhibit superior performance when problem-solving, especially when trying to understand reactions in terms of their mechanisms. They show the best learning performances since the stepwise AI commands help the students master each phase of the process and raise their analytical thinking level.

Furthermore, gaming platforms are prominently contributing to developing critical thinking too. For example, ChemCaper has players solve chemical problems, in a fun and engaging way. Francisco pointed out that student groups involved in games have more developed capacity for critical thinking because they can apply chemistry knowledge in new and unfamiliar scenarios. In gamification, special consideration is given to a class taught in an "Escape room" themed format. Students who experience this type of engagement within the classroom can solve chemical puzzles to "escape" from a virtual or real space. This format also fosters the further development of data analysis skills, the skill in synthesizing information, and teamwork, all of which contributes to the development of higher-level thinking skills.

Challenges in Translating Theory into Practice

Although technology has demonstrated efficacy for teaching chemistry, a commonality will soon become clear: implementation of those technologies in real teaching practice is a considerable challenge. The most significant challenge is digital inequality. The inability to access the newest tools available—particularly for those poor schools unable to pay for the tools and training necessary for student access to technology—presents a huge divide. Students in those schools do not have the same opportunity to explore learning using technology platforms with virtual reality, augmented reality, and virtual laboratories, as students in schools that have reduced inequities. The second major barrier is teacher professional development. Many teachers have little professional training in the effective use of technology in the learning process we need to understand that even if teachers are aware of technology platforms, like Labster and ChemCaper, their comfort, and selling points are detriment to making those tools fit into their lesson plans. Thus, they need to enable the means to have professional development opportunities that not only provide technical skills, but also teaching and learning strategies based on pedagogy; we've seen how TPACK and SAMR frameworks work. The third challenge is finding a balance of hands-on and technology learning. With virtual laboratories and the new AI-based tools acting as a supplemental tool for understanding concepts, those tools cannot stand-in for hands-on learning where collaboration and experience are engaged during real-world experimentation. Research shows that students that have only used virtual laboratories did not have practical experience of using lab equipment or making measurements with accurate instruments.

Finally, an often overlooked downside to overuse of technology is to adhere to fascination with new things. Often when you are working on a project and use AI too often, it becomes easy to eventually only rely automatic solutions and remove independent critical thinking. Gamification, in some cases, can increase engagement, but unless specifically designed for the explicit goal of learning, it can become gamifications call to entertainment culture as a substitute for depth of learning.

2.4 Challenges and Gaps

While the use of technology in chemical education creates enormous potential to improve learning, there are significant challenges to its extensive and viable adoption. The challenges to technology use in chemical education are framed in terms of limited access to technology, lack of adequately qualified teachers, uncertainty over the effects of technology on the promotion of critical thinking, and finding effective ways of incorporating technology into existing curriculum. Addressing these challenges is vitally important in order to fulfill the potential of technology to transform chemical education.

Barriers to Adoption: The Digital Divide

The greatest barrier to extensive use of technology in education is the inequity in access to digital tools and digital resources. This inequity means that, not all students are able to have the same opportunity to use digital tools and resources. Particularly, schools in poor and rural areas often do not have the infrastructure to work with today's technologies such as virtual laboratories, AR and VR tools, or educational platforms that rely on artificial intelligence. The cost of equipment such as VR helmets or AR tablets makes them unaffordable for often cash-strapped school districts. Thus students from these schools are unable to use these new tools that could innovate the quality of their education. Inequity in access also relates to students individually. Some students that are from low-income backgrounds also do not own personal devices (computer, tablets) or have long-term access to reliable Internet access that are critical to be able to use educational technologies. This exacerbates existing differences in opportunities, putting students without access at a disadvantage. As Francisco noted, in schools with sufficient funding, virtual labs and artificial intelligence tools have already changed the approach to learning. However, their impact is limited due to systemic inequalities in resource-poor schools.

To solve this problem, it is necessary to combine the efforts of Governments, educational institutions and private organizations. Financial support for technology programs and investments in school infrastructure are key steps to bridge the digital divide and ensure equal access to technology for all students.

Lack of Teacher Training

The main barrier to the successful implementation of technology in chemical education is the lack of qualified teachers. Many teachers do not have sufficient knowledge both in the technical aspects of modern tools (for example, Labster, ChemCaper, AR/VR) and in the pedagogical principles of their effective use. As noted by Chittleboro (2014), even with access to these technologies, teachers often feel insecure and do not know how to use them in practice. Existing teacher training programs often pay attention to the technologies themselves, but not enough attention is paid to how these tools fit into the learning process and meet educational goals. Just knowing how to use a virtual laboratory is not enough; it is necessary to understand how it promotes learning through research and meets assessment standards, as Dos Santos emphasizes (2023). According to Dos Santos, professional development programs should develop teachers' technical skills as well as the ability to apply TPACK and SAMR approaches in their work.

In addition, the lack of time and the overburdening of teachers with their responsibilities also complicate the situation. It is difficult for teachers to find time to study and experiment with new technologies. Resistance to change caused by skepticism about the effectiveness of digital tools compared to traditional methods is also a problem. To solve these problems, it is necessary to ensure the continuous, focused professional development of teachers, as well as to create support systems that will encourage experimentation and innovation in teaching.

Long-Term Impact on Critical Thinking Skills

Despite the fact that the introduction of technology into the educational process initially increased students' interest and understanding of the material, the long-term impact of this on the ability to think critically is still unclear. Artificial intelligence (AI)-based tools and game applications that offer instant feedback and ready-made solutions can be convenient, but potentially hinder the development of self-analysis and problem solving skills.

Dos Santos (2023) was concerned overall that what students need for chemical study, and professional activity is an authentic experience of critical thought discussions, and that frequent use of automated support applications for common tasks (problem solving, writing reports) may lead to over reliance on such applications and bad problem-solving behaviours, which is not conducive for the development of critical thinking. AI certainly can allow students to quickly and effectively develop a basic understanding of the mechanisms of reactions, yet at the same time deny the potential for them to analyse and explore complex problems through independent thought and analysis.

Gamification as an approach to engaging learners on the other hand also has potential cons. One of these is, similar to AI applications, poorly designed game based tasks have the potential to change the focus from developing a nuanced understanding of the disciplines to completing the tasks to receive rewards. Francisco (2023) noted students in gaming environments appear to be more focused on getting points and badges than learning important features of chemical concepts. To be able to address this issue, thoughtful pedagogical considerations should be followed as we consider the integration of technologies and techniques for learners to reach a learning equilibrium to provide support, and promote autonomous learning. One way teachers can interactively support the use of AI is for teachers to provide a context for learning through the use of the automated assistant, then, as the students begin to show confidence in learning or mastering a skill the teacher can reduce the amount of support feedback to the students and encourage independent thought and actions.

Curriculum Alignment Issues

Another notable problem is the degree to which an educational technology fits in with the curriculum. Most of the educational technologies were developed without any awareness of the educational standards that already exist, presenting problems for us during the educational process. For example, virtual labs and augmented reality could be used to develop some concepts that may not cover everything in the chapter, even though the exam or textbook may only cover these topics in the same chapter (Kobayashi et al., 2021). This can confuse both the teacher and students, ultimately decreasing learning potential when using technology in education. Another complication is that implementing new technology often requires relying on traditional methods of education, and the technology would replace traditional ways purposely or not. For example, in regards to chemistry teaching, the development of practical skills is paramount. The implementation of virtual laboratories required even more thoughtfulness between teacher and student as the latter may miss the chance to apply their knowledge contextualised to real life. Virtual labs are beneficial for the understanding of some concepts, however, they cannot replace the 'feel' of practical research to obtain those practical skills. Waymuth & Reicher (2020) conducted a study that further highlighted the lack of practical skills on behalf of students if learning virtually as opposed to experiential where possible. Perhaps, taking steps to do both is the answer! The last finding that concerns educators is the generalisation of assessments. For instance, many forms use gamification or AI assessment platforms geared towards feedback throughout the learning experience, however they do not usually meet the evaluation requirements for the final assessment. This non-conformity would also discourage educators from using educational technologies because of how difficult it would be to justify using it again during standardised testing as an example.

Limitations in Empirical Research

Constraining technologies’ placement into pre-existing pedagogy is actually really difficult. Many of technology did not consider the curriculum standards, so teachers are left when trying to introduce the technology. In the education technology protocol it’s pretty common that tablets with augmented reality could engage students in a topic that’s not explicitly stated in the text book or national testing. In fact, the first problem is how technology can be added in conjunction with traditional teacher centered pedagogy as a means to aid student learning. In chemistry, physical lab work is critical. When adding virtual labs to a chemistry curriculum it is important to consider whatever practical duties being taught. After students meet the virtual lab, they are not necessarily developing the requisite practical skills. Research has shown students who only studied using virtual reality appeared to have a gap in their practical ability simply because technology stands apart from a physical experiment. It is important to have a blend of experiences in physical and virtual worlds. The next drawback I saw was connecting assessment to technology. Lots of other tools like gamification and AI platforms provide feedback but do not map onto a standard test. This is important because it puts teachers in an awkward situation to justify some technology, even at the expense of student learning and engagement. Even though chemistry teaching technology has received attention and interest, we still lack meaningful ways of measurement. In theory students often seem to be improving with short-term benefits of better grades, improved student interest and rank in chemistry as a subject, but do not combine that with a higher rank on a long-term outcome too. The important thing is while the technology and virtual labs added to developing student theoretical understanding of chemistry, over long periods of time, we do not know if this affected their skill development for an experiment or data analysis.

Most of the research has occurred in schools that have access without considering the realities of teachers and students in schools that relies on public funding and state budget issues. Ignoring the actual features, limits and barriers makes it difficult to decide where technology could exist or be sustainable with increased discussions of successful techniques from institutes and researchers.

Accordingly, more adaptive long term research would provide even further analysis on how technology impacts chemical education. Both various studies and a more robust program of research is needed so we understand how transformative classroom experiences in psychotherapy using technology (AI, augmented reality, virtual reality, gamification) helps students learning outcomes, help them prepare for future life skills and develop their skills as scientists too.

Kazakhstani Researchers on Digital Chemistry Education

1. Enhancing Professional Competence through Digital Technologies

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. The research evaluated a training model, termed simulated learning experience, which consisted of simulation learning, virtual experimentation, and gamification to enhance content knowledge and digital skills. Based on this study, it was shown that pre-'serviced' teachers who apply games, simulation, and other types of digital platforms in their lessons would demonstrate improved lesson development and equity to engage their learners; they were also able to adapt their practice, due to their prior exposure to digital technologies. The study noted the substantial need for universities to advance their programs with digital pedagogical components. This is significant to afford a teaching experience reflective of Kazakhstan's central quest for digitalization; for instance, the 'Digital Kazakhstan' model aims for an education system future-focused on innovation.

2. STEM Approaches and Interdisciplinary Learning

Kusianova et al.'s (2023) article examined advancing students' learning in chemistry classes at the 8th grade level in the country of Kazakhstan using the use of STEM pedagogy. The authors used a mixed-methods methodology which included classroom observations of lesson plans that incorporated STEM, feedback from students, and student achievement. The authors found that STEM facilitates student understanding, motivation, and teamwork efforts in solving chemical problems, and when students combined STEM with technology (like simulation software, coding apps, and data loggers), they had a more meaningful experience in their learning. The authors argue two key takeaways stemmed from the use of STEM-related chemistry lessons when engaging students to apply "real-world" experiences and conducting experiments. For example, students completed a digital project, designing an eco-friendly filtration system, to demonstrate their understanding of chemical reactions, engineering and environmental studies. The authors conclude, in reference to the related literature and evidence in their study, interdisciplinarity in learning is correlated to higher academic performance, and connected to students developing needed knowledge and skills for the 21st century (creativity, digital communication, critical and analytical thinking). They suggest that STEM linked material be introduced into the Kazakhstan national science curriculum and provided teachers with means of innovative learning to engage students with the planned curricular outcomes.

3. Game-Based Learning for Chemistry Education

Game-based learning (GBL) is growing popularity as a strategy for improving student engagement and conceptual understanding of chemistry, as shown by Almesh et al. (2024), who incorporated digital chemistry games at the higher education level to measure pre-service teachers' retention of content, engagement, and creative teaching practices. The authors found that educational games presented opportunities for learners to visualize chemistry concepts, such as periodic trends, atomic structure, and balancing reactions in a more empowering and active way. Students could also challenge themselves and others through points, quizzes, and virtual labs embedded in educational games. Equally important, gamified learning environments fostered more than just individual learning. Much of the work was focused on collaborative learning, encouraging learners to engage in team-based problem-solving and peer discussion, resulting in a deeper understanding of chemistry concepts. These results align with some of the international literature that supports the use of gamification to connect with students negatively affected academically and emotionally by the learning of science. Almesh et al. suggest that teacher training programs should be more supportive of gamified learning and pedagogy, stating that chemistry teachers should be ready to develop and address learning through game-based methods in their practice.

4. Virtual Laboratories and Interactive Simulations

Kazakhstani researchers explored another modern reality: virtual laboratories for chemistry classroom work. In the research led by Karmanova, Madybekova, and Kavak, students used virtual laboratories to simulate experiments for titration, solubility, and chemicals in acid-base experiments. The virtual laboratories were aligned with the Kazakh National Curriculum and pedagogy where the students could manipulate the variable (before their eyes), observe the results, and do the same experiments multiple times safely, efficiently, with time to reflect on what they had done. The investigations showed the use of virtual labs had a most significant effect on students grasp of procedural knowledge and experimental reasoning in comparison to students in non-virtual lab conditions especially for schools where there are no physical laboratories (i.e. small rural schools; under-resourced schools). In the virtual space, students were able to explore their learning independently, go at their own learning pace, work through and come back to challenging concepts, and experience scientific inquiry learning. These researchers considered many aspects of virtual labs for chemistry education including scalability and affordability, especially for rural and underfunded schools in Kazakhstan. The researchers warned however, teacher professional learning that empowers teachers to integrate simulated tools in lesson and assessments. This is a lesson for inclusion of simulated learning and practical work for secondary and tertiary chemistry education in general.

3. Methodology

This chapter describes the methods employed in this research to investigate how technology can be integrated into chemistry education. It will describe the study's design as well as participants, data collection methods, and data analysis methods. The focus of this chapter will be on how students' results and the survey responses were conducted and reported statistically.

3.1 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.

3.2 Participants

The study involved a total of 193 participants, divided into two main groups: students and teachers.

3.2.1 Student Participants

Two student subgroups were involved:

a) Survey Respondents:

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.

b) Experimental Group:

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.

3.2.2 Teacher Participants

A total of 15 chemistry teachers from a range of school types (state and private) participated in the teacher questionnaire. Participants represented varying levels of experience (1 to 25 years) and technological proficiency. This purposive sample was selected to provide expert input into the current status and practical challenges of digital tool integration in chemistry education.

3.3 Data Collection

3.3.1 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?"

Collaboration and Accessibility: Student perceptions of collaborative opportunities and the inclusivity of technology tools are assessed. For example, how effectively does classroom technology enable collaboration with classmates?

3.3.2 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.

1. Digital Tools Used:

   - a. A virtual laboratory simulation platform
   - b. An interactive quiz/game app (e.g., Kahoot, Quizizz)
   - c. Multimedia content (animations and visuals)
2. 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.
3. Additional Observations:
   The classroom teacher recorded notes on student engagement, behavior, and digital interaction during the lesson to support qualitative analysis.

3.3.3 Teacher Questionnaire

A mixed-format questionnaire was developed to gather chemistry teachers' views on technology integration.

1. Section 1: Likert-Scale Questions
   Teachers responded to 12 statements about:
   - a. Frequency of using digital tools (e.g., simulations, videos, apps)
   - b. Effectiveness of tools for different learning objectives
   - c. Confidence and training related to educational technology
   - d. Institutional support and technical barriers
2. Section 2: Open-Ended Questions
   Teachers provided reflections on:
   - a. Their most and least effective digital strategies
   - b. Observed student engagement and improvement
   - c. Main barriers (technical, pedagogical, institutional)
   - d. Suggestions for improving digital integration

The questionnaire was distributed online, and 15 full responses were collected over a two-week period. Participation was voluntary and anonymous.

3.4 Data Analysis

Quantitative Analysis

Quantitative data from both the student survey and the experimental pre/post-test were analyzed using SPSS (version 26).

1. Descriptive statistics (mean, standard deviation, frequency) were used to summarize survey results.

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2. 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.

Qualitative Analysis

Qualitative responses from the open-ended teacher questionnaire and classroom observations were analyzed using thematic coding. Common themes emerged around:

1. Pedagogical strategies using technology
2. Institutional support and infrastructure
3. Student responsiveness to digital formats
4. Professional development needs

Triangulation of qualitative and quantitative findings helped strengthen validity and cross-verify trends.

Ethical Considerations

Before the start of the study, full ethical approval was gained. The participants were made aware of the study's purpose and were fully informed of their rights including the right to withdraw at any time. The data collected was anonymized and stored securely and privately, with access only available to the researchers part of the study team.

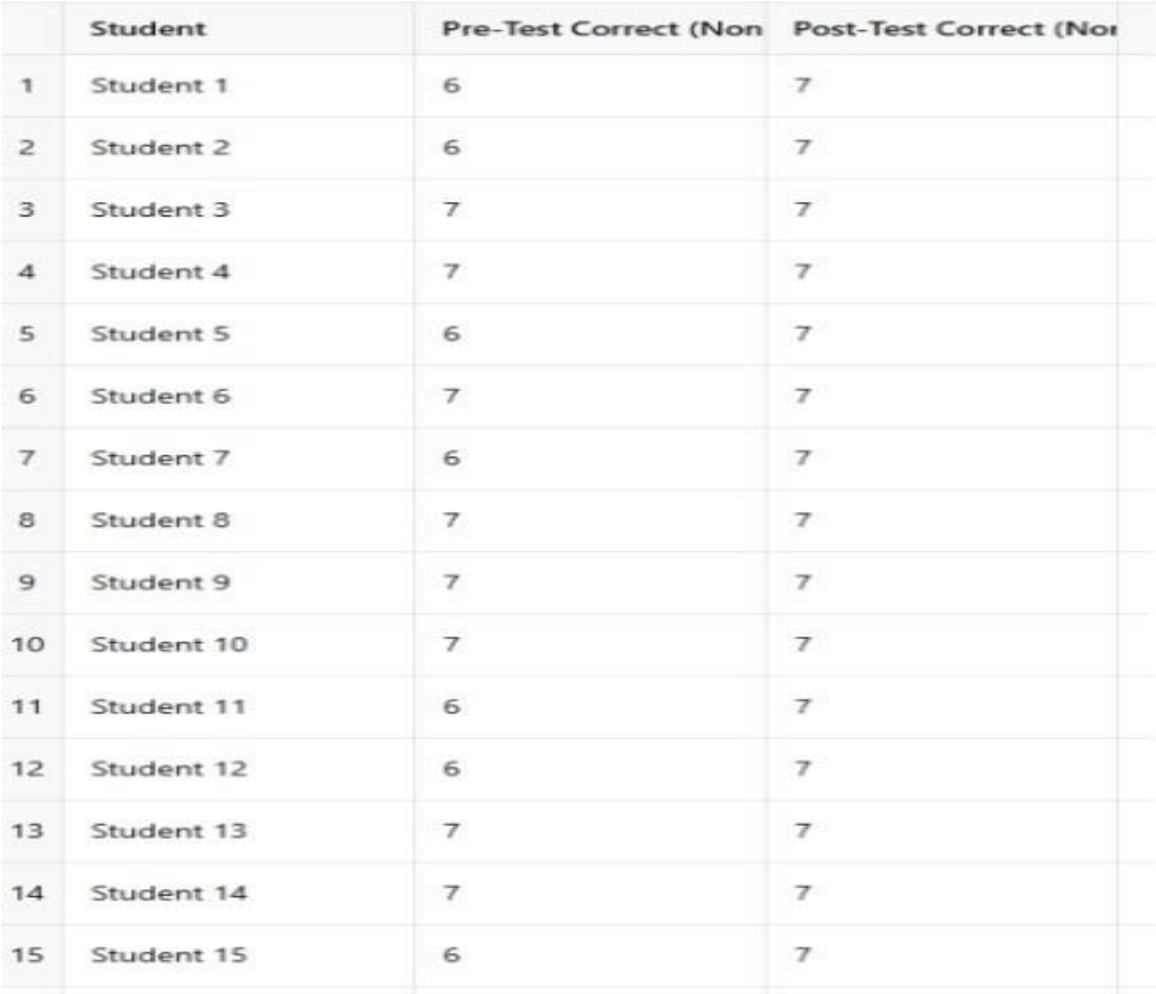
Results

Research Question 1

This 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.

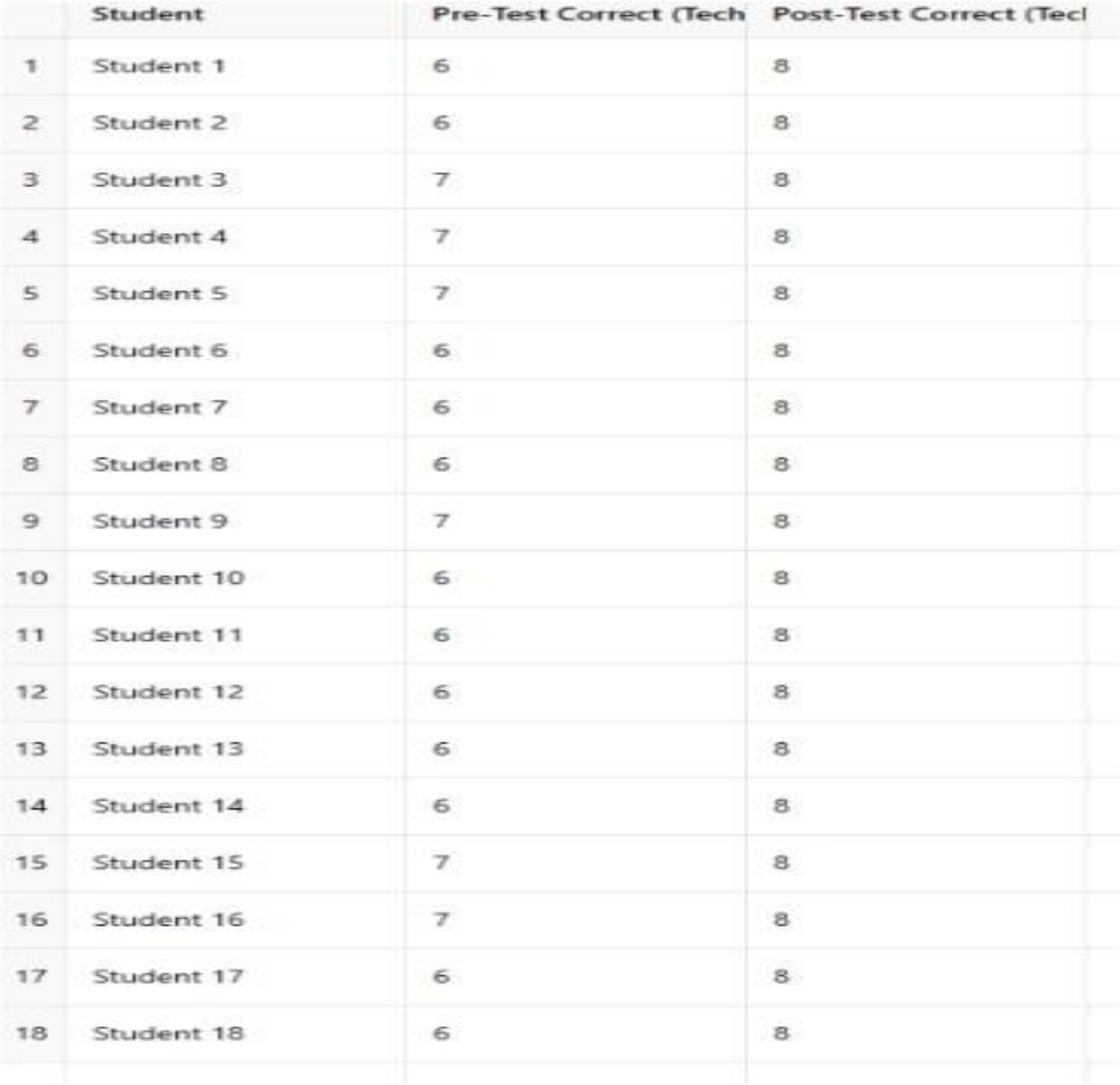
The main source of data came from a pre- and post-test comparison between a control group taught with traditional methods and an experimental group that experienced a lesson enhanced by modern technologies such as augmented reality (AR), virtual labs, simulations, and gamified tools. The results showed 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 traditional method group.



	Student	Pre-Test Correct (Non	Post-Test Correct (Nor
1	Student 1	6	7
2	Student 2	6	7
3	Student 3	7	7
4	Student 4	7	7
5	Student 5	6	7
6	Student 6	7	7
7	Student 7	6	7
8	Student 8	7	7
9	Student 9	7	7
10	Student 10	7	7
11	Student 11	6	7
12	Student 12	6	7
13	Student 13	7	7
14	Student 14	7	7
15	Student 15	6	7

Table 2. Results of pre and post-tests in tech method group.



	Student	Pre-Test Correct (Tech	Post-Test Correct (Tecl
1	Student 1	6	8
2	Student 2	6	8
3	Student 3	7	8
4	Student 4	7	8
5	Student 5	7	8
6	Student 6	6	8
7	Student 7	6	8
8	Student 8	6	8
9	Student 9	7	8
10	Student 10	6	8
11	Student 11	6	8
12	Student 12	6	8
13	Student 13	6	8
14	Student 14	6	8
15	Student 15	7	8
16	Student 16	7	8
17	Student 17	6	8
18	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

Descriptives

	item 1	item 2	item 3	item 4	item 5	item 6	item 7	item 8	item 9	item 10	item 11	item 12	item 13
N	163	163	163	163	163	163	163	163	163	163	163	163	163
Missing	24	24	24	24	24	24	24	24	24	24	24	24	24
Mean	2.47	3.49	3.87	3.67	3.96	3.73	3.73	3.66	3.64	4.00	3.92	3.17	2.45
Median	2	3	4	4	4	4	4	4	4	4	4	3	2
Standard deviation	1.22	1.08	1.11	0.929	0.981	1.30	1.11	1.16	0.954	1.01	0.930	1.50	1.29
Minimum	1	1	1	1	1	1	1	1	1	1	1	1	1
Maximum	5	5	5	5	5	5	5	5	5	5	5	5	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.

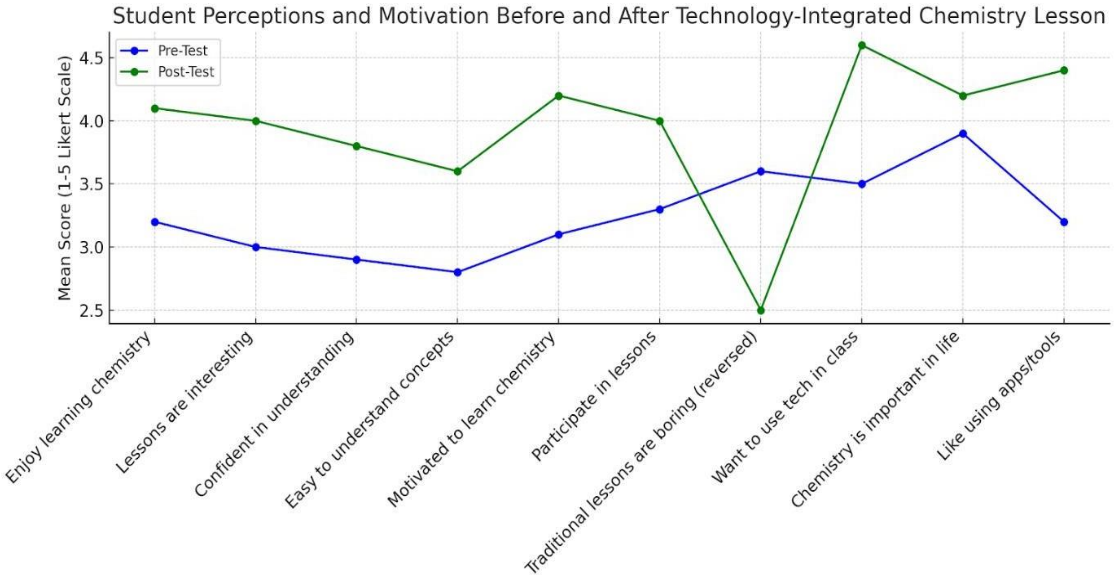


Figure 1. Analysis of Student Questionnaire (A part)

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.

Research Question 2

This research question aimed to explore how chemistry teachers perceive the integration of technology into their teaching practice, including its usefulness, challenges, and frequency of use. To address this, a teacher questionnaire was developed and distributed among 70 chemistry educators working across a range of grade levels (Grades 7–11) and with varying years of experience.

Teacher Profiles and Context

The questionnaire data showed that the sample included teachers with a diverse range of teaching experience: 31.4% had more than 10 years of experience, while 42.9% had less than 7 years, suggesting a balanced distribution between novice and experienced teachers. The majority of participants reported teaching multiple grade levels, with 57.1% teaching Grade 7 and over 40% teaching Grades 10 and 11 (see Figure 2 and Figure 3). This diversity allowed the study to capture a wide perspective on the use of technology across educational stages.

Figure 2. Teacher experience levels

Figure 3. Distribution of teachers by class

Figure 3. Distribution of teachers by class

Perceptions of Technology Use and Effectiveness

The responses to the questionnaire suggest that chemistry teachers generally hold positive views about the role of digital tools in improving student learning and engagement. The most widely used platforms were Kahoot! (70%), PhET simulations (67.1%), BilimLand (60%), and Google Classroom (54.3%), indicating a preference for interactive, gamified, and visual platforms (see Figure 4).

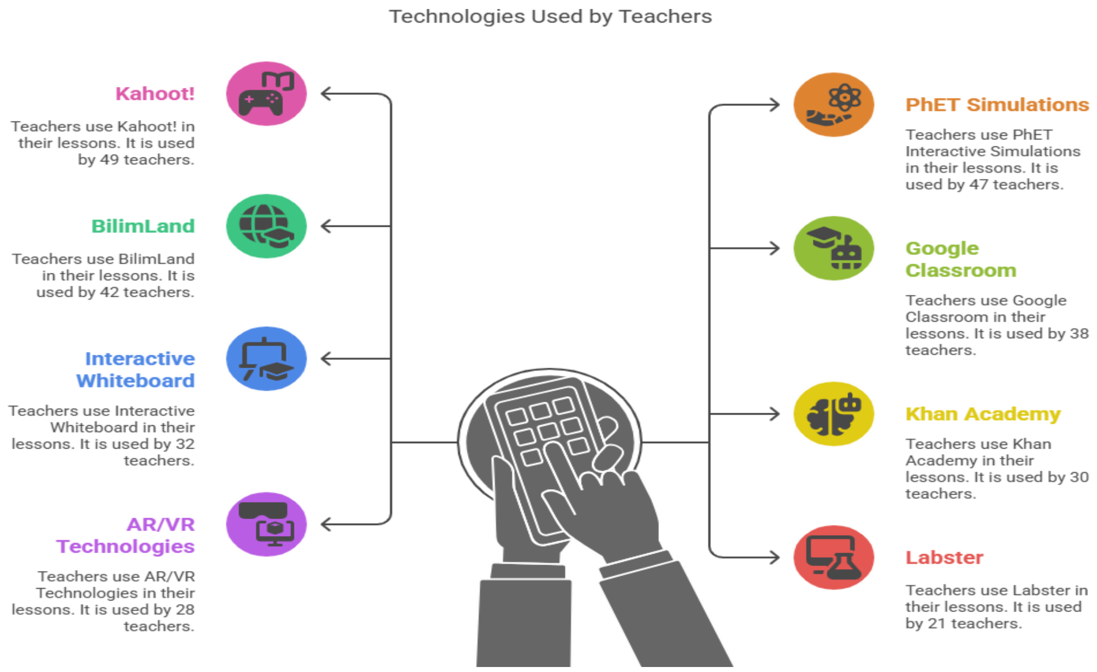


Figure 4. Technologies used by teachers

When asked specifically about virtual labs, 35.7% of teachers reported using them always, and 44.3% sometimes, with 61.4% stating that virtual labs had a strong positive impact on students' understanding of chemical concepts. Additionally, half of the teachers (50%) noted that AR/VR tools greatly increased student engagement, while another 30% observed moderate improvement in interest levels (see Table 9). These results clearly indicate that most educators recognize the value of technology for enhancing conceptual understanding and student motivation.

Table 4. Descriptive Statistics Table

Question	Language	N	Missing	Mean	Median	SD	Minimum	Maximum
Q4. Frequency of virtual lab use	R	120	0	3.2	3.0	1.06	1	5
	K	57	0	3.54	3.0	0.89	1	5
Q5. Effect on chemistry understanding	R	120	0	2.65	3.0	1.04	1	5
	K	57	0	3.12	3.0	1.05	1	5
Q6. AR/VR improves interest	R	120	0	2.61	3.0	1.14	1	5
	K	57	0	2.96	3.0	1.05	1	5

Qualitative comments provided by teachers echoed this positive trend. Many educators highlighted that virtual labs and simulations allow students to explore chemical reactions that would be too dangerous, expensive, or time-consuming to perform in real labs. Others mentioned that the visual nature of AR tools helps students visualize abstract molecular processes.

Challenges and Barriers Faced by Teachers

Despite the overall positive perception, the study also identified several challenges that hinder the effective integration of technology in chemistry instruction. The most commonly cited barriers included:

- Unstable internet access (65.7%)
- Lack of necessary equipment (55.7%)
- Limited time for preparation (45.7%)
- Insufficient technical skills (30%)

Only 10% of teachers reported that they did not face any challenges. These results suggest that while the pedagogical value of digital tools is well understood, infrastructural and professional barriers still exist and limit full implementation. In particular, teachers from rural or underfunded schools noted that they often lacked sufficient devices or experienced frequent connectivity issues, which made technology use unreliable during lessons.

Moreover, some teachers expressed that they felt unprepared to use complex digital platforms, particularly AR/VR tools, due to a lack of professional training opportunities. This points to the need for targeted professional development programs that focus not only on technical training but also on pedagogical strategies for effectively integrating these tools into the chemistry curriculum.

Interpretation and Link to Broader Literature

These findings are in line with previous research that emphasizes the dual reality of technology integration in education: while digital tools can enhance student learning and engagement, their success depends heavily on teachers' readiness and the availability of infrastructure. In the case of chemistry education, where abstract concepts and safety concerns often limit traditional lab activities, the use of simulations and AR/VR offers particularly meaningful alternatives.

However, the challenges identified in this study highlight a need for system-level support, such as improved funding for equipment, better internet infrastructure, and continuous teacher training. Without addressing these barriers, even the most effective tools may fail to reach their full potential in everyday classroom practice.

Research Question 3

This research question aimed to explore the practical and pedagogical challenges that both teachers and students encounter when using technology in chemistry education. While the integration of digital tools offers clear benefits for engagement and conceptual understanding, this study also uncovered several barriers that may limit their full potential in classroom practice.

Student-Reported Challenges

Student responses revealed two key areas of difficulty: limited access to devices and internet, and challenges in navigating digital platforms. As presented in Section 4.1 of the findings, 45% of students reported problems with accessing tablets or computers, particularly in schools with fewer resources. In some cases, students were required to share a single device during the lesson, which hindered active participation. One student noted, "In class, we had to use one tablet. If other students were using it, it was difficult to keep up with the information."

In addition to access-related issues, 17% of students indicated that the complexity of the tools or technical problems distracted them from learning. Students mentioned difficulties using augmented reality applications or virtual lab environments, particularly when these tools were not introduced with sufficient guidance. Although many expressed interest in the technology, they also felt unsure how to use it effectively without teacher assistance.

These findings suggest that students are generally open to learning through digital tools, but require stable infrastructure and adequate onboarding to truly benefit from the technology.

Teacher-Reported Challenges

The teacher questionnaire results, summarized in Section 4.5, reflect a similarly complex picture. While many educators expressed positive attitudes toward using digital tools in their lessons, they also described several obstacles that impacted their ability to implement them effectively. The most frequently mentioned issues included:

- Unstable internet access (65.7%)
- Lack of necessary equipment (55.7%)
- Limited time for preparation or lesson design (45.7%)
- Insufficient digital skills or training (30.0%)

These percentages are also visually represented in the bar chart in Section 4.5, and supported by the descriptive statistics in Table 9. In particular, Question 7 of the teacher questionnaire, which asked about technology-related difficulties, showed a mean score of 2.22 for Russian-speaking teachers and 2.61 for Kazakh-speaking teachers, indicating a moderate level of difficulty overall. Standard deviations of 0.99 and 0.86 show some variability, suggesting that while some teachers were comfortable with digital tools, others faced more consistent challenges.

Table 5. Descriptive Statistics Table

Question	Language	N	Missing	Mean	Median	SD	Minimum	Maximum
Q7. Technology difficulties	R	120	0	2.22	2.0	0.99	1	5
	K	57	0	2.61	3.0	0.86	1	5

Qualitative responses added important depth to these findings. Several teachers mentioned that although they were eager to incorporate simulations or AR/VR into their lessons, they often lacked access to the right devices or sufficient time to plan activities. Others stated that the absence of professional development left them uncertain about how to use the tools to support learning objectives effectively.

Interpreting the Findings: What Can Be Improved

Together, the student and teacher feedback point to four interrelated areas that deserve attention:

1. Access and Infrastructure:

Digital learning cannot thrive without reliable access to technology. For both students and teachers, the availability of devices and stable internet emerged as a fundamental concern. Schools need to ensure that classrooms are equipped with functional, accessible hardware and strong network connectivity.

2. Training and Support:

Teachers need more than just access to tools—they need structured, ongoing opportunities to learn how to use them. This includes both technical guidance (how the tools work) and pedagogical training (how to integrate them into meaningful lessons). Without this, even motivated teachers may struggle to incorporate digital methods consistently.

3. Time and Curriculum Alignment:

Many teachers expressed a lack of time to prepare lessons using technology. This points to a need for curriculum materials that come with pre-developed digital resources, or flexible lesson templates that reduce the planning burden. Administrators and curriculum developers can play an important role in supporting this integration.

4. Student Readiness and Usability of Tools:

Some tools were too complex for students to use independently, especially without prior experience. Developers and school leaders should prioritize platforms that are user-friendly, age-appropriate, and ideally available in the students' native language. Small investments in training—such as introductory tutorials—could make a significant difference.

Broader Implications

These findings echo broader trends in the education field. While the enthusiasm for technology is strong, especially in subjects like chemistry where abstract concepts and experimentation can be supported by simulations and models, the practical realities of implementation can be a limiting factor. Teachers and students alike seem willing to explore digital approaches, but face external constraints that must be addressed at the institutional and policy levels.

It is important to emphasize that motivation is not the problem—both groups are open to innovation. The challenge lies in building the conditions that allow innovation to succeed. With the right infrastructure, support systems, and training, the same tools that now feel difficult or inaccessible could become everyday parts of teaching and learning.

In answering Research Question 3, the study found that key barriers to the use of digital tools in chemistry education include insufficient access to technology, unreliable internet, limited professional training, and time constraints. These challenges were consistently reported across the student and teacher data, and are supported by both descriptive statistics (Table 9) and qualitative reflections in Sections 4.1 and 4.5.

Despite these difficulties, the findings also show that there is a strong foundation for moving forward. With targeted investment in infrastructure, professional development, and the creation of intuitive, curriculum-aligned resources, it is possible to reduce or eliminate these barriers. Doing so will help ensure that technology becomes not just a novelty, but a sustainable and effective part of chemistry education for all learners.

DISCUSSION

Alignment Between Research Questions and Methodology

The research questions in this study were developed to explore different aspects of technology integration in chemistry education. To answer them thoroughly, a mixed-methods approach was used, combining both quantitative and qualitative methods. This allowed for a deeper understanding of how technology affects students' learning, how teachers perceive its use, and what barriers may stand in the way of effective implementation.

Research Question 1:

This question aimed to determine whether technology-enhanced instruction improves students' ability to apply chemistry knowledge meaningfully, and whether these effects differ across grade levels or age groups. To explore this, students participated in a lesson that incorporated virtual simulations, AR/VR tools, gamified platforms, and AI-based applications. Their performance was measured using pre- and post-tests, allowing for the comparison of learning gains in both experimental and control groups

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, M., 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, J. L., & Linn, M. C. (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.

Research Question 2:

This question looks at the teacher's point of view. Since teachers are the ones who plan and deliver lessons, their experiences are essential to understanding how technology is being used in classrooms.To explore this, a teacher questionnaire was distributed. It included both Likert-scale questions (e.g., rating confidence in using digital tools) and open-ended questions (e.g., describing personal experiences). These responses provided both measurable data and more detailed insights into their attitudes, challenges, and successes with using technology.Descriptive statistics were used to analyze the closed questions, while the open responses were examined using basic thematic analysis to identify common themes and patterns.How this

connects to the methodology: The teacher questionnaire allowed for both quantitative and qualitative data collection.
It helped understand not only how often or how confidently teachers use technology, but also how they feel about it and what they've experienced in real classroom settings.
Barak (2017) highlights that teachers' confidence in using digital tools significantly influences their ability to successfully integrate technology into chemistry instruction.Chittleborough (2014) found that teachers often face barriers such as inadequate training and resources, which hinder effective technology integration in the classroom.Lehtola and Karttunen (2022) suggest that teachers' perceptions of the effectiveness of digital tools are crucial for their adoption and success in enhancing student learning.Chiu and Linn (2012) emphasize that proper training and institutional support are essential to overcome barriers and maximize the benefits of technology in science education.

Research Question 3:

This question examined some of the practical barriers that certainly could hamper effective technology use in schools. These include lack of hardware (e.g., devices to use technology), poor (or total lack of) internet connectivity, insufficient training on technology, or limited time in the curriculum to use technology. The open-ended questions in the teacher questionnaire were especially valuable here. Teachers were asked to describe any obstacles to use they had faced, and to share suggested ways of overcoming them. We valued the responses to these questions a lot, as they were read carefully to decipher themes around common issues and possible solutions. In some instances, the student feedback also agreed with the teacher responses, particularly the comments about slow devices, or confusion over some tools they were given to use.
How this fits with the methodology:

1 - Open-ended responses are important as they reflect real, practical barriers from the teachers' views.

2 - Thematic analysis allowed us to bring together and make sense of these challenges.

This section of the study directly gives voice to the teachers and provides helpful information for improved technology use in the future. "Hagos and Andargie (2022) identified that inadequate resources, such as limited access to hardware and poor internet connectivity, are significant barriers to effective technology use in chemistry classrooms.Teachers and students in our study echoed the challenges outlined by Mahbub et al. (2024), including slow devices and insufficient training, which hindered the effective use of technology in teaching and learning."Esselman and Hill (2016) suggested that overcoming these barriers requires targeted professional development and better infrastructural support to ensure sustainable technology integration in education."Belford and Gupta (2019) argue that long-term, systematic studies are crucial for identifying persistent challenges and developing strategies to ensure the sustainability of technology in chemistry education.

Implications

For Teaching Practices

Technology opens the door to many possibilities for improving the way chemistry is taught by allowing a different form of engagement with the learning for students. Tools such as AR/VR allow students to see molecular interactions that can be difficult to visualize in a traditional learning environment, allowing them to experience concepts that would otherwise be difficult to grasp. In contrast, gamification can encourage students to be active participants in solving problems, so they can see how the application of chemistry may be applied to a problem in real-life contexts. While blended learning is the use of interactive and immersive experiences that can enhance student engagement, deeper learning can be achieved through immersion and active involvement.

When combined within a blended learning approach, both experiences (lab and virtual) provide students with both experiences, as they gain the authentic learning experience in a practical experiment, however also access all the interactive and flexible experiences offered by virtual experiences and via AR/VR. Blended learning allows students to enact or experience various concepts, but also allows for the application of theoretical knowledge to real-world contexts.

Teacher training is an important aspect of any initiative for implementing new technology in a classroom context. For professional development programs, the training should focus on enabling teachers to acquire skills to use the technical aspects of the tools but applying the pedagogical practices to incorporate the idea of these tools into their current practice. These claims align with the recommendations of Chittleborough (2014) and specifically, targeted training that develops both the technical aspects of the technology, but also the usage of it in a classroom context.

For Policy Development

Policymakers are key players in ensuring that equitable access to technology is genuine and implemented with the intent of ensuring each student has access and engages with technology. One of the most significant issues in the realm of technology in learning is access because of the digital divide (McMahon 2021), which prohibits schools, particularly those that are underfunded or located in rural places, from providing advanced educational technologies. Therefore, through the provision of affordable devices, improved internet access and quality, and subsidized software for education, the aim is to allow all students to access opportunities to learn through technology, and overcome the challenges that their families' financial status may have provided.

In the future, curriculum frameworks should be revised so that they are specific to the teaching and learning processes that utilize technologies. Perhaps even more importantly, any curriculum framework must ensure that the pedagogies associated with technology do not disconnect the technologies from the educational standards or assessment practices. Doing so diminishes the effectiveness of the technology. Guidelines for integration would provide an opportunity for the use of technology to be an integral component of the learning experience rather than an additional layer to it.

For Developers

Education tool developers should focus on optimizing to create usable interfaces to reduce technical entry points for both students and educators. Many students participating in this study stated that they had difficulties with moving around complicated tools, and even more so, teachers recommended requiring platforms that are more user-friendly. Designing something that is flexible and customizable will not only support the usability increase but could also support scalability adding ability to apply to many contexts of classrooms and learning situations. Additionally, developers should try to ensure tools have wide use across devices, operating systems and levels of access to internet. Ultimately they need to try to reduce more technological access concerns. Ongoing collaboration is important if they are going to work with educators to check on usability and function of their tools to improve student learning by alignment to education needs enacted in classrooms.

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

CONCLUSION

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 first 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.

The second research question examined teachers' experiences and perceptions of technology use in chemistry instruction. The data from the teacher questionnaire indicated that most educators view digital tools positively, especially in terms of student engagement, conceptual understanding, and motivation. Tools such as virtual labs, PhET simulations, and AR/VR were frequently highlighted as effective. However, many teachers also noted a lack of training, time, and pedagogical support, which limited their ability to integrate these tools consistently into their lessons.

The third research question focused on barriers to implementation. Both teacher and student responses identified several recurring challenges: lack of equipment, unstable internet access, insufficient professional development, time constraints, and tool complexity. Students from under-resourced schools often faced difficulties accessing devices, while teachers struggled with aligning digital tools to the curriculum and managing technical difficulties during lessons. These findings underscore the importance of addressing systemic limitations if technology is to be effectively and equitably used in education.

In summary, this research confirms that digital technologies can enhance chemistry education—particularly by supporting engagement, skill development, and knowledge application. However, these benefits can only be fully realized when supported by adequate infrastructure, accessible training, and curriculum-aligned resources.

Personal Reflection

In this study, the researcher explored in-depth pedagogical, technological, and contextual factors involved with teaching chemistry in a digital world. The exploration of integrating new technologies into secondary chemistry education presented important perspectives regarding both the efficacy of these technologies, as well as the practical challenges of incorporating digital resources into legitimate educational pursuits.Exploring technologically-enhanced chemistry instruction made it possible to investigate the opportunities and challenges of these tools, and the researcher was already using a few digital resources in a limited way in their teaching practice that, prior to the research process, hadn't been critically examined in terms of their usefulness in education since minimum education technologies were overall merely perceived as enhancing education. The research process allowed for systematic consideration of how virtual laboratories, augmented and virtual reality, and gamified on-line platforms could intervene in long-standing issues in chemistry education, especially issues related to visualization, abstraction, and motivation, in relation to chemistry education. The study also illuminated some hurdles facing educators in relation to using educational technologies. These hurdles included penalties due to technological limitations (e.g. poor connectivity; poor hardware), pedagogical issues (e.g. confidence, questioned value of some technologies, and alignment with national curriculum), and context-specific barriers. These perspectives and experiences presented in this study are unique to the study and tend to align with perspectives and relevant findings in other studies in this field that offer justification for evidence-based decision making regarding digital integration.During this research, I began to reflect on the importance of education in preparing students for a technology-rich world that is changing at an alarming pace, and specifically thought about Kazakhstan given the scope of educational reform and the tensions in the educational system regarding the need for technology and digital skills. Innovations in chemistry teaching need to make students' learning environments more engaging, accessible, and lined to their lives and their experiences. Overall, the research process revitalized my sense of value and purpose; it was much more than enhancing education with technology, this transitioned into the realm of a paradigm shift in pedagogy for agency, innovation, and ultimately empowerment of both students and educators. The study also presented different perspectives on the importance of collaboration between teachers, researchers, and policymakers, and the important role that educators serve to connect capability with equity of education with technology.

Future Work and Contributions

The findings of the research provide opportunities for future research and developments in chemistry education. One of the most crucial developments would be creating and implementing professional development opportunities. These programs provide interaction among educators to develop their technological pedagogical content knowledge (TPACK) and develop ideas about utilizing tools and artifacts like AR/VR simulations, AI feedback mechanisms, and virtual experimentation platforms. The professional development programs would also need to focus on educators understanding when to be misusing these types of technology and which tools supported that decision, based on their own learning outcomes an approach supported by the educational technology literature. The research findings could also serve as motivation for or forms of the development of a technology-enhanced chemistry curriculum. A new curriculum could consist of lesson plans and digital resources responding to national standards or similar structure. This would help situations where schools may not have physical laboratories and would allow students to develop experimental skills virtually. Additionally, integrating technology into assessments is crucial. This ensures that evaluation methods align with the interactive and inquiry-based approach of contemporary science education.

This work's primary value lies in its commitment to educational equity through technology. Kazakhstan faces significant disparities between urban and rural schools, especially in device access, internet connectivity, and teacher proficiency. Urgently needed are scalable and affordable digital solutions. Collaborations with local EdTech innovators, universities, and international sponsors could accelerate the deployment of accessible educational technologies nationwide. Additionally, fostering teacher communities of practice, both online and offline, can promote enduring peer learning and professional collaboration.

Future research should delve deeper into the long-term effects of technology-enhanced instruction. While many studies, including this one, focus on immediate impacts like engagement and comprehension, the lasting benefits, such as critical thinking, scientific literacy, self-efficacy, and interest in STEM careers, remain largely uncharted. By employing mixed-methods approaches, future investigations can uncover the subtle, enduring influence of these tools on students' development.

Finally, this study provides a foundation for policy making and advocacy. By sharing the findings with school leaders, educational officials, and curriculum developers, the researcher aims to influence the incorporation of evidence-based digital approaches into national education policy. This could bolster Kazakhstan's overarching goals of digital transformation and educational modernization, as outlined in the national 'Digital Kazakhstan' initiative.

In conclusion, this dissertation is more than an academic endeavor. It is a call to action: to infuse chemistry with excitement, inclusivity, and real-world relevance through the transformative power of technology. Yet, this must be done while upholding strong teaching methods, cultural sensitivity, and educational fairness.

Recommendations

Based on the findings and limitations of this study, the following recommendations are proposed for educators, policymakers, developers, and future research:

For Educators

Continuous professional development can boost your confidence to incorporate technology effectively in the classroom. The training should address aspects of how to use a digital tool and how to include it in a lesson. A hybrid approach that encourages the use of virtual labs and simulations, along with traditional experiments, will provide students the best possible learning opportunities and allow them to interact with their learning in many different ways.

For Policymakers

Distribute resources to guarantee equitable access to educational technologies across all schools, notably in schools with limited resources. This involves investing in devices, increasing internet access, and subsidizing digital educational resources. Partner with educators and developers to create inclusive curricula that are technology-integrated, ensuring that technology is aligned with educational standards and assessment.

For Developers

Focus on making tools that are user-friendly and accessible for different learning contexts. With the goal of optimizing accessibility across the technology for the purpose of all student and educator use, ensure you build things with easy to use interfaces, customizability and the ability to work across devices and platforms.

Be sure to build in feedback mechanisms to ensure that design for usability and classroom need are ever evolving. Work with teachers closely throughout the development process to ensure the tools provide the learning outcome and promote productive pedagogy.

For Future Research

Carry out longitudinal studies investigating sustained effects of technology on critical thinking, problem solving, and professional skills. The studies will give important insights into how technology affects learning trajectories across grades and influences career readiness. Investigate educators' attitudes and training to successfully integrate these educational tools. Exploring how teachers' outlook and personal preparation affects their adoption of technology will assist in the development of professional development programs in a more informed fashion.

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Appendices

Appendix 1. Chemistry Survey Questions with Answer Options for Students

School name:
(Open-ended)

Institution type:
a. State school
b. Private school
c. Center

Grade:
a. Grade 7
b. Grade 8
c. Grade 9
d. Grade 10
e. Grade 11

Part 1: Multiple Choice and Likert Scale

How often are technology tools (simulations, digital labs, online resources) integrated into your chemistry lessons?
a. Never
b. Rarely
c. Sometimes
d. Often
e. Always

How do technology-integrated lessons affect your engagement with chemistry topics?
a. I feel less engaged
b. I feel the same level of engagement as traditional lessons
c. I feel more engaged

Technology-integrated chemistry lessons help you improve your critical thinking and problem-solving skills:
a. Strongly disagree (1)
b. Disagree (2)
c. Neutral (3)
d. Agree (4)
e. Strongly agree (5)

How well do you feel you retain information from technology-integrated chemistry lessons compared to traditional lessons?

a. Much worse retention
b. Slightly worse retention
c. The same
d. Slightly better retention
e. Much better retention

How effective are technology-integrated lessons in helping you apply chemistry concepts to real-world scenarios?

a. Not effective at all
b. Not very effective
c. Somewhat effective
d. Very effective
e. Extremely effective

You feel that using technology in chemistry lessons makes complex topics easier to understand:

a. Strongly disagree
b. Disagree
c. Neutral
d. Agree
e. Strongly agree

How often do you collaborate with peers during technology-integrated chemistry lessons?

a. Never
b. Rarely
c. Sometimes
d. Often
e. Always

Do you think technology integration in chemistry lessons has improved your laboratory skills?

a. Strongly disagree
b. Disagree
c. Neutral

d. Agree
e. Strongly agree

How accessible is technology (e.g., devices, internet) for you during chemistry lessons?

a. Not accessible at all
b. Hardly accessible
c. Somewhat accessible
d. Accessible
e. Very accessible

How confident are you in using the technology tools provided during chemistry lessons?

a. Not confident at all
b. Not confident
c. Neutral
d. Confident
e. Very confident

Would you prefer more or less technology integration in future chemistry lessons?

a. Much less
b. Less
c. The same amount
d. More
e. Much more

How well do you think technology-integrated lessons prepare you for the Chemistry exams?

a. Not at all
b. Poorly
c. Somewhat well
d. Well
e. Very well

Part 2: Multiple Selection & Open-ended

What challenges do you face during technology-integrated chemistry lessons? (Select all that apply)

a. Difficulty understanding the technology
b. Technical issues (e.g., slow internet, faulty equipment)

c. Lack of engagement with the content
d. Too much information in a short time
e. No significant challenges

Which technology tools do you find most helpful in understanding chemistry concepts? (Select all that apply)
a. Simulations (e.g., PhET, ChemCollective)
b. Interactive whiteboards
c. Educational videos (e.g., YouTube, Khan Academy)
d. Online quizzes and assessments
e. Digital lab experiments

In what ways do you think the integration of technology in chemistry lessons could be improved
(Open-ended)

Appendix 2. PRE-TEST QUESTIONNAIRE

Topic: Chemical Reactions – Types, Signs, and Energy Changes

Part A – General Questions (Before the Lesson)

Please select the best option for each question:

1. How interested are you in learning chemistry?
    a. Not interested
    b. Slightly interested
    c. Neutral
    d. Interested
    e. Very interested
2. How confident do you feel using digital tools (videos, simulations, etc.) in chemistry?
    a. Not confident
    b. Slightly confident
    c. Neutral
    d. Confident
    e. Very confident
3. How often do your chemistry lessons include digital tools?
    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always
4. Do you think using digital tools will help you understand chemistry better?
    a. Yes
    b. No
    c. Not sure
5. Rate your current understanding of today’s topic (Chemical Reactions)
    a. I don’t know anything
    b. I know a little
    c. I know the basics
    d. I understand it well
    e. I fully understand it

Part B – Content Knowledge Quiz (Before the Lesson)

Choose the correct answer. Only one answer is correct.

6. What is a clear sign that a chemical reaction has occurred?
    - a. Change in shape
    - b. Formation of gas bubbles
    - c. Freezing of water
    - d. Mixing without change
7. What type of reaction is this?

    $$2H_2 + O_2 \rightarrow 2H_2O$$

    - a. Decomposition
    - b. Double replacement
    - c. Synthesis
    - d. Combustion
8. Which statement is always true for chemical reactions?
    - a. Atoms are destroyed
    - b. Heat is always released
    - c. Mass is conserved
    - d. Water is always produced
9. What happens during a decomposition reaction?
    - a. Two substances combine
    - b. A compound breaks into simpler substances
    - c. Ions exchange places
    - d. A metal replaces another metal
10. Which of the following is a chemical change?
    - a. Boiling water
    - b. Cutting wood
    - c. Burning paper
    - d. Melting ice
11. What is the correct word equation for this reaction?

    $$Mg + HCl \rightarrow MgCl_2 + H_2$$

    - a. Magnesium and hydrogen chloride yield magnesium chloride and hydrogen
    - b. Magnesium and water produce salt and gas
    - c. Magnesium oxide and hydrogen form magnesium and chlorine
    - d. Magnesium mixes with hydrochloric acid to make fire
12. What type of chemical reaction is most likely occurring in fireworks?
    - a. Neutralization

    b. Endothermic
    c. Combustion
    d. Decomposition

13. Which of the following does NOT indicate a chemical reaction?
    a. Change in color
    b. Temperature change
    c. Formation of a new substance
    d. Evaporation of water

14. What is the correct balanced chemical equation for the reaction between sodium and chlorine?

    a. $Na + Cl \rightarrow NaCl$

    b. $2Na + Cl_2 \rightarrow 2NaCl$

    c. $Na_2 + Cl \rightarrow 2NaCl$

    d. $Na + 2Cl \rightarrow NaCl_2$

15. In an exothermic reaction:
    a. Energy is absorbed
    b. The products are colder than the reactants
    c. Heat is released into the surroundings
    d. There is no energy change

POST-TEST QUESTIONNAIRE

Topic: Chemical Reactions – Types, Signs, and Energy Changes

Part A – Student Reflection (After the Lesson)

Please select the best option for each question:

1. Did you enjoy the chemistry lesson using digital tools today?
    a. Not at all
    b. A little
    c. Neutral

    d. Yes
    e. Very much
2. Which digital tools did you use during the lesson? (Select all that apply)
    ☐ Simulation
    ☐ AR
    ☐ Online quiz
    ☐ Virtual lab
    ☐ Educational video
3. Did technology help you understand the topic better?
    a. Yes
    b. No
    c. Not sure
4. How confident do you now feel using digital tools in chemistry?
    a. Not confident
    b. Slightly confident
    c. Neutral
    d. Confident
    e. Very confident
5. How would you rate your understanding of Chemical Reactions now?
    a. I still don’t understand
    b. I understand a little
    c. I understand most of it
    d. I understand well
    e. I completely understand
6. What did you like most about today’s lesson? (Open-ended)
7. Any suggestions to improve lessons using technology? (Open-ended)

Part B – Content Knowledge Quiz (After the Lesson)

Same questions as Pre-Test (6–15):

Appendix 3. Teacher Questionnaire

Section A: General Information

1. What is the name of your school? (Open-ended)

2. What type of institution do you work at?
   a) State school
   b) Private school
   c) Educational center

3. What is your teaching experience?
   a) Less than 3 years
   b) 3–5 years
   c) 6–10 years
   d) More than 10 years

4. Have you received any training in educational technologies?
   a) Yes
   b) No

Section B: Technology Integration in Chemistry Teaching

How often do you use digital technologies in your chemistry lessons?
a) Never
b) Rarely
c) Sometimes
d) Often
e) Always

Which of the following digital tools do you use in your teaching? (Choose all that apply)
a) Virtual labs (e.g., PhET)
b) Augmented Reality / Virtual Reality
c) Gamification platforms (e.g., Kahoot, Quizizz)
d) AI tools (e.g., ChatGPT, Socratic)
e) Simulations / animations
f) Other: ______________

What benefits do you observe when using digital technologies in chemistry lessons? (Choose all that apply)

a) Increased student engagement
b) Improved understanding of abstract concepts
c) Better assessment and feedback
d) Time-saving for teacher
e) Other: _____________

What challenges do you face when integrating digital tools? (Choose all that apply)

a) Lack of access to technology
b) Lack of time
c) Lack of training
d) Curriculum constraints
e) Student distraction
f) Other: _____________

Do you think the use of digital technologies enhances students' academic performance?

a) Strongly agree
b) Agree
c) Neutral
d) Disagree
e) Strongly disagree

Would you like to receive further training in using digital tools in science education?

a) Yes
b) No
c) Maybe