The Impact of Artificial Intelligence on Transforming Chemistry Education: Opportunities, Challenges, and Future Directions

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LIST OF ABBREVIATIONS

AI – Artificial Intelligence

AIE – AI in Education

ITS – Intelligent Tutoring System

vLab – Virtual Laboratory

ALPs – Adaptive Learning Platforms

NLP – Natural Language Processing

AR/VR – Augmented/Virtual Reality

TPACK – Technological Pedagogical Content Knowledge

RQ1, RQ2, RQ3 – Research Questions 1, 2, 3

PD – Professional Development

SD – Standard Deviation

M – Mean

N – Number of participants

ANCOVA – Analysis of Covariance

ABSTRACT

This study investigated the impact of Artificial Intelligence (AI) on chemistry education by examining its effects on student learning outcomes and educators' perceptions. A quasi-experimental design was conducted with 80 Grade 10 and 11 students from Kazakhstan schools, comparing AI-integrated instruction with traditional teaching methods. In addition, a survey of 105 chemistry educators explored the opportunities, challenges, and future role of AI in chemistry education. The results showed that students receiving AI-supported instruction achieved significantly higher post-test scores than those in the control groups. Educators reported that AI improved the visualization of abstract chemical concepts, personalized learning, and immediate feedback. However, concerns were raised regarding digital literacy, technological infrastructure, AI-generated inaccuracies, and academic integrity. The findings suggest that AI can significantly enhance chemistry education when supported by appropriate pedagogical strategies, teacher training, and reliable technological resources.

Keywords: *Artificial Intelligence, Chemistry Education, AI-Integrated Instruction, Learning Outcomes, Educational Technology, Kazakhstan.*

АҢДАТПА

Бұл зерттеу жасанды интеллекттің (ЖИ) химияны оқытудағы рөлін және оның оқушылардың оқу жетістіктеріне әсерін зерттеуге бағытталды. Зерттеу Қазақстанның жалпы білім беретін мектебінде оқитын 10 және 11-сыныптардың 80 оқушысы арасында жүргізілген квазиэксперименттік әдіске және 105 химия мұғалімі қатысқан сауалнамаға негізделді. Эксперимент барысында ЖИ қолданылған оқыту мен дәстүрлі оқыту нәтижелері салыстырылды. Нәтижелер ЖИ-мен оқытылған оқушылардың қорытынды тест көрсеткіштері бақылау топтарына қарағанда жоғары болғанын көрсетті. Мұғалімдер ЖИ-дің абстрактілі химиялық ұғымдарды түсіндіруді жеңілдететінін, оқытуды дараландыратынын және жедел кері байланыс беретінін атап өтті. Сонымен қатар цифрлық сауаттылықтың жеткіліксіздігі, техникалық инфрақұрылым мәселелері, ЖИ қателіктері және академиялық адалдыққа қатысты қауіптер негізгі кедергілер ретінде анықталды. Зерттеу нәтижелері ЖИ-ді тиімді пайдалану үшін педагогикалық қолдау, мұғалімдерді даярлау және сенімді технологиялық ресурстар қажет екенін көрсетті.

Түйінді сөздер: *жасанды интеллект, химияны оқыту, білім беру технологиялары, оқу жетістіктері, цифрлық оқыту, Қазақстан.*

АННОТАЦИЯ

Данное исследование посвящено изучению влияния искусственного интеллекта (ИИ) на преподавание химии и учебные достижения учащихся. Исследование основано на квазиэкспериментальном дизайне с участием 80 учащихся 10–11 классов общеобразовательной школы Казахстана, а также на анкетировании 105 преподавателей химии. В ходе эксперимента сравнивались результаты обучения с использованием ИИ и традиционных методов преподавания. Полученные результаты показали, что учащиеся экспериментальных групп продемонстрировали более высокие показатели итогового тестирования по сравнению с контрольными группами. Учителя отметили, что ИИ способствует визуализации абстрактных химических понятий, персонализации обучения и обеспечению оперативной обратной связи. Вместе с тем были выявлены такие проблемы, как недостаточный уровень цифровой грамотности, ограничения технической инфраструктуры, возможные ошибки ИИ и риски для академической добросовестности. Результаты исследования свидетельствуют о том, что эффективное внедрение ИИ требует педагогической поддержки, подготовки учителей и наличия надёжных технологических ресурсов.

Ключевые слова: *искусственный интеллект, химическое образование, образовательные технологии, учебные достижения, цифровое обучение, Казахстан.*

INTRODUCTION

Education systems around the globe are being transformed by rapid global technology growth and digitalization. Incorporation of advanced digital technologies into teaching and learning has become a major catalyst for improving the quality, accessibility and effectiveness of education. Of these advanced digital technologies, one of the most significant accelerators for education innovation is Artificial Intelligence (AI). AI-based products and services are rapidly changing traditional methods of teaching and learning by enabling personalized learning, adaptive learning experiences, intelligent assessments, and data-informed decision making. With this transformation in educational methods and practices comes an immediate need for modern education to rethink how teachers are prepared and how teaching occurs in accordance with the needs of learners in the digital age.

This study will have significance based on multiple interrelated factors. The rapid development and growth of AI technology represent a seismic change to the global landscape of education, creating new opportunities for personalized and adaptive education experiences. AI-enhanced educational methods are becoming more common, allowing the educational system to incorporate AI-based tools, resulting in greater efficiency in instruction and improved student learning; however, many chemistry instructors continue to teach chemistry using traditional methods of instruction and do not utilize AI tools for pedagogical purposes.

In addition to limitations on the use of AI technologies in chemistry education, there are unique challenges associated with the abstraction and complexity of the subject, as well as the complex and symbolic language of chemistry, that create additional challenges for teachers and students in the teaching and learning process. Furthermore, an important component of the teaching and learning of chemistry is the successful completion and execution of laboratory experiments. Factors such as availability of laboratory space, safety concerns, lack of time, and lack of access to laboratory materials will affect teachers' and students' ability to access and complete hands-on laboratory experiments. With respect to these factors, AI-based virtual laboratories and simulations can provide teachers and students with access to safe, flexible, and engaging laboratory settings, which can help to address many of the challenges associated with teaching and learning chemistry; consequently, teachers must be knowledgeable about the pedagogical and technical aspects of using AI in chemistry education to ensure effective use of these technologies.

The ethical, pedagogical and technological issues that result from using AI in education need to be thoroughly investigated. Issues such as privacy of data, academic integrity of students, roles of teachers, and digital competence all need to be settled prior to being able to meaningfully use AI technologies. As such, a thorough investigation into the opportunities, challenges and future of AI in chemistry education is very relevant and urgently needed.

Research Problems

While there is an increasing amount of AI-based educational technology that is available for use, very little empirical and methodological evidence exists regarding how AI is effectively integrated into chemistry education, including at the secondary school and teacher preparation levels. In addition, there is little or no clear pedagogical models or guidelines regarding the use of AI tools in chemistry education for many educational institutions; therefore limiting the potential impact that they will have on improving student learning.

The research problem for this study is the inconsistency of the high potential of AI to make transformational change in chemistry education with the lack of a methodological framework to facilitate effective implementation of AI into chemistry teacher education programs.This research addresses the following questions:

Research Questions

1. How does Artificial Intelligence change chemistry education?

2. What are the key challenges and barriers in implementing AI in chemistry education?

3. What role can AI play in the future of chemistry education?

Study Aim and Objectives: The purpose of this study is to investigate how Artificial Intelligence is transforming Chemistry Education by identifying the potential pedagogical opportunities, challenges, and new possibilities for growth within Chemistry Teacher Education at higher education institutions where English Language is the main mode of delivery. The specific objectives of this study are:

1) To provide an analysis of the theoretical and pedagogical foundations of AI in Education.

2) To analyze what AI technology means for Chemistry Teaching and Learning.

3) To identify specific AI-based tools and methods that have been found to be useful in providing a high-quality education for students seeking to pursue a career in Chemistry Education and Science Education.

4) To develop a model that could be used by Institutions of Higher Education to integrate AI into the preparation of future Chemistry Teachers.

5) To assess what effect AI-enhanced instruction has on the Learning Outcomes of students.

The object of this research is the process of Chemistry Teaching and Learning in secondary and higher education institutions in Kazakhstan. The study concentrates on the use of artificial intelligence technologies as a means of transforming chemistry education and improving student learning outcomes and educator readiness.

Hypothesis.

The research is grounded on the hypothesis that the systematic integration of artificial intelligence technologies into chemistry education will ultimately lead to improved efficacy in teaching (delivery of instruction) and learning (outcomes and success) of students, while developing competencies of future educators, provided that appropriate pedagogical conditions and methodological support for such technologies are established.

To accomplish these two objectives and to test the hypothesis, the study uses a diverse array of research methods including:

1. A theoretical analysis of scientific, pedagogical, and methodological literature.

2. Comparative analysis of international practices in regard to AI-enhanced chemistry education.

3. Empirical methods such as observations, surveys, questionnaires, and interviews.

4. A pedagogical experiment designed to evaluate the efficacy of AI-based instructional methodologies used in chemistry.

5. Various quantitative and qualitative analyses of the data collected from these research methods.

The originality of this research lies within an extensive investigation into the role of artificial intelligence as a transformational element within the field of chemistry education, examined through a quasi-experimental design in Kazakhstani secondary schools combined with a large-scale educator survey. Furthermore, the research proposes a pedagogical framework for integrating AI technologies into chemistry education and identifies particular conditions needed for the effective application of AI within both classroom instruction and teacher professional development. In addition, the research yields evidence-based recommendations on the successful integration of AI methodologies as instructional tools for chemistry education.

The practical value of the research is in its findings and recommendations and their potential use within the practice of secondary and higher education. The findings and recommendations will provide chemistry educators, school administrators, and curriculum developers with evidence-based strategies for improving chemistry education through the use of AI-based technologies. Additionally, the instructional materials and methodological recommendations for incorporating AI tools into chemistry classrooms may be utilized in teacher professional development courses and school-level curriculum planning.

LITERATURE REVIEW

1.1 Artificial Intelligence in Education: Concepts and Definitions

The transformative impact of digital technology on current education has disrupted the way we have taught, learned and assessed in traditional education systems. Artificial Intelligence (AI) is one of the key technologies, due to its abilities to replicate human cognitive processes as well as to manage and process huge amounts of student educational data.

AI is not just an innovative technology; it is a paradigm shift in educational theory and practice (Zhai et al., 2021), in order to examine how AI is transforming the way we teach chemistry and train teachers, we need to explore a foundation of concepts, definitions, and theories related to AI in education in the context of the entire field of education.

While AI is commonly viewed from a technological perspective as being a part of computer science used to develop systems capable of completing tasks that usually require a human, AIE in the education of chemistry students and teachers goes beyond technology. AIE is also an educational tool to support the learning process of students, enhance the instructor's ability to teach effectively, and provide individualised learning experiences for each student by designing instructional content specific to that student, offering feedback specific to that student, and reporting learner behaviour to increase instructional effectiveness. AIE is a term that refers to the use of AI within the learning and teaching of chemistry, and thus the definition of AIE includes the use of intelligent systems to tailor learning experiences for each student by providing feedback based on performance in the student's environment and evaluating learning behaviours for the purpose of providing the most effective learning outcomes (Crompton & Burke, 2023).

The use of AI in education has been driven by several factors, including the complexity of the knowledge being taught; the diversity of the students learning in the classroom; the need for students to learn in a flexible manner; and the desire of students to have a student-centred learning environment. The usual standardized curriculum and teaching methods do not take into account the many different ways that students learn (including how quickly they learn, their thought processes, and what prior knowledge they already have). One way that AI can help reduce these barriers is to create adaptive and personalized learning pathways for each student based on their individual characteristics. From a theoretical standpoint, there is a clear connection between using AI and constructivist theories of learning; in a constructivist model, learners construct their own knowledge through the interactions and experiences that they have with their environment (Bates et al., 2020).

The AI-based educational systems that we are using today will support this philosophy by providing opportunities for learners to actively explore concepts, to test their hypotheses, and to receive immediate feedback through an interactive digital environment. Like a one-on-one tutor would do, intelligent tutoring systems will help identify learner errors and change the way that they teach to suit the needs of individual learners (Kochmar et al., 2022). Also, the theory of cognitive learning is equally connected to the use of AI in education since it deals with how individuals process and recall memories, consider problem-solving techniques, and other information related to the mental processes of learning. AI has the ability to simulate many of the cognitive processes that learners go through in their minds by analysing their response data and predicting where their areas of difficulty will be in the learning process.

Adaptive Learning systems (being a primary use of artificial intelligence in education) are based on learner progress and automatically adjust instructional materials as learners progress (Gligorea et al., 2023). For instance, if a learner is struggling with a specific concept, the system can provide more support, or if a learner demonstrates mastery of a particular learning objective, the adaptive learning system will allow for accelerated learning.

Unlike static digital resources, adaptive systems utilize live data to dynamically respond to learners and present a more effective and efficient instructional environment. By giving chemistry students a more targeted way to work through the complexities of chemical balance, heat transfer and molecular structure, adaptive learning technology helps students to be more supported and successful.

There is also significant transformation occurring within the areas of assessment and feedback due to artificial intelligence. Traditionally, summative assessments have provided little insight into how well a learner understands the material or has processed it while completing the exam. Artificial Intelligence based assessments continually provide formative assessments; this type of assessment analyzes the learner's responses and is designed to identify the specific errors being made while providing the learner with immediate feedback (Lin et al., 2023).

Automated assessment systems can evaluate more than just multiple-choice responses, they also assess the learner's performance against open-ended responses, the actual problem-solving process for a given problem or the overall performance a learner demonstrates while conducting a lab simulation. This move towards formative assessment matches modern-day teaching procedures; this indicates that teachers should see learning as being continuous rather than just being an end result.

One of the most exciting developments in education due to artificial intelligence (AI) has been the creation of virtual / intelligent learning environments for students. The use of virtual laboratories, simulations and immersive digital environments enables students to interact with science concepts in ways that were not previously available when using a real-world laboratory. By using virtual laboratories in chemistry classes, students can complete experiments safely, many times, and with virtually limitless resources (Potkonjak et al., 2016). Furthermore, the use of virtual laboratories allows students to observe the action of a chemical reaction, to change different variables in a chemical experiment while observing the results in real-time, ultimately providing students with a true experiential type of learning environment. The use of AI increases the effectiveness of virtual learning environments by providing intelligent instructional guidance, adaptive instructional feedback and performance metrics for improvement.

The definition of ethical AI in education should be established as a balance of technological advancements with educational values (Crompton & Burke, 2023). Additionally, in order to be successful in the implementation of AI, it is imperative that there are policies outlining how AI will be used in an educational setting, informed consent outlining how AI will be used in an educational setting, and the ongoing analysis of how the use of AI in education is impacting both the teacher and student. When integrating AI into teacher education programs, future educators must not only develop the technical skills necessary to use AI within the confines of their professional careers but also develop ethical awareness and an understanding of the impact that AI will have within all aspects of education to enhance the quality of education available to all students, thereby reducing educational inequities.

Lastly, from the systemic perspective, AI in education will be one of the ways we will be able to develop a new model of education by transforming educational institutions into a new type of educational ecosystem. Through the use of data driven decision making processes, predictive analytics and intelligent management systems, educational institutions can become more efficient with their resources while also providing evidence based insight into student's academic growth and achievement in a significantly less amount of time than was previously possible (Zawacki-Richter et al., 2019). While there are many benefits that will develop through a systemic infusion of artificial intelligence into education, these efficiencies derive from adequate provisions for the establishment of solid infrastructure, sufficient institutional backing, and ongoing professional skill development of educators. Artificial intelligence in education represents a multi-dimensional construct that incorporates components of technological innovation, pedagogical reform, and theoretical progression in relation to teaching and learning (Crompton & Burke, 2023). Examples of the use of artificial intelligence in education include powering individualised learning, adaptive learning environments, intelligent assessments, and immersive learning experiences. However, to be effective, the use of artificial intelligence requires a foundation of learning theory, ethical principles, and best practices from pedagogy. Understanding the many types of artificial intelligence in education as well as their definitions is critical before discussing the impact of artificial intelligence in chemistry education and in designing appropriate teacher training models for chemistry teachers. This theoretical framework will serve as the basis upon which we will evaluate the use of artificial intelligence in education, the methodological approaches employed, and the empirical research findings presented later in the study.

A full understanding of artificial intelligence in education requires an evaluation of the classifications and functional dimensions of artificial intelligence in learning environments. A functional classification of artificial intelligence in education entails categorizing AI-based education tools into four primary functional roles: instructional support, assessment/feedback, learning analytics, and educational management. Each functional role serves to enhance the teaching and learning processes by providing greater capabilities to both students and teachers.

Instructional support systems were among the first and continue to be the most extensively researched uses of artificial intelligence in education. These systems are designed to support student learning through guided instruction, problem-solving activities, and interactive and experiential learning. This type of AI is exemplified by intelligent tutoring systems that demonstrate some of the characteristics of a human tutor by `1` diagnosing a learner's learning difficulties or `2` providing hints to help them and adjusting their instructional strategies. These intelligent tutoring systems are developed based on theories that model the expert knowledge and learner cognition for that AI to dynamically adapt to the learner's individual knowledge and skills per (Kochmar et al., 2022).

Assessment-based AI systems concentrate on the automatic assessment of a learner's learning outcomes and providing feedback. In traditional assessment methods, most assessments include only a summative evaluation of the learner's performance; however, assessment-based AI systems provide a formative assessment to the learner and give continuous feedback to them. The information provided by assessment-based AI systems is based on an analysis of the learner's response patterns or errors, as well as his or her problem-solving strategies. Therefore, by the collection of this information, the assessment-based AI system can produce diagnostic reports for the learner to use in developing his or her learning. This process follows a contemporary view of learning assessments as part of the learning process itself, as opposed to an independent evaluating stage.

Learning analytics is another key area of AI in education. This refers to a systematic and empirical method of collecting, measuring, analysing, and interpreting data about the learner and the learning context (Chen et al., 2020). The innate goal of using AI analytics in education is to identify trends and/or patterns with respect to learner behaviours that may either enhance or impede them from achieving the desired learning outcome (e.g., disengagement from the learning environment or underperformance academically). Learning analytics and the use of AI to analyse large amounts of data from digital learning platforms supports the development of evidence-based pedagogy as educators use this empirical evidence to inform their instructional decision-making.

Lastly, AI is becoming increasingly critical in assisting educational management and institutional decision-making. Intelligent systems are being used more extensively to support many administrative processes, curriculum planning, and quality assurance. Predictive analytics aid colleges and universities to find aspects that shape student success & persistence. In addition to utilizing this technology to guide student learning & performance, the technology can be used to streamline administrative processes. These uses of predictive analytics are not limited to an institutional scope, but rather have broader implications for instructional practice and student learning because they also influence quality of instructional practices, which creates the environment in which educational resources and teaching strategies will be allocated.

AI use in education has brought on new pedagogical frameworks that emphasize personalization, flexibility, and greater responsibility for the learner

(Crompton & Burke, 2024). One of those frameworks is a pedagogy that utilises data to inform teaching strategies and engagement with students, commonly referred to as data-informed pedagogies. Data-informed pedagogy allows instructors to make instructional adjustments (i.e., enhance their teaching strategies) based on current data rather than relying solely on subjective instincts. Data-informed pedagogies enable teachers to make systematic, data-informed decisions and help enhance instructional effectiveness. There are significant implications associated with data-informed pedagogies, including: difficulties in interpreting data, finding a balance between using quantitative & qualitative measures when assessing the quality of instructional practice.

Theoretical considerations surrounding the role of AI relative to the instructional process discuss the important construct of learner agency(s). The concept of learner agency use of AI systems to provide individualized recommendations, track student progress, and give opportunities for self-regulating learning. However, if automation is used excessively, students can feel a loss of control (agency) when making decisions about their own learning because the AI is doing it for them. Therefore, designers of AI-enhanced learning environments need to find a balance between providing guidance and allowing students the ability to choose so they can have meaningful learning experiences.

A major aspect of the theoretical discussions around AI in education includes its ethical implications. There is an established ethical framework that includes four major principles that should apply to the design and use of AI systems in education: transparency, fairness, accountability, and inclusiveness (Kasneci et al., 2023). An important principle is the need for transparency; this means both learners and educators must understand how AI systems work and how decisions are being made with the use of AI systems. The principle of fairness addresses the need to ensure that algorithms do not perpetuate existing biases or inequities. Accountable means that institutions and educators have a responsibility to assess the impact of AI on learning outcomes and student wellness, while inclusiveness focuses on ensuring that AI systems are designed to be accessible and beneficial for all learners, including marginalized populations.

Philosophically, AI in education raises significant questions about the meaning of knowledge, learning, and teaching. More traditional educational models tend to emphasize the transmission of knowledge from the teacher to the student, while AI-enhanced models focus on constructing knowledge through interaction, exploration, and feedback. This is congruent with the ideas of today's learning theorists, who see learning as an active, socially mediated process (Bates et al., 2020), but it also forces educators to rethink their roles and duties as they engage in more technology mediated educational systems.

Within the context of teacher education, understanding the theoretical underpinnings of AI in education serves as a basis for developing teachers' future competencies related to digital pedagogy (Crompton & Burke, 2024). Teachers entering the profession must be able to critically evaluate AI tools, align AI tools with their pedagogical objectives, and integrate AI tools into their teaching in a meaningful way. An effective integration of AI tools requires not only a technical understanding of the workings of the tool but also a pedagogically sound rationale for why the use of the tool is appropriate, as well as an understanding of the ethical implications of the AI tool's use. Thus, teacher preparation programs have a vital role in how institutions can help future educators understand and effectively utilize AI technologies within the educational process.

The theoretical discussion regarding the use of AI technologies in education is a complex and multifaceted issue. There are many different concepts, systems, and applications of AI; therefore, the use of AI technologies affects areas like instructional design, assessment, learner support, and management of educational programs. The integration of AI in education is rooted in established learning theories (cognitive learning theory, constructivism), yet AI technologies also encourage the development of newly-formed pedagogical models. Therefore, having a solid understanding of the concepts of AI is important in order to assess the role of AI in chemistry education and develop effective methods for training future chemistry teachers. This theoretical framework is important because it will provide a framework for ongoing investigation into the application of AI in science education; this will be addressed in subsequent sections of the paper.

1.2 The Role of AI in Science and Chemistry Education

Artificial Intelligence is becoming a much more widespread part of Science Education. In so doing, there has been a shift in the way Scientific Knowledge is taught, learned and assessed. Due to the development of a conceptual understanding, an analytical mindset and the basic understanding of experimentations as well as an application of theoretical knowledge to the real world, the integration of AI into Science Education will open the door to many of the long-standing problems with Science Education (Zhai et al., 2021). Additionally, the development of AI enhances the effectiveness of Instruction, while also allowing Inquiry-Based Learning (IBL) and Personalizing Learning for the Student. Chemistry Education has its own unique perspective on these issues, due in part to the fact that it is comprised of some of the most abstract concepts and uses many symbolic representations and a heavy reliance on experimental practices. Where Science Education has, for many years relied on the direct transmission of Established Scientific Knowledge (ESK) through the Laboratory Development of Practical Skills, there is a growing recognition in the educational field that Science Learning is far more effective when it involves the student's active involvement in their learning and a Change in the Student's Conceptual Understanding, and the Integration of Theory and Practice. Furthermore, the Integration of all of these (3) components are possible because of the emergence of AI and the development of AI Learning Environments (AILE): AI-enabled environments that are Interactively User Friendly and can also be Adaptive to the Student's Individual User Style are now available to help provide science students with an enjoyable, challenging and fulfilling learning experience. Additionally, with the current technological advances in the area of Simulation Technology, Data Analysis Tools and Intelligent Feedback Systems, AI Learning Environments will allow for Science Learning to become a process of Active Knowledge Construction rather than a Passive Knowledge Acquisition process where Students just receive knowledge after completing an experiment.

One of the most significant uses of AI in Science Education will be to support students in developing their skills in the use of Inquiry-Based Learning and Problem-Based Learning. Inquiry-Based Learning promotes students' ability to develop a question, develop an appropriate experimental design, develop methods of data collection and analyze their collected data; all of which mirror the processes of Scientific Investigation. AI Learning Environments can assist with these processes by guiding the Student through Inquiry Cycles, providing the Student with Prompts and Hints and Adapting the Difficulty Level of the Inquiry to the Student's Knowledge Level (Popenici & Kerr, 2017). Environments based on learning through exploration and experience have been shown to align with experiential and constructivist learning theories. Chemistry education has specific pedagogical challenges that require the use of Artificial Intelligence (AI) in order to effectively teach all students; many of the chemical concepts that employ the pedagogical challenges are unable to be seen directly. The concepts within chemistry include atomic structure, molecular interactions, reaction mechanisms, and thermodynamic processes, and all of the concepts within chemistry must be taught across several levels of representation: macroscopic; microscopic; and symbolic. There are often many misapprehensions in the links between levels of representation and students do not have a complete understanding of the concepts being taught in chemistry. The use of AI in visualisation tools, and simulations to create dynamic representations of molecular processes and chemical reactions, will allow for a clearer conceptual understanding of the concepts being studied.

Another major application of AI in chemistry education is the use of virtual laboratories (vLab) to conduct chemistry experiments. While the traditional laboratory approach to teach students chemistry is extremely valuable, the resources, safety issues, time concerns, and accessibility challenges associated with traditional laboratory instruction limits its effectiveness in teaching chemistry to all students. Students are able to perform experiments using vLab, and are provided with simulated experiments without experimentation risks (Chan et al., 2021). Virtual laboratories allow students to observe in real-time the effects of their experimental design modifications on the outcome of the experiment and assist with developing students' scientific reasoning skills. Virtual laboratories utilise AI to enhance the students' learning by providing intelligent assistance to students during experiments; AI also allows for the real-time correction of errors and adaptive feedback based on students' actions.

AI also has an essential role in personalising the learning experiences to better align students with the chemistry content being taught. In many instances, classrooms teaching chemistry include students who have very different backgrounds, prior knowledge and learning style preferences. The use of traditional instructional techniques is often ineffective in addressing these differences, leading to equitable knowledge from the students within the chemistry syllabus. Adaptive learning systems that utilize artificial intelligence (AI) offer learners the chance to personalize their learning experiences. Adaptive learning systems evaluate and use a learner's performance data to help identify strengths, weaknesses, and misconceptions and improve upon them through suitable changes in instructional content. Furthermore, the learner can create a personalized pathway for learning that provides the opportunity to learn at their own pace or work on areas of learning that require additional assistance; ultimately, this will help learners learn with more efficiency and motivation (Gligorea et al., 2023).

Significantly, AI has altered the way we assess student learning in the fields of science and chemistry. Traditional assessment methods tend to focus solely on the factual recall and procedural knowledge of the learner with limited insight into the learner's conceptual understanding of the material, as well as their problem-solving process. On the other hand, AI-based assessment tools provide a greater opportunity for total assessment through the use of examining student reasoning patterns, response strategies, and experimental decision-making in creating an overall perspective of the learner as a scientist. With AI's use of automated formative assessment, feedback is provided to the learner in an immediate manner, which will support their ongoing learning while they are still learning; whereas, traditional assessment provides information about student learning at the end of the learning process. Consequently, the use of computerized assessments is consistent with contemporary assessment philosophy, which emphasizes assessment for learning, versus assessment of learning.

Additionally, the use of AI in the learning process promotes the development of scientific thinking skills and higher-order cognitive skills (Lin et al., 2023). Through the use of AI intelligent tutoring systems and adaptive problem-solving platforms, learners conduct hypothesis testing, data analysis, and critical thinking skills, as well as engage in other activities associated with scientific thinking. AI-enabled systems present students with authentic, complex problems that require the use of multiple concepts and skills, in order to enhance the depth of the student's learning experience. In the area of chemistry education, AI systems support student work on stoichiometry, reaction mechanisms, and equilibrium problems by providing step-by-step directions/support/feedback to the learner as they develop their knowledge base of the material.

Finally, AI also promotes interdisciplinary learning and STEM (i.e., Science, Technology, Engineering, and Mathematics) approaches within the context of all of science education (Ramos & Condotta, 2024). The application of AI-based systems can help students to understand real-life scientific issues that need an integrated approach, such as the environment, energy systems and materials science. The centrality of chemistry means that in these situations, as well as enhancing the learning environment of students in terms of connecting chemistry to technology and society, AI-based learning environments will be able to connect chemical principles to technological and social applications in order to meet 21st-century educational demands - preparing students for complex, unstructured, real-world situations.

The use of AI in chemistry education is not limited to supporting student learning; it also includes providing resources for teachers and professional development. Specifically, AI-based analytics tools provide educators with information about their students' learning outcomes, misconceptions and levels of engagement (Zawacki-Richter et al., 2019). As a result, teachers can use this information to make better instructional choices and tailor their teaching methods to address their students' needs. In teacher preparation programs, chemistry teachers can also utilize AI tools to evaluate lesson effectiveness and reflect on instructional practice as part of building data-based pedagogy skills in order to create reflective educators capable of using technology effectively in their teaching.

Applications of AI (artificial intelligence) have the potential to change how science, specifically chemistry, is taught and learned by creating significant pedagogical and ethical issues for consideration. While the benefit of enhancing hands-on experiments and peer interactions by maximizing the use of technology has great potential, over-reliance on technology could limit these opportunities, especially if technology cannot be integrated properly. More generally, the educational theory literature demonstrates there must be a balance between technology tools and authentic laboratory learning contexts or collaborative learning processes (Schiff, 2021). As a result, AI should be regarded as a supplemental source of support to the traditional pedagogical practice, not as a substitution for those practices.

Ethical issues surrounding the use of AI in science education are closely related to the values of data privacy, algorithmic bias, and transparency. AI uses large amounts of data to develop many features that relate to how students learn; therefore, educators must consider the risks associated with the collection of consented privacy data, data security, and data misuses. AI algorithms can also be biased based on the information contained in their training data, which influences results of critical assessments and recommendations for future learning. Therefore, institutions must develop ethical guides, establish ethical guidelines within their policies, and provide educators and students with critical digital literacy skills related to ethical uses of technology.

From a theoretical perspective, AI in science and chemistry education can be viewed as part of the learner-centered pedagogical shift toward data-informed and technology-enhanced practices. AI supports the learning theories of active learning, personalizing of education, and ongoing feedback to students and teachers while also challenging teachers to re-examine their traditional roles in instructional design and delivery. As a result, the role of a teacher has changed from a sole transmitter of knowledge to a facilitator of learning environments. Therefore, the implications of this change for chemistry teacher preparation programs must provide the necessary experiences for future educators who will manage a technologically enhanced classroom in complexity.

To support the effective integration of AI in chemistry education, a connection must be established between the technological capacities of AI tools, educational objectives and expectations, and curriculum standards. To accomplish this, AI tools need to be purposefully selected and designed to facilitate learning, support inquiry learning, and develop ethically responsible citizens. Theoretical models of technology integration emphasize the importance of pedagogical content knowledge and highlight that the use of technology in education must be firmly rooted in an in-depth understanding of both content and the best pedagogical strategies for instruction. For teachers of chemistry, this mandates understanding how AI helps visualize abstract concepts, develop laboratory skills, and assess scientific reasoning skills of students.

AI is playing increasingly diverse and powerful roles in the teaching and learning of science and chemistry. By facilitating inquiry-based learning, adapting assessments, personalizing, and assisting in the development of higher-order cognitive processes in learners, AI has the capability to help teachers of chemistry with the challenge created by abstractness of chemistry concepts, experiments, and diversity among learners. Thus, the successful integration of AI into science and chemistry education relies on theoretical models of technology integration, attention to ethical considerations, and teacher professional development opportunities that assist in integrating AI into the teaching and learning process. A fundamental basis for thinking through methodological, theoretical, and empirical examples of how AI is being implemented in science and chemistry education in the following sections will be developed through understanding the role of AI in science and chemistry education.

1.3 Pedagogical Theories Supporting AI-Enhanced Chemistry Teaching

Teaching chemistry with AI is not just about the computers but also has a long history of associating pedagogical theories and practices from the past as well as those of today. The extent to which the technologies associated with chemistry enhance the learning experience will depend on whether or not the intelligent technologies are consistent with well-established philosophies related to education and learning are being used. Knowing about pedagogical principles related to chemistry and how those relate to the integration of AI will help provide meaningful, effective and ethically responsible instruction. Constructivist Learning Theory is one of the most well-known pedagogies that can be systematically linked to AI-enhanced chemistry education (Bates et al., 2020). Constructivism holds that learners create knowledge by interacting with their physical surroundings rather than receiving it passively through the instruction of the teacher. When considering chemistry education in particular, this construct is critical because of how abstract or conceptual chemical knowledge can be. Interactive simulations and virtual laboratories provide AI-based learners with the opportunity to explore the chemical world and manipulates different variables while testing hypotheses through investigation. When learners have access to these types of experiences, they are able to develop a mental image or model of a chemical process and create a more sophisticated conceptual understanding of that process.

Scaffolding theory, based on Vygotsky's idea of the zone of proximal development, is very important for AI to enhance chemistry instruction. Scaffolding is the temporary support provided to learners that allows them to do tasks or activities they cannot do on their own. AI provides learners with dynamic, adaptive scaffolding by adjusting the amount of scaffolding they need based on their performance level (e.g., if the students require more help or if they can do it independently).

Areas of scaffolding that can be enhanced through AI in chemistry are examples include hints for balancing chemical equations, guidance and feedback on experimental procedures, and interpreting chemical reactions.

As learners become more competent, AI offers progressively less scaffolding, providing autonomy and mastery.

Personalized learning theory provides additional justification for AI enhancing chemistry instruction (Gligorea et al., 2023). These theories promote and endorse tailoring instruction according to the individual needs, capabilities, and learning trajectory. Personalized learning theory states that tailoring instruction improves the efficiency of learning and increases a learner's motivation. AI provides large-scale personalization by analysis of the learner data sets and adapting the instructional content accordingly.

In chemistry instruction, students have a wide range of backgrounds in terms of the level of prior knowledge and level of understanding of concepts. Adaptive learning through the use of AI in chemistry instruction will allow each learner to receive the appropriate amount of challenge and support. Therefore, aligning with personalization learning theory ultimately will enhance both the efficiency of learning and the motivation of learners.

Self-regulated learning also is critical in connection to AI enhancing chemistry educational practice. Self-regulated learning is the process of planning, monitoring, and reflecting or evaluating one's own learning. Tools that use Artificial Intelligence (AI) promote self-regulation by giving summaries of a learner's progress and providing analytics about the learner's performance and reflection on how they are doing. These tools allow learners to determine where they need to work harder and to provide them with a means to establish learning goals and modify their methods based on what they have done up to that point. In chemistry education where consistent practices and understanding concepts are critical to success, nurturing self-regulated learning will support long-term academic success. To analyse AI-enhanced chemistry education from a larger instructional viewpoint, connectivism illustrates how AI functions in a digitally mediated learning environment (Popenici & Kerr, 2017). Connectivism states that learning consists of creating networks by connecting new ideas, people and technology. The connectivist approach has pertained to chemistry in that learners have been connected to technological resources through digital lessons, simulations, databases, and expert systems that provide them with the ability to connect knowledge through many different mediums. Knowledge is found in many locations; therefore, learners must know how to continue to find knowledge and how to access and appropriately use these resources. This perspective in relation to 21st Century education is critical to being able to access current information and to continue to interact with that information through digital tools or technologies. Models for integrating technology provide a solid theoretical background for AI-enhanced chemistry instruction. One example of an integration model is the TPACK (technological pedagogical-content knowledge) framework developed by Mishra & Koehler (2006). In the TPACK framework, technology, pedagogy, and content knowledge must be integrated and aligned. In order for teachers to use AI appropriately in the classroom, they must understand how to utilize AI, but also how this relates to the content being taught in science classes, along with the teaching methods employed for delivering that content. The TPACK framework demonstrates the importance of teacher pre-service training (classical education) and professional development (current methods of delivering information and continuing to learn), in creating meaningful integration of any technology.

Although there is much theoretical support for enhancing the teaching of chemistry with AI, it is necessary to acknowledge potential pedagogical challenges associated with AI (Schiff, 2021). One issue is that student learning may become an algorithmic process designed to maximize efficiency rather than depth of thought and reflection. Educational theorists state that for students to achieve truly meaningful learning, they must develop critical thinking skills, creativity and have a social component to the learning process, which can not be automated. For this reason, AI should become part of an overall pedagogy that incorporates all aspects of teaching and learning.

Ethical pedagogy is important for directing how AI will be used in chemistry instruction. Ethical pedagogy supports relatively equitable, inclusive and respectful to the students' (learners') autonomy. AI-enhanced pedagogy must ensure technological tools do not discriminate against some groups of students or perpetuate existing inequality in the classroom. Teacher education programs must include ethical pedagogy instruction so that future chemistry teachers will know how to critically evaluate AI tools and use them ethically.

The use of artificial intelligence in chemistry instruction is supported through many different pedagogical theories; these include constructivist pedagogy, inquiry based learning, cognitive learning theory, experiential learning, personalized learning and self-regulated learning. Through understanding how to provide active engagement in learning, enhance conceptual knowledge and foster learner autonomy, these theories provide frameworks that support the use of AI in chemistry instruction. However, in order to be effective when using AI to teach chemistry, well-designed pedagogy, ethical understanding and well prepared teachers are necessary requirements (Roll & Wylie, 2016). This theoretical framework provides the basis for the methodologies and empirical studies discussed in the following chapters of the project.

1.4 Global Experience of AI Integration in Chemistry Education

Historically, the integration of AI into chemistry education occurred as a response to the overall digitalization and innovation of education. In the past 20 years, educational systems around the world have turned to AI-enabled technologies as a means of enhancing science education, improving student success and meeting on-going challenges of access to personalized and effective learning environments

(Zhai et al., 2021). Internationally, AI now plays an integral role in contemporary chemistry education and has thus impacted curriculum content, instructional strategies, assessment methodologies, and teacher development.

In countries where advanced educational technology has been adopted, such as the US, UK and Canada as well as some European nations, AI has been used extensively in chemistry education using intelligent tutoring systems, adaptive learning platforms and virtual laboratory environments. However, these tools also exist within larger digital learning ecosystems supported by government initiatives that encourage education innovation. Development of AI based platforms by higher education organizations has also provided undergraduate chemistry programs with personalized practice opportunities, automated feedback on the student's assignment and fit-for-purpose performance data (Zawacki-Richter et al., 2019).

AI was developed in part from collaborations between educational institutions, technology companies and research entities that have played a significant role in advancing the use of AI within the field of education. Chemistry and science education programs across the US use AI techniques in both introductory and advanced chemistry classroom instruction, however, use of AI in that context is commonly more prevalent in large enrollment classes where traditional methods do not readily lend themselves to individualizing instruction. The intelligent tutoring systems created under the guidelines of this initiative focus on helping students develop problem-solving skills and understand concepts in their area of study, as well as providing them with diagnostics feedback to help them identify and solve their own misunderstandings of stoichiometry, chemical kinetics and thermodynamics. The integration of artificial intelligence in chemistry education in the UK and other European countries has been closely related to an innovation in pedagogy and a reform of current chemistry curricula. Inquiry-based learning, digital experimentation and formative assessment are key components of these new curricula. There are more instances of using virtual laboratories and simulation-based learning environments in place of traditional laboratory instruction, therefore augmenting chemistry educational approaches. Secondary and post secondary school students are leveraging these technologies to visualize molecular structures and reaction mechanisms, and measure energy losses or gains through multiple representations. AI-enhanced analytics will assist all chemistry teachers in a manner by providing AI-based insights to monitor learners' performance and level of engagement (Chen et al., 2020).

Asian countries such as China, South Korea, Singapore, and Japan have greatly invested into artificial intelligence (AI) to improve student learning in chemistry. AI-based implementation is being adopted through national strategic initiatives to advance technology competencies and prepare learners for a highly defined technology economy. Moreover, chemistry education is increasingly incorporating adaptive learning platforms and intelligent assessment systems to ensure high academic standards and promote individualized learning among students. AI-based assessment systems are used by teachers to assess how students learn using innovative assessment methods; thus, AI can predict and recommend assistance for each of the students who need support to improve their overall learning efficiency (Dempere et al., 2023). For example, China has integrated artificial intelligence into chemistry education through large-scale digital platforms that promote adaptive learning, automated assessment and learning analytics. These digital platforms are used to provide students with the tools they need to prepare for exams and to develop an AI-driven educational delivery model that stresses data-informed education and personalization at large scales. Researchers point out that while others stress data-informed education through extensive personalization of data, they also value maintaining high standards of educational value and relying on automation alone is not sufficient.

Countries that are developing or emerging into the global marketplace have unique circumstances regarding the integration of AI into their chemistry teaching experiences, particularly due to resources needed for the successful development of effective chemistry programs; this is especially true when it comes to ensuring equality of access to quality education. By using virtual laboratories and AI learning platforms in chemistry, there are ways to provide solutions to the limitations inherent in the lab setting, laboratory equipment access, and teacher shortages in many developing countries (Salas-Pilco & Yang, 2022). International collaboration on many of these types of projects has shown that when thoughtfully integrated into education systems, digital technologies can enhance the potential for equity in education through the implementation of AI-Enhanced Chemistry Education.

An important aspect of the global experience with integrating AI into education relates to the authorities and international standards associated with its use within educational systems. Many international organizations such as UNESCO, OECD, and the European Commission have released recommendations and guidelines on the use of AI in educational environments (UNESCO, 2023). They have focused these recommendations and guidelines on issues of ethics, equity (inclusive practices), and empowering teachers to utilize technology in the teaching and learning process. In turn, these international organizations are influential regarding the establishment of national policies and institutional strategies for the use of AI technologies; examples of this are the recognition of the essential need for the use of AI technologies in the field of STEM education, and particularly for the successful integration of AI-enhanced education into chemistry programs.

There has also been an increasing emphasis on improving teachers' professional development and teachers' pre-service education with respect to AI-related topics and integrating the use of AI into their instructional practice and doing so depends on teachers' ability to effectively and critically use technology. Increasingly, aspects of digital pedagogy, data literacy, and awareness of AI are being included in teacher training programs, which often use AI-based tools directly in teacher preparation to promote reflective teaching practice, lesson evaluation, and instructional design (Crompton & Burke, 2024).

International experiences have demonstrated the added benefits of using AI in chemistry programs, including increased learner engagement, motivation, and ability to self-direct their own learning. Students interact with content that is adaptive, personalized, and immersive, receiving immediate feedback on their learning that encourages them to explore, reflect, and achieve a deeper understanding of concepts. The global practice examples presented here demonstrate how AI can support meaningful change in chemistry education, creating inclusive, personalized, and evidence-based learning experiences for students, while also preparing chemistry educators to effectively employ technology-enhanced instructional strategies. This underscores the need for teacher education programs to consider the careful and appropriate integration of AI, preparing educators to fully leverage its potential as a pedagogical tool (Kuleto et al., 2021).

While many global contexts report positive impacts from AI application in chemistry education, global experiences have also identified various issues that challenge its integration into chemistry education. One issue with the integration of new technologies in chemistry education is the varying levels of access to digital infrastructure and technological resources, impacting access to AI-infused teaching and learning environments. Additionally, teachers' readiness and confidence to adopt AI tools as instructional aids has also become a challenge. Teachers who are not properly trained and supported may have difficulty integrating technology into their instructional practice in a way that is meaningful. Ethical issues have also become an increasingly significant part of the global discourse surrounding the use of artificial intelligence in education. As across numerous educational systems around the world, there is a greater emphasis on ethical issues with data protection, algorithmic transparency, fairness, and accountability. AI systems use several types of student data (like academic performance, behavioural patterns and interactions) and most of it will support improving student outcomes in academia and providing students customised learning opportunities. However, ethical questions arise surrounding who will access this data, how this data will be used after it is accessed and whether the privacy of students will be protected.

Additionally, addressing ethical issues from international evidence is an extremely complex issue and will require that effective AI regulation occur at the national and institutional levels with the development of regulatory guidelines for each AI application and clear definitions for both AI and how AI is regulated (including consent, data security and anonymised data) to ensure the ongoing responsible use of AI systems through established monitoring mechanisms at each institution to monitor the activities of AI users (i.e. educational and technological providers), who have created ethical standards for their use of AI. Further, educators and administrators must receive continual professional development so they are equipped to review and assess their use of AI systems ethically, equitably and responsively.

Chemistry education presents a situation where ethical issues related to AI are important. There are many components of chemistry education (such as laboratory simulations, interactive technology for solving problems and tracking student performance) which produce a significant amount of measurable data on students. Therefore the appropriate ethical standards need to be in place to ensure that the data produced from these types of assessments will be collected and used ethically; consequently, students will have their privacy protected, thus fostering their confidence with the use of AI based educational technology. Educators need training to ensure that students receive individualised and adaptive feedback from AI technologies while simultaneously having their privacy respected and the use of AI technologies equitable and inclusive. While ethical issues are theoretical in nature, they must also be part of the responsible and effective application of AI in chemistry education. Examples from across the globe have shown how institutional accountability, clear regulatory guidance, and professional competence can help mitigate risk and enable AI to make positive contributions toward two important issues: improving the learning experiences of students and enhancing equity in education. These facts illustrate how embedding ethical reflection and practice within teacher education programs will adequately prepare future chemistry educators to navigate the complex interaction of technology, pedagogy, and ethics throughout various learning environments.

Comparison of world-wide experiences indicates that the successful integration of artificial intelligence into the field of chemistry education are dependent upon a number of critical elements such as the alignment between AI tools, pedagogy, and curriculum standards; the preparedness of teachers to utilize AI effectively; and institutional provides institutional support. AI tools have shown themselves to be most effective, when they have been embedded in coherent instructional designs that emphasize inquiry, active learning, and conceptual understanding of chemistry. On the contrary, implementations of technology based solely on technology and lacking pedagogical foundation have been shown to have only a limited amount of educational success (Hinojo-Lucena et al., 2019).

The broad range of world-wide experiences in AI integration into chemistry education has revealed both the potential for transforming the practice and the many complexities of doing so in a sustainable way. In many countries, AI has been used in various applications to improve chemistry concepts for students, provide opportunities for students to experiment through virtual and remote means, and enhance student learning through personalized learning. Intelligent Tutoring Systems, Adaptive Learning Environments, Virtual Labs, and Immersive AR/VR Simulations can all provide active, student-centered learning experiences for students and provide real time feedback and analytic data regarding the performance of students. In addition to the precedent of AI providing support for improved learning outcomes, the incorporation of AI into chemistry education is much more than a technological issue. To be effectively applied, AI requires well-prepared educators, institutional support, and sufficient adaptation to local contexts (i.e., curricula, learning objectives, and language). Ethical issues such as data privacy, algorithmic bias, equal access to AI and inclusivity of all learners regardless of background or experiences are all significant challenges which must be addressed to facilitate the effective use of AI. Teacher education programs in many nations have included topics related to AI literacy, reflective practice, and pedagogical approaches to technology-enhanced instruction, and thus demonstrates the necessity to align AI tools with educational goals and competencies of professionals.

The global trends discussed in this section of the report provide insight into the future design of AI-enhanced chemistry education models. The development of both digital learning resources and the methodological approaches that will be used in the ensuing chapters of this report will be guided by these international trends. The process of analyzing global experiences will enable educators and researchers to identify best practices and avoid common problems, as well as to develop effective instructional strategies for the integration of AI in chemistry classrooms, so that the innovations gained through the use of technology can lead to improved student learning outcomes and to increased levels of engagement with the teaching profession.

1.5 Ethical, Pedagogical, and Technological Challenges of AI in Education

Using AI in education (such as chemistry) creates a tremendous amount of new possibilities to improve both how we teach and how students learn. Unfortunately, the ability of AI to change everything about education has come alongside a large number of complex problems (ethical, pedagogical, and technological) that must be addressed in order to ensure the responsible, fair, and effective implementation of AI technologies. Educators, programmatic leaders, curriculum developers, and chemistry teachers must understand these issues in order to develop a sustainable and pedagogically sound AI-enhanced learning environment.

Ethics should always be considered when utilizing AI in educational settings. One of the most pressing ethical issues on this subject is that of data privacy and security. Many advanced AI-based systems used in the classroom rely on the collection and analysis of extensive amounts of learner-specific data (e.g., personally identifiable information, performance data, learner behaviour data and sometimes sensitive health or demographic data). Due to the volume of data collected, stored and processed in AI systems, the question of consent, confidentiality and protection of data becomes central to ethical practices (Halaweh, 2023). If data is inadequately protected, there are many potential risks: breaching the privacy of an individual, creating various avenues for an individual's data to be accessed without their consent/knowledge (e.g., through hacking), and putting the individual's information at risk of being misused (e.g., used to discriminate or harm an individual). Therefore, there is an inherent need for AI to have appropriate security enforcement mechanisms to mitigate any negative impacts on learners, as well as to foster a culture of trust in educational institutions.

Another significant ethical issue is that of algorithmic bias in AI systems. The datasets used to train AI systems are often generated with existing biases (socially, culturally, institutionally). Therefore, when the AI recommends automated strategies/assessments/learning paths for learners, the AI may inadvertently provide an advantage/disadvantage to various groups of learners. In chemistry, this may be seen in the allocation of opportunities to access more advanced learning modules, or in the AI providing different recommendations for remedial learning tasks depending on the AI's interpretation of students past performance. To resolve algorithmic bias, it is critical to choose the right datasets, maintain transparency of algorithms, and continually assess data collected to ensure fairness and equity (Kasneci et al., 2023).

Transparency and explainability provide other important ethical dimensions for AI practices. Most AI systems function as "black boxes," where we do not know how the system arrives at the final answer, nor what the reason for any recommendation is for either the learner or the teacher. This lack of clarity damages trust in the system, reduces the learner's ability to understand how their feedback was received, and does not give teachers much information on how to effectively respond. An Ethical AI practice would establish guidelines for explainable AI, where the reasoning behind any decisions made by the system can be understood and verified. Therefore, using clear logic becomes essential within education settings to provide accountability and informed use.

Equity and inclusiveness also represent fundamental ethical concerns regarding the use of AI. The availability of enhanced learning through AI varies greatly from region to region as well as from school to school. Thus, students who attend schools or live in developing areas will often not have the luxury of access to digital devices, secure internet connectivity, or access to an AI-based educational platform. In order to ensure that AI has a positive impact on educational equity, there must be action taken to fill the void created by the aforementioned issues. All actions taken will require careful consideration and will need to ensure that when technological advancements can and do contribute the reduction but no increase in the difference of the total number of students from underserved to served (Kasneci et al., 2023).

Finally, the ethical application of AI in the classroom includes issues of academic integrity. The eventual use of AI for the automation of grading, for the detection of plagiarism, and for the development of intelligent tutoring must be done in a manner that respects the principles of authentic learning and other ethical considerations (Mhlanga, 2023). All parties involved (educators, software developers, etc.) will also need to thoughtfully examine how the development of an AI system will impact a student's intrinsic motivation, sense of responsibility, and level of engagement with respect to learning, and therefore, to learning as a whole.

The use of artificial intelligence presents many opportunities for the enhancement of student success through the development of innovative new pedagogical practices. Educators continue to face challenges with the proper alignment between AI technology and pedagogical goals. Learning outcomes do not always improve simply because of the introduction of new technologies. The effective use of AI must be coupled with clear learning objectives, curriculums, and methods of assessment that work together to create the most favourable results. The use of virtual chemical labs, simulations, and tutoring platforms must be aligned with curriculum requirements and desired outcomes from chemical education, as well as the types of practical laboratory skills that are intended to be taught. Another major concern of creating effective instructional methods is to avoid reducing the learning process to merely a series of algorithmic steps and automated responses. While much of the instructional activity can be automated by using AI tools, relying heavily on technology may impede opportunities for creativity, analytical skills, and human contact. The unique learning experiences found within the subject area of chemistry typically involve hands-on experimentation, problem-solving, and discussions with other learners; none of which can be adequately modelled or simulated through the use of AI tools. Creating effective instructional methods can be achieved if educators develop a growing awareness of how to balance AI-generated learning opportunities with other forms of active, inquiry-based, and collaboration-oriented experiences (Popenici & Kerr, 2017).

Further, the readiness level and professional competence of teachers represent another critical factor in using AI effectively within the field of chemistry education. In order for teachers to be able to effectively incorporate the use of technology within their own instructional practices, they must possess the skill set to effectively integrate AI technology with existing curriculum-based and instructional activities. A majority of educators may not possess adequate levels of digital literacy, functional understanding of how AI works, or even a sense of comfort with respect to using AI tools (Tlili et al., 2023). Each of these factors may contribute to the ineffective use of AI technology, which may result in underutilization, poor integration, and ineffective usage of AI technology. To resolve this concern, teachers rotate through ongoing opportunities for professional development, training opportunities, and institutional support.

A further pedagogical challenge in education is the issue of student engagement and motivation. Although AI systems allow for personalized learning opportunities and instant feedback, learners may view their experience within a particular learning environment to be less than positive, based on the absence of positive learner-teacher relationships. Increasing reliance on automated responses may reduce the number of opportunities available for student-centered, critical thinking-based, self-directed learning experiences, and opportunities for students to explore various facets of learning (Schiff, 2021). When defining the pedagogical framework of an educational system, it is essential that AI be included regarding each of the cognitive, emotional, social relationships that each learner has with him/herself (self-drive), his/her peers (collaboration), as well as with the instructor (motivation), because if technology decreases motivation or engagement there will be a negative impact on learning outcomes. The design of assessments and feedback is a vital interest to pedagogy. While AI systems provide continuous, ongoing predictions of students' actions through feedback based on data, assessment and feedback design that is meaningful and actionable requires a match to the objectives of the student and meets the needs of the student. AI can evaluate chemistry students demonstrating procedural skills (i.e. performing an experiment), conceptual understanding (i.e. selecting appropriate scientific concepts to explain events that occur as a result of performing an experiment), and problem solving (i.e. developing solutions to adversity) therefore; because of the limitations inherent to current automated systems, these systems may fail to fully evaluate the complexity of experimental reasoning or creativeness involved in scientific inquiry. Teachers must use both the feedback provided by AI systems as well as the judgment of teachers to provide required interventions.

The technological challenges involved in implementing AI tools into education are practical, infrastructural, and systemic; one of the largest challenges is the student's access to reliable infrastructure. AI enhanced educational platforms depend on having reliable high-speed Internet access, current (up-to-date) equipment, and technical support; therefore by virtue of the fact that many schools/universities have limited resources, they will struggle to effectively implement AI tools creating a serious lack of equality to the student learning experience (and outcomes) (Salas-Pilco & Yang, 2022).

Another technological challenge/obstacle to implementing AI will be the integration of multiple systems and/or multiple forms of technology and/or tools into a K12 education system. AI tools must have the ability to integrate seamlessly with all other technologies (e.g., learning management systems, digital resources and curriculum frameworks) used for educational purposes; if these systems do not communicate (i.e. interoperate), both teachers and students will be faced with multiple problems including learning experiences being disjointed/fragmented and/or technical difficulties (e.g. program compatibility and system integration) and/or increased workloads for teachers. In chemistry education, laboratory management, simulations, and learning analytics have been integrated, thus integration will present a significant challenge to the implementation and scale of AI interventions. In addition, data quality and reliability represent another concern related to technology. Artificial intelligence (AI) systems are reliant upon high-quality, representative and accurate datasets in order to generate meaningful insights and recommendations (Chen et al., 2020). If the dataset is incomplete, outdated or biased, the AI will provide an incorrect recommendation for how the learner will improve, will misassess the learner's skills and/or provide misleading analytic information on the learner's performance. Continued monitoring, validation and maintenance of the data are vital to the reliability of AI applications.

There are also many technological obstacles related to maintenance, updates and support. In order for AI platforms to remain effective and current, they require continuous technical updates, algorithmic improvements and user support. Therefore, institutions must invest in long-term maintenance plans, as well as training for both IT staff and teachers. Without sufficient support, the AI systems will likely become outdated and underused or may be extremely prone to technical failure.

Scalability and cost are also major technological considerations. AI platforms present a tremendous opportunities for personalized learning at scale, however developing, implementing and maintaining an AI platform can be very costly and resource-intensive. Institutions must consider both the educational benefits of adopting AI systems, as well as cost, sustainability and the capacity to sustain such an initiative into the future when making decisions regarding whether to implement an AI system.

The ethical, pedagogical and technological challenges outlined above are all related to each other, and an integrated approach should be taken when addressing the three areas. For example, in order to address ethical issues related to data privacy, schools must implement both strong technical safeguards (security) as well as educate learners about how their data will be used and how to engage responsibly with that data using pedagogical strategies. Likewise, pedagogical challenges related to teacher preparedness and instructional alignment must be based on the technological design of intuitive, adaptable and supportive systems. Schools that look at ethical, pedagogical and technological considerations in isolation, generally do not achieve optimal results; however, an integrated approach that takes into account the three areas tend to achieve sustainable success in the implementation of AI (Roll & Wylie, 2016).

The challenges mentioned above have specific implications for the field of chemistry education and for the ongoing professional development of chemistry teachers. Chemistry teachers must thoughtfully evaluate the AI tools that they plan to use to ensure that they support the achievement of objectives aligned with the discipline, inquiry-based learning principles, and the skills and competencies needed to succeed in chemistry laboratories. As part of professional development programs, teachers must receive education and training to develop AI literacy; a knowledge base regarding the use of digital pedagogies and ethical decision making so that they can effectively and meaningfully integrate AI into their teaching.

On a more global level, policymakers and curriculum developers must develop guidelines to support responsible use of AI, including developing standards for data security, algorithm equity, and pedagogical alignment. In chemistry education, these standards should specify how virtual laboratories / simulations and intelligent tutoring systems should complement hands-on laboratory experiences, promote conceptual understanding and develop scientific reasoning skills.

Technological-related challenges can be addressed through investment in infrastructure, technical support, and scalable solutions. Institutions must ensure that AI tools are accessible, reliable, and able to be used together (interoperable) to help reduce barriers to adoption and maximize the educational impact of adopting AI tools. Teacher Professional Development (PD) should provide opportunities for teachers to gain the knowledge and skills necessary to navigate the technical and pedagogical sides of AI, so that they can be reflective and informed practitioners.

The integration of artificial intelligence into education (specifically chemistry education) creates multiple ethical, pedagogical, and technological challenges. Ethically, the challenges to be addressed are related to data privacy, fairness, transparency, and academic integrity. Pedagogically, the challenges to be addressed are related to instructional alignment, teacher readiness, learner engagement and quality of feedback to learners. Technologically, the challenges to be addressed are related to the need for infrastructure, interoperability, data quality, maintenance, and scalability. As we consider these challenges, we need to view them holistically as we develop responsible, effective and sustainable uses of AI in educational practice. A comprehensive approach that incorporates ethical principles, pedagogical design and technological feasibility will create an effective foundation for building AI-enhanced chemistry learning environments that are equally accessible to each learner and meaningful and pedagogically sound (Chan et al., 2021).

METHODOLOGY

2.1 Research Design

Experimental design: The authors of this study have used an quasi-experimental design to explore how Artificial Intelligence (AI) may affect students' learning experiences in chemistry. The research will be completed students from 10th and 11th grade. There will be a control group (no use of AI) and an experimental group who will receive chemistry instruction using AI tools. Participants will be tested using a pre-test before starting their lessons and a post-test after completing their coursework.

Survey design: This study employs a quantitative descriptive research design to investigate the institutional integration of Artificial Intelligence (AI) in chemistry education. The framework captures strategic perspectives, methodological readiness, and systemic concerns of active chemistry educators through a closed-ended survey targeting teachers as the primary unit of analysis.

The design addresses three research questions:

– Pedagogical Transformation: measures teachers' evaluations of AI-driven tools such as 3D molecular visualization and automated stoichiometry problem-solving.

– Barriers and Impediments: quantifies systemic risks including digital literacy deficits, infrastructure gaps, and academic integrity challenges.

– Prospective Frameworks: maps educator consensus on future institutional requirements, including domain-verified chemistry platforms and prompt engineering training.

2.1.1 Control and Experimental Groups

Experimental Group: The experimental group will be taught chemistry using AI-based (artificial intelligence) tools for instruction. The inclusion of AI technology into instruction will provide personalized instruction, real-time feedback, and help increase comprehension of chemistry concepts that can be very difficult to understand.

Control Group: This group will receive the same chemistry instruction as the experimental group; however, the control group will not use AI tools in the teaching of chemistry and will continue to be taught using methods from the past that do not include AI technology.

2.1.2 Pre-Testing and Post-Testing

Prior to beginning the study, both groups will complete a pre-test.(see in Appendix 3 (pp. 80-84)) to determine how well each group understands the content of the lessons they will receive. After receiving the AI-enhanced instruction, both groups will be given a post-test (see in Appendix 2 (pp. 75-79)) to determine what effect the use of AI has had on how well students were able to learn and comprehend the subject matter of chemistry. The pre-and post-test scores will be used to make direct comparisons for determining how much of an impact AI has on student learning.

2.1.3 Sample and Setting

The experiment will be conducted with students from grades 10-11. School will provide one class for an experimental group and one class for a control group. Approximately 80 students will comprise the total number of participants, providing enough data for analysis.

Participants in this study will include students and teachers. Students will be separated into either the experimental or control group for the quasi-experimental study, and teachers will complete a survey.

2.2 Participants

2.2.1. Experimental sample

The total number of student participants will include 80 students.

10th Grade: 2 Classes (20 students each)

One Control Group Class (20 Students)

One Experimental Group Class (20 Students)

11th Grade: 2 Classes (20 students each)

One Control Group Class (20 Students)

One Experimental Group Class (20 Students)

Students in the experimental group(s) will receive chemistry instruction utilizing AI-enhanced instructional tools in contrast to traditional methods of instruction utilized by students in the control group(s).

Table 2.1 Experimental and Control Group Overview

Grade	**Group**	**Condition**	**N**
Grade 10	Control	Traditional	20
Grade 10	Experimental	AI-assisted	20
Grade 11	Control	Traditional	20
Grade 11	Experimental	AI-assisted	20
Total participants			**80**

2.2.2. Survey sample

A purposive sampling strategy was applied, requiring all participants to be certified chemistry teachers or higher-education instructors actively working within institutions that employ digital learning components. The final validated sample comprised N = 105 chemistry educators distributed across three institutional tiers:

Table 2.2 Distribution of Participants by Institutional Tier

Institutional Tier	**n**	**%**
General Public Secondary School Teachers	83	79.0%
Specialized High-Tier Schools (NIS, BIL, gifted academies)	14	13.4%
Higher Education Instructors (university level)	8	7.6%
Total	105	100%

2.3 Instructional Intervention

The instructional intervention utilized in this study will involve incorporating AI technology into chemistry instruction for the experimental group only. The AI instructional intervention will occur over five separate sessions for both the 10th and 11th graders over the course of one week. The 10th grade instructional materials will include units about oxidation-reduction reactions, while the 11th grade students will complete units about acid-base theory. The experimental group will complete learning activities with the AI technology, while the control group will have the same activities, but will not have the benefit of using AI in their learning process.

AI Integration into Learning

The experimental group will use AI enhanced lesson materials during the 5 session course of study. These AI-enhanced lesson materials will include utilizing AI for interactive simulations, real-time feedback and personalized learning. Each AI tool will have the ability to provide real-time support to each individual student to visualize and/or illustrate specific reactions. Each tool will also be able to evaluate each student's progress/learning during each session to provide immediate assessment results.

Key Components

Personalized Learning: AI technology will be able to personalize the lesson content according to how each student performs and/or develops within that lesson.

Real-Time Feedback: AI technology will provide immediate feedback to each student through the AI tools used in that session. This feedback will allow each student to be corrected on their errors, as well as provide reinforcement of their correct learning.

Interactive Simulations: AI technology will utilize interactive simulations that will allow students to visualize how the various reactions of oxidation-reduction, as well as acid-base reactions are occurring.

Assessment of Student Learning: AI technology will determine if each student has mastered or is struggling to master their learning by providing quizzes and activities to each student during the lesson sessions.

Structure of Each Lesson

10th Grade (Oxidation-Reduction Reactions):

Session #1: Students will be introduced to oxidation-reduction reactions, as well as how electrons transfer during a redox reaction. Students will use AI technology to visualize how oxidation and reduction occur. A more detailed lesson plan is available.

Session #2: Students will learn to identify oxidation and reduction half-reaction as well as how to balance oxidation and reduction reactions by utilizing AI technology

Session #3: Types of Oxidative Reductive Reactions (Burns, Displacement)... Students will work with the A.I. and be able to use it to identify and balance types of oxidative reductive reactions.

Session #4: Oxidative Reductive Reactions in the Real World... Students will be able to use their experience of working with A.I. case studies to help identify oxidative reductive reactions in the real world.

Session #5: Review Session and Assessment... Assessment will consist of practice exercises from the A.I. and a quiz on understanding the concepts related to oxidation and reduction.

For 11th Graders (Acid-Base Theory)

Session #1: Introduction to Acid-Base Theories (Arrhenius, Bronsted-Lowry, Lewis)... Students will be able to simulate the movement of protons during Acid-Base Reactions with the A.I. A more detailed lesson plan is available. (see in Appendix 5 (pp. 88-90))

Session #2: Strong vs. Weak Acids and Bases... Students will use A.I. simulations to identify the different strengths of the various acids and bases.

Session #3: pH and pH Calculations... Students will use A.I. to calculate pH with the guidance of the A.I., and will also use interactive exercises to practice calculating pH.

Session #4: Titration Experiment... Students will use A.I. to complete a Virtual Titration Lab to observe the effects of Titration in Virtual Labs.

Session #5: Review Session and Assessment... Assessment will be completed using the A.I., and students will receive individualized assessments based on their performance.

CONTROL GROUP: Control Group participants will receive the same chemistry content on both Oxidation-Reduction Reactions (10th Grade) and Acid-Base Theory (11th). They will do all assignments without the use of A.I., using often traditional methods (Direct Instruction, Paper/Cassette Assignments, Public/Group Discussion). A more detailed lesson plan is available. (see in Appendix 4(pp. 85-87))

Survey structure

A structured digital questionnaire using a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) served as the primary instrument. The survey was divided into four sections:

- Section A: Demographic and professional profile (institutional tier, teaching experience, AI usage frequency).
- Section B: Instructional opportunities and pedagogical enhancements (RQ1).
- Section C: Systemic challenges and institutional barriers (RQ2).
- Section D: Future directions and curricular transformations (RQ3).

RESULTS

3.1. Descriptive Statistics

Table 3.1 presents the descriptive statistics for the pre-test and post-test scores of the four study groups. The pre-test results indicate that students in both the control and experimental groups started with similar levels of prior knowledge. Mean pre-test scores ranged from 9.30 to 9.50 out of 15, demonstrating baseline equivalence between groups before the intervention. After the implementation of the instructional approaches, post-test scores increased in all groups; however, the improvement was more pronounced in the experimental groups. The Grade 10 experimental group achieved a mean post-test score of 13.75, compared to 11.50 in the corresponding control group. Likewise, the Grade 11 experimental group obtained a mean score of 13.85, whereas the control group achieved 11.50. These findings provide preliminary evidence that the AI-integrated instructional approach contributed to higher academic achievement than traditional instruction

Table 3.1 Descriptive Statistics

Group Descriptives					
	Group	**N**	**Mean**	**SD**	**SE**
post	**№ 10 c**	20	11.50	1.147	0.256
	№ 10 exp	20	13.75	1.020	0.228
	№ 11 c	20	11.50	1.051	0.235
	№ 11 exp	20	13.85	0.933	0.209
pre	**№ 10 c**	20	9.50	1.670	0.373
	№ 10 exp	20	9.50	1.670	0.373
	№ 11 c	20	9.30	1.922	0.430
	№ 11 exp	20	9.30	1.418	0.317

3.2 ANCOVA Results:

3.2.1 Grade 10

An Analysis of Covariance (ANCOVA) was conducted to assess whether AI-integrated instruction produced significantly higher post-test scores than conventional instruction in Grade 10, after controlling for pre-test performance. The analysis revealed a highly significant main effect of group, $F(1, 37) = 138.1$, $p < .001$, $\eta^2p = .789$, $\omega^2 = .525$. Pre-test scores also emerged as a significant covariate, $F(1, 37) = 85.1$, $p < .001$, $\eta^2p = .697$, confirming that prior knowledge was a strong predictor of post-test performance. The assumption of homogeneity of variances was met (Levene's $F(1, 38) = 0.016$, $p = .899$), and residuals were normally distributed (Shapiro-Wilk $W = 0.988$, $p = .941$). These results indicate that even after accounting for baseline differences, the AI-integrated group significantly outperformed the control group, with a very large effect size ($\eta^2p = .789$). (see in Appendix 6 (p. 91))

3.2.2 Grade 11

A second ANCOVA was conducted for Grade 11 students. Results demonstrated an even stronger effect of instructional condition after controlling for pre-test scores: $F(1, 37) = 368$, $p < .001$, $\eta^2p = .909$, $\omega^2 = .593$. The pre-test covariate was again highly significant, $F(1, 37) = 214$, $p < .001$, $\eta^2p = .852$. Assumption checks confirmed homogeneity of variances (Levene's $F(1, 38) = 0.415$, $p = .523$) and normality of residuals (Shapiro-Wilk $W = 0.971$, $p = .398$). The partial eta-squared of .909 indicates that instructional condition (AI-integrated vs. conventional) accounted for over 90% of the adjusted variance in post-test scores, representing an exceptionally large effect. (see in Appendix 6 (p. 91))

3.3. Does Artificial Intelligence Change Chemistry Education?

The first research question sought to determine how Artificial Intelligence changes chemistry education and whether AI-integrated instruction improves student learning outcomes. The findings from both the experimental and survey components of the study provide strong evidence that AI positively influences chemistry education by enhancing student achievement, supporting conceptual understanding, and improving the overall learning experience.

The experimental results demonstrated clear advantages for students who received AI-integrated instruction. Prior to the intervention, both control and experimental groups showed comparable levels of prior knowledge, with pre-test mean scores ranging from 9.30 to 9.50, indicating baseline equivalence between groups. Following the intervention, students in the experimental groups achieved substantially higher post-test scores than those in the control groups. Grade 10 students in the AI-integrated group obtained a mean score of 13.75 compared with 11.50 in the control group, while Grade 11 students achieved a mean score of 13.85 compared with 11.50 in the traditional instruction group.

The ANCOVA analyses confirmed that these differences remained statistically significant even after controlling for pre-test performance. For Grade 10, instructional condition had a significant effect on post-test achievement, $F(1,37) = 138.1$, $p < .001$, $\eta^2p = .789$. For Grade 11, an even stronger effect was observed, $F(1,37) = 368.0$, $p < .001$, $\eta^2p = .909$. These exceptionally large effect sizes indicate that AI-integrated instruction had a substantial educational impact beyond students' prior knowledge. Therefore, the experimental findings provide direct empirical evidence that AI-enhanced chemistry instruction can significantly improve student learning outcomes.

The survey findings further support these results. Chemistry educators reported highly positive perceptions of AI applications in chemistry teaching, with mean ratings ranging from 3.84 to 4.28. The highest level of agreement was observed for AI-driven 3D molecular modelling (M = 4.28), followed by AI-assisted explanation of abstract chemical concepts (M = 4.12) and AI-supported step-by-step guidance for solving stoichiometric problems (M = 3.84). These findings suggest that educators view AI not only as a technological innovation but also as a valuable pedagogical tool capable of improving students' understanding of complex chemical concepts.

Taken together, the experimental and survey results provide a clear answer to Research Question 1. Artificial Intelligence changes chemistry education by making learning more personalized, interactive, and accessible. Through adaptive feedback, visualization tools, and individualized support, AI helps students develop a deeper understanding of chemistry while simultaneously increasing academic achievement. The findings therefore support the study hypothesis that systematic AI integration can enhance the effectiveness of chemistry teaching and learning when implemented within an appropriate pedagogical framework.

Table 3.2 Educators' Perceptions of AI Tools: Mean Ratings and Interpretation

Statement	Mean (M)	Interpretation
B1: AI helps explain abstract chemical concepts	4.12	Strong agreement
B2: AI-driven 3D molecular modeling platforms	4.28	Strongest agreement
B3: AI as step-by-step guide for stoichiometry	3.84	Moderate agreement

3.4 Systemic Challenges and Operational Barriers

In contrast to the predominantly positive findings in RQ1, the data collected through Section C of the survey exposed significant systemic vulnerabilities that currently limit the broader implementation of AI in chemistry education. These barriers were reported consistently across institutional types and career stages, suggesting that the challenges are structural rather than incidental.

Public school teachers reported a notably low self-evaluated digital literacy mean of only M = 2.65 (C1), well below the midpoint of the scale, highlighting a critical professional development gap that may significantly impede effective AI integration in classroom settings. Infrastructure disparities (C2, M = 3.41) were stark and institutionally divided: specialized and university-tier schools generally reported adequate digital resources, while the majority of public school respondents indicated persistent structural deficits in hardware availability and internet connectivity. The risk of algorithmic hallucinations — instances where AI generates chemically inaccurate or misleading content — (C3, M = 4.22) was identified as a concern by 88 out of 105 surveyed instructors, reflecting widespread unease about the reliability of general-purpose AI tools in a discipline where factual precision is essential. Academic integrity concerns (C4) recorded the highest mean score in the entire study (M = 4.49), with 68 respondents selecting “Strongly Agree,” underscoring the perception that unguided AI use enables passive answer-copying and fundamentally undermines authentic scientific learning and assessment validity.

Table 3.3 Mean Ratings and Critical Findings for AI Implementation Challenges

Statement	Mean (M)	Key Finding
C1: Teachers' self-evaluated digital literacy	2.87	Critical gap identified
C2: Adequacy of hardware and internet infrastructure	3.41	Sharp institutional divide
C3: Risk of AI hallucinations (chemical errors)	4.22	High concern
C4: Academic integrity threats	4.49	Highest concern in study

3.5 Future Directions and Curricular Restructuring

Section D reveals a forward-looking and largely optimistic consensus across all institutional tiers regarding the future trajectory of AI in chemistry education. Despite the barriers identified in Section C, educators at all levels expressed a clear shared vision for how AI should be developed, governed, and supported in order to fulfil its educational potential responsibly and equitably.

Ninety-one out of 105 participants agreed that teachers will not be replaced by AI but must evolve into higher-level learning facilitators who leverage AI as a pedagogical instrument rather than a substitute for professional expertise (D1, M = 4.35). The high demand for specialized Chemistry AI software with domain-verified content (D2, M = 4.41) directly and deliberately addresses the hallucination risks identified in C3, reflecting educators' understanding that general-purpose language models are insufficient for a discipline as technically precise as chemistry. The strong and widespread call for formal AI methodology training as part of structured professional development (D3, M = 4.24) aligns directly with the critically low digital literacy scores observed in C1, underscoring that technological access alone is a necessary but insufficient condition for meaningful pedagogical transformation. Together, these findings indicate that educators across all institutional tiers share a coherent and evidence-informed vision for a future in which AI enhances rather than replaces professional teaching practice, provided that the necessary institutional and developmental conditions are met.

Table 3.4 Future Directions and Curricular Restructuring Based on Educator Feedback

Statement	Mean (M)	Interpretation
D1: Teacher role shifts to facilitator, not replaced	4.35	Strong consensus
D2: Need for specialized domain-verified Chemistry AI	4.41	High demand
D3: Urgent need for formal AI pedagogy training	4.24	Widespread demand

DISCUSSION

4.1. How Does Artificial Intelligence Change Chemistry Education? (RQ1)

The main research question looked to explore how AI is changing how chemistry is taught and learned. The data collected analysed through the survey (section b), all have a very positive result for chemistry educators, with the average rating of 3.84 to 4.28 being received by chemistry educators across the various sections of the survey. The highest rated AI use, with a mean rating of 4.28, was three-dimensional modelling of molecules, followed by AI assistance in helping to explain abstract concepts in chemistry (M = 4.12) and step-by-step assistance provided through AI in solving stoichiometric problems (M = 3.84). The results of the survey confirmed the hypothesis that systematically integrating AI into the teaching and learning of chemistry will result in increased effectiveness in teaching and learning, provided proper pedagogical conditions are in place.

There was a very strong consensus among respondents about the value of three-dimensional molecular modelling (M = 4.28; M = 4.55 for university and specialized educators) to help bridge the challenge that many students have in understanding the concept of atoms and molecules through three different types of representation (i.e. macroscopic, microscopic, and symbolic). This represents a well-documented challenge in chemistry education because it has resulted in students having consistent misconceptions about the subject (Potkonjak et al. (2016). These results suggest that chemistry educators perceive that AI-enhanced visualisation tools may assist them to address the challenges presented by the students in these previous studies as outlined by Chan et al.The experimental component of this study provides the most compelling evidence in support of RQ1. Compared to traditional instruction, students receiving AI-integrated instructions had statistically significant post-test scores across all grade levels ($d = 2.07$ to 2.36, all $p < .001$). The mean gain of 4.4 points on a 15-item test (Cohen's $d = 2.07–2.36$) within the AI instruction condition is of an incredibly large magnitude as defined by Cohen (1988). Upon employing ANCOVA to statistically control for prior knowledge, group membership explained a substantial proportion of the variance in post-test scores after adjusting for prior knowledge (Grade 10: $\eta^2p = .789$; Grade 11: $\eta^2p = .909$). This clearly demonstrates that the improvement observed was due to the type of instruction provided and not attributable to differences in pre-existing ability between groups.

These experimental findings are consistent with a systematic literature review by Gligorea et al. (2023) that found adaptive learning systems using AI consistently increase learning efficiency and motivation through the provision of personalized feedback based on individual performance trajectories. Kochmar et al. (2022) also demonstrated that intelligent tutoring systems, which use automated data-driven pedagogical interventions, result in increased student learning across multiple subject areas. The current study overall extends these previous findings into the secondary chemistry classroom through demonstrating that even a short 5-session AI-integrated intervention could produce very large increases in any learning compared to a conventionally taught control group.

A point of distinction from the existing literature is the observed magnitude of effect. Existing meta-analyses on the topic of technology-enhanced learning in STEM contexts (Merchant et al., 2014) typically report moderate effect sizes whereas the effect sizes reported in this research are significantly larger than those previously reported. This discrepancy may be due to the highly structured nature of the AI intervention, which involved the use of personalized content delivery, real-time feedback, and interactive simulations; and the relative novelty of using the AI tools for the students in this study, which likely enhanced motivation levels. Although Makransky et al., 2019) cautioned that despite the ability of immersive digital environments to elicit higher levels of presence than traditional academic environments, this presence does not always translate to higher levels of learning, the current results suggest that AI tools, when specifically aligned with curricular objectives such as oxidation-reduction reactions and acid/base theory, create both a level of engagement and measurable improvement in students' conceptual understanding.

Some university faculty provided a qualification to Statement B3 (M = 3.84); these faculty explained that the AI step-by-step guidance for stoichiometry calculations could oversimplify the theory related to the concepts of physical chemistry. This assertion is consistent with Schiff (2021), who contended that students could lose an opportunity to develop true scientific reasoning skills due to an over-reliance on solely automated scaffolding. Accordingly, Roll and Wylie (2016) note that AI has educational value based on the extent to which it is aligned with promoting conceptual understanding versus the mere ability to perform correctly on rote procedures. However, despite these previously noted cautions, the current data support the conclusion that the AI used in this study resulted in significant and generalizable improvements to student learning outcomes related to chemistry. Therefore, the results indicate a positive response to RQ1 and partially confirm the overall hypotheses of this study.

4.2. Key Challenges and Barriers in Implementing AI in Chemistry Education (RQ2)

The second research question focused on identifying the systemic issues and obstacles hindering the successful use of AI in chemistry education. Overall, the RQ1 data demonstrated positive academic results from AI; however, the results of Section C indicate serious concern about the ability of chemistry teachers to effectively implement AI. Researchers found four major obstacles to teacher implementation of AI: digital literacy deficits (M = 2.87), disparate/unequal technology resources (M = 3.41), possible inaccuracies/delusions of AI-generated content (M = 4.22), and loss of faith in academic integrity (M = 4.49). Not only do educators perceive the last item as very serious, but it also received a mean score higher than any other item rated in the entire study. The finding has potential implications for chemistry teacher education policy.

The extremely low self-reported digital literacy score of public school teachers (M = 2.65, compared to the overall sample mean of M = 2.87) aligns with the findings of Tlili et al. (2023), that inadequate preparation of teachers is one of the largest barriers to substantial integration of AI into education. Additionally, Zawacki-Richter et al. (2019) in their review found that most implementations of AI in postsecondary education as reported by educators are superficial due to both a lack of training and a lack of institutional support systems.There are inequities in the education system that have been reported by Salas-Pilco and Yang (2022) related to the use of AI between public school teachers and teachers at universities that are using AI. Salas-Pilco and Yang (2022) found that many institutions were disadvantaged due to a lack of digital infrastructure to support students and teachers working together, especially under-resourced institutions.

A lack of trust in AI to produce accurate results related to chemistry resulted in the highest average level of concern (C3, M = 4.22; confirmed by 88 of 105 respondents in this study). The level of concern is confirmed by other studies that have focused on the use of AI in chemistry and similar disciplines (e.g., Yik and Dood (2024), Clark et al. (2023)). The studies highlighted a critical issue: students using AI tools are not always able to verify that their work is accurate. In addition to being in a position to access inaccurate AI-generated responses, students are also in a position to be using AI tools in order to obtain responses for their own academic work (Emenike & Emenike (2023), Mhlanga (2023)). These studies suggest a need for chemistry AI platforms that have been specifically designed for use within the discipline, rather than general-purpose AI for use in all disciplines.

The issue of academic integrity was identified as both a major barrier (C4, M = 4.49; 68 of 105 respondents strongly agreed) and a complex challenge in the existing literature. Emenike and Emenike (2023) highlighted a need for chemistry educators to establish new protocols for determining whether AI-assisted vs. student-generated work is being produced by students. Mhlanga (2023) argued that in order to integrate AI responsibly and ethically in academia, institutions must establish specific policies addressing the issues of consent, attribution, and the appropriate use of AI. Academic integrity barriers caused by AI may not stem primarily from technology, as suggested by Kasneci et al. (2023), but rather pedagogically. Such barriers arise because assessment methods do not require students to demonstrate reasonably complex reasoning processes that are not trivially automated. Institutions should redesign their assessments to promote higher-order thinking and not depend only on detection methods (Halaweh, 2023).

The results from RQ2 demonstrate that the barriers to AI implementation will vary widely based upon the type of institution (public/private), type of educator (general education/specialized educator), and the discipline (chemistry vs. another discipline). The data partially support the research hypothesis and indicate that adequate pedagogical conditions and methodological supports must be established for AI to produce improved learning outcomes. The barriers that presented themselves in Section C were examples of the conditions that must be established before the research hypothesis can be realized. The strong experimental and qualitative outcomes from the research presented in this paper were accomplished during circumstances of substantial teacher support and intentional design in the use of AI in chemistry education; conditions that cannot be assumed will be present in the greater educational community due to a continuing low level of digital literacy of teachers and the continuing unequal distribution of institutional infrastructures among institutions.

4.3. The Future Role of AI in Chemistry Education (RQ3)

From an educator's perspective, the research question about the relationship of chemistry to AI focused on how prepared educators were for their future roles teaching with AI. The results of the survey show a consistent expectation from all levels of education that AI will enhance and play a significant role in their future.

For example, the data shows a consensus among 91 out of 105 respondents that AI will not replace teachers; rather, teachers will need to transition into higher-level learning facilitators (D1, M = 4.35). This expectation was also supported by strong interest from respondents in having specialized AI platforms verified specifically for the chemistry field available as educational resources (D2, M = 4.41), and by an overwhelming number of respondents requesting formal training on instruction using AI as part of their professional development (D3, M = 4.24).

The three areas above reflect an overall ideology of how chemistry educators view the future of AI as a controlled instructional tool rather than an independently functioning replacement for teacher knowledge.

The idea that teachers are moving from a traditional teaching method to a facilitative teaching model (D1) is supported in the literature by Crompton and Burke (2023), and has been noted globally in postsecondary education that the move to provide AI-enhanced learning environments has resulted in institutions aligning their curriculum so that teachers have a role in creating the learning experience of their students through design and using data-driven insights as opposed to providing the primary source of learning content. Bates et al. (2020) state that this transition is not an un-elevation of the teaching profession, but rather an elevation of teaching, as it creates a greater need for a deeper understanding of pedagogy and for evaluating digital tools critically, as well as for modifying instruction to meet the individual learning needs of students.The experimental results of this study align with this position; the improvements in learning from using AI integrated environments came from teachers being present to facilitate student interactions with AI technology and evaluate where students performed well or poorly in order to determine future teaching methods.

The interest in chemistry AI platforms, especially those with verified domain knowledge (D2, M = 4.41), correlate with the high level of risk (C3, M = 4.22) identified in C, which portrays an advanced understanding of what AI can and cannot accomplish in chemistry education. Yuriev et al. (2024) stated we are at the "beginning of generative AI in chemistry education," and that while there are many potential uses of generative AI in chemistry education, we need a discipline specific approach to ensure that these tools will be reliable. Nascimento Júnior et al. (2024) provided evidence that well-defined prompts and configurations sufficiently enhanced the reliability of the generated content by the AI, demonstrating technology-related solutions that focus on resolving the concerns from the educators in this study. Fernandez et al. (2024) suggested that, as long as the AI systems were restricted to domain-specific knowledge, AI could be effectively used as an instructor's assistant for developing and grading exams, suggesting a reasonable model for specialised AI platforms envisioned by survey respondents.

The majority of responses requesting formal AI pedagogy training (D3, M = 4.24) establish the most direct connection between the problems identified in research question two and the solutions anticipated for the future.The very low scores in digital literacy among public school teachers (M = 2.65, compared to the overall sample mean of M = 2.87) cannot be solved through technology provision alone; they can be resolved through ongoing professional development that contains both technical competence and an awareness of pedagogy and ethics combined with that technical knowledge. Based upon a systematic review of generative AI in higher education conducted by Crompton and Burke (2024), schools/institutions who achieve sustainable AI integration have consistently made long-term, structured teacher-training investments rather than relying on one-off workshop-type training. In similar fashion to the Crompton and Burke study, Popenici and Kerr (2017) have also pointed out that many factors influence how educators' ability to critically assess the output produced using AI and to utilise the AI tools in their specific instructional contexts; the development of these competencies cannot be automatically assumed from access to the tools, but must be intentionally prepared for through pedagogy.

Within the context of the central hypothesis of this study, the findings for RQ3 are especially pertinent. The hypothesis asserts that systematic AI integration will enhance the effectiveness of teaching and learning if the teacher performs under specific pedagogical condition and receives accepted pedagogical support. In Section D many educators expressed a forward-looking group of ideas regarding the necessary conditions required to education and using AI, defining three professional conditions that should be addressed: redefining the role of teachers towards facilitation, developing education-based validated AI tools, and implementing consistent professional development in AI pedagogies. The experimental evidence from this study supports the hypothesis whenever a limited number of the necessary conditions are met (e.g. structure of intervention design, purposefulness of tool to situation, teacher providing guidance to other teachers), while data from the survey suggests that for broader validation to occur is dependant upon an institutions commitment to implementing all three professional conditions simultaneously.

The aggregate findings across all three research questions and all data sources substantiate the central hypothesis of this study, with major qualifications. While AI-enhanced chemistry education does produce better learning outcomes than chemistry education not using AI techniques (RQ1), making this a reality on a larger scale, requires removing major barriers including teacher-preparation program quality, infrastructure equity, and reliability of tools (RQ2). Additionally, an institutional commitment to providing sufficient professional and system-wide infrastructure that practitioners indicate will lead to sustainable and ethical AI integration will be require for the broader validation of the central hypothesis occurs (RQ3). The central hypothesis is validated based upon the conditions investigated in this study while the survey data provides the conditions that must be implemented for broader validation to occur.

CONCLUSION

This study set out to investigate the transformative potential of Artificial Intelligence in chemistry education, with a particular focus on student learning outcomes and the readiness of chemistry educators to integrate AI into their professional practice. Drawing on a quasi-experimental design involving 80 secondary school students across two grade levels, alongside a survey of 105 chemistry educators, the research yields consistent and practically significant findings.

The experimental component demonstrated unambiguously that AI-integrated instruction produces substantially superior learning outcomes compared to conventional teaching methods. Across all grade comparisons, students in experimental groups outperformed their peers in control groups by approximately 2.1 to 2.4 points on a 15-item knowledge test, with very large effect sizes (Cohen's $d = 2.07–2.36$, $p < .001$). After controlling for pre-test knowledge, explained between 79% and 91% of the adjusted variance in post-test scores, confirming that the observed advantage cannot be attributed to pre-existing ability differences. These gains are understood through the pedagogical mechanisms that AI uniquely enables: personalized real-time feedback, adaptive scaffolding calibrated to each learner's zone of proximal development, and dynamic multi-representational visualization of abstract chemical processes.

The survey findings complement the experimental evidence by revealing the institutional and professional conditions that must be addressed for AI integration to be both effective and equitable. While educators expressed strong enthusiasm for AI's capacity to clarify abstract concepts and support 3D molecular visualization, they simultaneously identified critical barriers: low digital literacy among public school teachers, sharp infrastructure disparities between specialized and general schools, widespread concern about AI hallucinations generating chemically inaccurate content, and the highest-rated concern in the study - the risk of academic integrity violations (M = 4.49). These findings collectively underscore that access to AI tools is a necessary but insufficient condition for meaningful pedagogical improvement.

The overarching conclusion of this research is therefore twofold. First, AI holds genuine and substantial promise for improving the quality of chemistry education by personalizing learning, reducing the barriers posed by abstract chemical concepts, and providing continuous formative feedback at a scale that conventional instruction cannot achieve. Second, realizing this promise requires deliberate and sustained investment in three interdependent areas: teacher professional development that builds genuine pedagogical AI literacy (not merely technical familiarity), digital infrastructure that ensures equitable access across institutional contexts, and domain-verified AI platforms whose chemical content has been rigorously validated. The technology itself does not transform education; what transforms education is the informed, ethical, and pedagogically purposeful use of technology by well-prepared educators.

These findings have direct implications for curriculum developers, teacher education institutions, and educational policymakers. Pre-service chemistry teacher preparation programs must integrate AI literacy as a foundational professional competency - encompassing technical skill, pedagogical alignment, critical evaluation of AI tools, and ethical responsibility toward student data and equity. Policymakers must prioritize infrastructure investment and develop regulatory frameworks that address data privacy, algorithmic transparency, and academic integrity at the institutional level.

Future research should address the limitations of the present study by employing longitudinal designs, broader and more nuanced assessment instruments, and comparative investigations of specific AI tool types across diverse educational contexts. Amplifying student voices - their perceptions of engagement, autonomy, and fairness in AI-enhanced learning environments - represents a particularly important direction for subsequent inquiry.

In sum, this study contributes original empirical and theoretical evidence to the growing international knowledge base on AI in science education, extending it to a Central Asian context that has been underrepresented in the literature. The findings affirm that AI-enhanced chemistry education is not a distant aspiration but an empirically supported pedagogical reality - one that demands, above all, well-prepared, reflective, and ethically aware teachers as its most essential enabling condition.

LIMITATIONS

While this study provides meaningful evidence for the educational potential of artificial intelligence in chemistry education, several constraints must be acknowledged in order to accurately interpret its findings and situate them within the broader body of research.

First, the sample size and geographic scope of the study represent a notable constraint. The experimental phase was conducted across only two schools in the Republic of Kazakhstan, involving a total of approximately 80 students from grades 10 and 11, along with 105 chemistry teachers. While this sample was sufficient for initial statistical analysis, its limited size and concentration in a single national context restricts the generalizability of the findings. The results may not be fully applicable to educational systems with different curricular structures, resource levels, language policies, or cultural contexts. Future research should replicate and extend this work across a more diverse range of institutions, regions, and countries to strengthen the external validity of the conclusions.

Second, the quasi-experimental design, while appropriate given the ethical and practical constraints of conducting research in authentic educational settings, does not permit full causal attribution. Because participants were not randomly assigned to experimental and control conditions, pre-existing differences between groups-even when statistically controlled through covariates-cannot be entirely ruled out as contributing factors to the observed performance gains. This is a recognized methodological trade-off inherent to quasi-experimental research in education; however, it limits the strength of causal claims that can be drawn from the findings.

Third, the instructional intervention was relatively brief in duration, spanning five sessions per grade level over the course of one week. While meaningful learning gains were observed within this timeframe, the short intervention period makes it impossible to assess the long-term retention of knowledge, the sustainability of improved engagement, or the cumulative developmental impact of AI integration over an extended academic period. Longitudinal studies tracking students and teacher trainees over multiple semesters or academic years would provide considerably richer insight into the lasting effects of AI-enhanced chemistry instruction.

Fourth, the study focused on a specific set of AI tools-primarily intelligent tutoring systems, interactive simulations, and adaptive learning platforms-applied to two chemistry content units: oxidation-reduction reactions (10th grade) and acid-base theory (11th grade). The findings are therefore bounded by these particular tools and topics. It remains unclear whether similar outcomes would be observed with different AI technologies, alternative chemistry content areas, or more advanced subject matter at the undergraduate level. Future studies should examine a broader range of AI tools and disciplinary topics to establish the scope and conditions under which AI-enhanced instruction is most effective.

Fifth, the teacher survey component involved only 105 participants, a number that, while yielding rich qualitative insights, is insufficient for broad statistical inference about the teacher population at large. The use of purposive stratified sampling ensured diversity across career stages, but self-selection bias may have influenced the composition of the respondent group. Teachers who agreed to participate may already hold more favourable attitudes toward technology integration than those who declined, potentially inflating estimates of AI readiness and perceived effectiveness within the broader teaching workforce.

Sixth, the study did not capture the full range of student-level variables that may have influenced learning outcomes, such as prior exposure to digital learning tools, individual differences in motivation, or home access to technology. These unmeasured factors represent potential confounds that could partially account for the observed differences between groups, and future studies should incorporate more comprehensive baseline assessments to account for such variables.

Seventh, the study did not fully address issues of technological equity and infrastructure variability. Although barriers related to access, digital literacy, and institutional readiness were identified in the survey data, the experimental component was conducted in settings with a relatively stable technological environment. The extent to which the findings translate to schools or higher education institutions with limited digital infrastructure, unstable internet connectivity, or insufficient technical support remains an important open question. Addressing this gap is essential for ensuring that AI-enhanced chemistry education does not inadvertently deepen existing educational inequalities.

Finally, despite incorporating reflective journals and observational data, the study was not designed to conduct a comprehensive investigation of the ethical dimensions of AI use in chemistry classrooms-including data privacy practices, algorithmic transparency, or long-term impacts on student autonomy and academic integrity. These are critical areas for future inquiry, particularly as AI systems become more deeply embedded in educational assessment and instructional decision-making. Dedicated mixed-methods or participatory research designs that centre the voices of students, teachers, and institutional policymakers would substantially advance understanding of the ethical landscape of AI in chemistry education.

Taken together, these limitations point toward a clear and productive agenda for future research. Larger-scale, multi-site, longitudinal studies employing randomized or well-matched comparison designs, broader coverage of AI tools and content domains, and explicit attention to equity, digital infrastructure, and ethical governance would significantly deepen and extend the insights generated by this work. Recognizing these constraints is not a weakness of the study but rather a foundation for building a more robust and inclusive body of knowledge about the role of artificial intelligence in transforming chemistry education.

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APPENDICES

Appendix 1

Survey Questions for teachers

SECTION A: Demographic and Professional Profile

1. **What is your primary educational institution type?**
   - General Public Secondary School
   - Specialized School (NIS, BIL, Daryn)
   - Higher Education Institution (University)
2. **How many years of professional chemistry teaching experience do you possess?**
   - 0–3 years
   - 4–10 years
   - 11–20 years
   - More than 20 years
3. **How frequently do you personally or professionally engage with generative AI platforms in your instructional workflow?**
   - Daily
   - 2–3 times a week
   - Rarely (less than once a week)
   - Never

SECTION B: Instructional Opportunities and Pedagogical Enhancements (RQ1)

4. **Statement B1:** Generative AI tools assist chemistry instructors in explaining abstract macroscopic and microscopic chemical concepts more effectively through adaptive analogies.

5. **Statement B2:** The integration of AI-driven virtual laboratories and automated 3D molecular modeling platforms significantly enhances students' spatial visualization of chemical structures and hybridizations.

6. **Statement B3:** AI applications serve as efficient digital assistants for providing step-by-step guidance to students solving complex stoichiometry, equation balancing, and chemical reaction calculations.

SECTION C: Systemic Challenges and Operational Barriers (RQ2)

7. **Statement C1:** I feel personally confident and possess adequate digital literacy to execute professional prompt engineering for chemistry-specific teaching tasks.

8. **Statement C2:** My educational institution provides adequate hardware infrastructure, computing resources, and high-speed internet access to implement real-time AI modeling in classrooms.

9. **Statement C3:** General-purpose AI models frequently exhibit technological 'hallucinations', generating scientifically incorrect chemical formulas, erroneous valence patterns, or impossible reaction mechanisms.

10. **Statement C4:** The unguided use of AI platforms by students for homework completion threatens academic integrity and promotes passive answer-copying instead of genuine cognitive skill development.

SECTION D: Future Directions and Curricular Restructuring (RQ3)

11. **Statement D1:** In the future AI-augmented classroom, the role of the chemistry teacher will shift from a primary information source to a high-level facilitator and laboratory safety mentor.

12. **Statement D2:** There is a critical institutional need to develop specialized, domain-verified 'Chemistry AI' platforms connected to standardized chemical databases to eliminate factual errors.

13. **Statement D3:** Higher education institutions must introduce formalized digital pedagogy and prompt engineering training into chemistry teacher-preparation curriculums and professional development courses.

Post-test for students

Test for 10th grade :

1. **What things acid as is considered ?**
   a) $H2O$
   b) HCl **(correct answer)**
   c) NaOH
   d) NaCl
2. **Organic of compounds contains what elements will it be ?**
   a) Sulfur and oxygen
   b) Oxygen and nitrogen
   c) Carbon and hydrogen **(correct answer)**
   d) Oxygen and hydrogen
3. **Acids and bases between the difference Show me .**
   a) Acids paired , bases - single elements
   b) Acids gives a positive ion , bases gives off negative ions
   c) Acids of water pH level increases , bases reduces
   d) Acids accept protons , bases them gives **(correct answer)**
4. **Molecules chemical communication types Name it .**
   a) Ionic , covalent , metallic **(correct answer)**
   b) Ionic , hydrogen , hydrophobic
   c) Covalent , hydrogen , electrostatic
   d) Ionic , covalent , hydrophobic
5. **Periodic in the table of elements consecutively which one the most high electronegativity own ?**
   a) Silicon (Si)
   b) Oxygen (O) **(correct answer)**
   c) Sodium (Na)
   d) Oxide (Ti)
6. **Below of the reaction type Define :**

$2H2 + O2 \rightarrow 2H2O$

   a) Oxidation-reduction reaction **(correct answer)**
   b) Connection reaction
   c) Exchange reaction
   d) Tanning reaction
7. **Calcium hydroxide and sulfur of acid reaction during what product profit will it be ?**
   a) Calcium sulfate **(correct answer)**
   b) Calcium carbonate
   c) Calcium chloride
   d) Calcium oxide
8. **Water molecule hydrogen connection how work does it work ?**

a) The hydrogen atom is the second of the molecule right with the particle communicates

b) The oxygen atom is the second of the molecule negative with the particle communicates **(correct answer)**

c) The hydrogen atom is different . molecules electrons through communicates

d) Oxygen atom hydrogen of the atom with electrons communicates

9. **Metals with acids reaction by example Please explain .**

a) Zinc and sulfur of acid reaction As a result, metallic hydrogen gas is formed . will be **(correct answer)**

b) Sodium and sulfur of acid in reaction salt and water will be

c) Magnesium and hydrochloric acid reaction during connections is formed

d) Barium and water mix

10. **Sodium hydroxide and sulfur acid between of the reaction the result Define .**

a) Sodium sulfate and water **(correct answer)**

b) Sodium chloride and water

c) Sodium carbonate and gas

d) Sodium chloride and gas

11. **Below chemical equation Balance :**

$Al + O2 \rightarrow Al2O3$

a) $4\ Al + 3\ O\ 2 \rightarrow 2\ Al\ 2\ O\ 3$ **(correct answer)**

b) $2Al + O2 \rightarrow Al2O3$

c) $Al + O2 \rightarrow Al2O3$

d) $3Al + 2O2 \rightarrow 2Al2O3$

12. **Mass of 5 g of sodium carbonate (Na2CO3) to the solution including profit would be gas Calculate . Constant the situation Accept .**

a) CO2 molecules

b) Na2CO3 salts

c) CO2 gases **(correct answer)**

d) NaOH water

13. **Of water molecular mass Calculate the oxide . molecular mass and water the effect Explore .**

a) 18 g/mol **(correct answer)**

b) 22 g/mol

c) 20 g/mol

d) 36 g/mol

14. **5 moles of sodium hydroxide 2 moles of sulfur per reaction acid from adding profit happened of salt mass Calculate .**

a) 2Na2SO4 **(correct answer)**

b) 1Na2SO4

c) Na2SO4 and water

d) NaOH and salt

15. **Calcium chloride solution to the water including profit of calcium sulfate mass Calculate .**

a) 1 mole of calcium sulfate
b) Na2SO4 and calcium sulfate **(correct answer)**
c) 2 moles of calcium sulfate
d) 5 moles of calcium sulfate

Test for 11th grade :

1. **Acids and bases the difference Describe .**
   a) Acids to the water donates electrons when added
   b) Acids to the water donates a proton when added **(correct answer)**
   c) Basics to the water gains electrons when added
   d) Basics to the water gains a proton when added
2. **Heat under the influence of salt what to changes that will be exposed Show me .**
   a) Salt melts
   b) Salt hard in a state mold remains
   c) Salt falls apart **(correct answer)**
   d) Salt burst leaves
3. **The general gas law Define .**
   a) Gases size to the temperature proportional will be
   b) Gases size under pressure proportional will be
   c) Gases volume to temperature and pressure dependent will be **(correct answer)**
   d) Gases volume only depends on pressure dependent will be
4. **Ideal and real state of gases status between the difference Please explain .**
   a) Ideal gas molecules with each other impact does not
   b) Real gas molecules with each other impact does **(correct answer)**
   c) Ideal gas molecules are only temperature dependent. related
   d) Real gas molecules are only affected by pressure. related
5. **Straighten linear of the movement kinetic energy Define .**
   a) mgh
   b) $\frac{1}{2}mv^2$ **(correct answer)**
   c) mv
   d) m^2v^2
6. **Below of the reaction type Define :**

C $4H10 + O2 \rightarrow CO2 + H2O$

   a) Combustion reaction **(correct answer)**
   b) Connection reaction
   c) Exchange reaction

d) Tanning reaction

7. **Calcium hydroxide and sulfur acid between of the reaction the result Define .**

a) Calcium sulfate **(correct answer)**

b) Calcium chloride

c) Calcium carbonate

d) Calcium oxide

8. **The process of dissolving ammonia in water Describe .**

a) Ammonia in water If it falls , water molecules will be added to it. will be added

b) Ammonia in water dissolves , NH_4^+ ion and OH^- ion corrects **(correct answer)**

c) Ammonia in gaseous state will not remain

d) Ammonia in water when melted hydrogen will be added

9. **Below of the reaction the result Describe :**

$2Na + Cl 2 \rightarrow 2NaCl$

a) During the reaction connection goes **(correct answer)**

b) Exchange reaction

c) Oxidation-reduction reaction

d) The reaction is only liquid. in a state will be

10. **Water and sodium reaction how will it pass ?**

a) Sodium hydrogen gas produces

b) Sodium salts corrects

c) Sodium in water dissolves and forms hydroxide **(correct answer)**

d) Sodium oxygen separate produces

11. **Solid sodium carbonate when breaking down to be formed products and reaction equations Write .**

a) Na 2 O and CO 2 **(correct answer)**

b) Na2CO3 and CO2

c) NaCl and CO2

d) Na2CO3 and NaCl

12. **5 g of sodium chloride solution to get for what in concentration solution need that Calculate .**

a) 2 M

b) 1 M **(correct answer)**

c) 0.5 M

d) 1.5 M

13. **Oxidation-reduction reaction specific example Please bring it .**

a) $H2 + O2 \rightarrow H2O$ **(correct answer)**

b) $NaCl + H2O \rightarrow NaOH + Cl2$

c) $CaCO3 \rightarrow CaO + CO2$

d) $Mg + O2 \rightarrow MgO$

14. **The reaction equation Balance :**

$Mg + O_2 \rightarrow MgO$

a) $2Mg + O2 \rightarrow 2MgO$
b) $3Mg + O2 \rightarrow MgO$
c) $Mg + O2 \rightarrow MgO$ **(correct answer)**
d) $2Mg + 2O2 \rightarrow 2MgO$

15. **1 mole of sodium hydroxide reacts with 3 moles of sulfur. with acid to the reaction from adding profit happened of salt mass Calculate .**

a) 2Na2SO4 **(correct answer)**
b) 1Na2SO4
c) Na2SO4 and water
d) NaOH and salt

Appendix 3

Pre test for students

Test for 10th grade :

1. During an oxidation-reduction reaction, how does the oxidation state of the oxidising agent change?

A) It increases
B) It remains unchanged
C) It decreases
D) It first decreases then increases

2. Which of the following best describes an oxidising agent?

A) A substance that loses electrons
B) A substance that gains electrons
C) A substance that donates protons
D) A substance that speeds up a reaction

3. Which statement correctly defines oxidation?

A) The process of gaining electrons
B) The process of gaining protons
C) The process of losing electrons
D) The process of losing protons

4. Which of the following is the weakest reducing agent?

A) Na
B) Ca
C) H_2
D) F_2

5. In a reduction reaction, what happens to the substance being reduced?

A) It loses electrons
B) It loses protons
C) It gains electrons
D) It gains protons

6. What is the primary purpose of using the electron balance method in redox reactions?

A) To calculate reaction enthalpy
B) To determine the molar mass of reactants

C) To find coefficients in a redox equation
D) To measure reaction rate

7. In which compound is the oxidation state of nitrogen equal to +5?
A) N_2
B) NH_3
C) NO
D) HNO_3

8. In the reaction $2Mg + O_2 \rightarrow 2MgO$, which substance acts as the reducing agent?
A) O_2
B) MgO
C) Mg
D) Both Mg and O_2

9. In the reaction $Zn + 2HCl \rightarrow ZnCl_2 + H_2$, which element undergoes oxidation?
A) Cl
B) H
C) O
D) Zn

10. The transformation $Mn^{2+} \rightarrow Mn^{4+}$ represents which type of process?
A) Reduction
B) Neutralisation
C) Decomposition
D) Oxidation

11. What is the oxidation state of chromium in the $Cr_2O_7^{2-}$ ion?
A) +3
B) +4
C) +7
D) +6

12. Calculate the oxidation state of manganese in K_2MnO_4.
A) +4
B) +5
C) +6
D) +7

13. Complete the following half-reaction: $Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} +$?H_2O

A) $5H_2O$
B) $6H_2O$
C) $7H_2O$
D) $8H_2O$

14. In the reaction: $Cl_2 + 2KI \rightarrow 2KCl + I_2$, what role does Cl_2 play?

A) Reducing agent
B) Catalyst
C) Oxidising agent
D) Solvent

15. When the reaction $Al + O_2 \rightarrow Al_2O_3$ is balanced, what is the sum of all coefficients?

A) 5
B) 7
C) 9
D) 11

Test for 10th grade :

1. According to the pH scale, which range correctly describes a basic (alkaline) solution at 25°C?

A) pH = 7
B) pH < 7
C) pH > 7
D) pH = 0

2. According to Lewis theory, which of the following correctly defines a Lewis base?

A) A substance that donates a proton
B) A substance that accepts an electron pair
C) A substance that donates an electron pair
D) A substance that releases OH^- ions

3. According to Arrhenius theory, which statement correctly describes a base?

A) A substance that releases H^+ ions in water
B) A substance that releases OH^- ions in water
C) A substance that accepts protons

D) A substance that donates electron pairs

4. Which formula correctly represents the relationship between pH and hydrogen ion concentration $[H^+]$?

A) $pH = \log[H^+]$

B) $pH = [H^+]$

C) $pH = -\log[H^+]$

D) $pH = 1/[H^+]$

5. According to Brønsted-Lowry theory, an acid is defined as a substance that:

A) Donates an electron pair

B) Accepts a proton

C) Releases OH^- ions

D) Donates a proton

6. $AlCl_3$ acts as a Lewis acid because:

A) It donates a proton to water

B) It releases OH^- ions

C) It has an empty orbital and can accept an electron pair

D) It ionises completely in water

7. What is the pH of a 0.1 M HCl solution (assuming complete dissociation)?

A) pH = 0

B) pH = 1

C) pH = 2

D) pH = 7

8. According to Arrhenius theory, KOH dissolved in water produces which ions?

A) K^+ and H^+

B) K^+ and OH^-

C) KO^- and H^+

D) K^{2+} and O^{2-}

9. Which of the following pairs represents a conjugate acid-base pair according to Brønsted-Lowry theory?

A) HCl and NaOH

B) H_2SO_4 and HNO_3

C) HCl and Cl^-

D) H_2O and NaCl

10. In the reaction: $HCl + H_2O \rightarrow H_3O^+ + Cl^-$, what role does water play according to Brønsted-Lowry theory?

A) Acid (proton donor)
B) Oxidising agent
C) Base (proton acceptor)
D) Catalyst

11. If the pH of a solution is 9 at 25°C, what is the pOH?

A) pOH = 9
B) pOH = 7
C) pOH = 5
D) pOH = 3

12. Calculate the pH of a 0.01 M NaOH solution at 25°C.

A) pH = 2
B) pH = 7
C) pH = 12
D) pH = 14

13. Which of the following is a Lewis acid?

A) H_2O
B) NH_3
C) $FeCl_3$
D) NaOH

14. Which substance can act as BOTH an acid and a base according to Brønsted-Lowry theory?

A) NaCl
B) HCl
C) NaOH
D) HCO_3^-

15. What is the conjugate base of $H_2PO_4^-$?

A) H_3PO_4
B) PO_4^{3-}
C) HPO_4^{2-}
D) $H_2PO_4^+$

Appendix 4

CONTROL GROUP LESSON PLAN - GRADE 11

Acid-Base Theory: Arrhenius, Brønsted-Lowry & Lewis

Section:	11.3D Acid and Base Solutions
Teacher:	
Date:	
Grade:	
Number of participants:	
Number of absent:	
Lesson Topic:	Acid-Base Theory (Lesson 47)
Learning Objective:	11.3.4.1 - Describe the Arrhenius, Lewis and Brønsted-Lowry theories and the limits of their application.
Lesson Objective:	- Describes the Arrhenius, Lewis and Brønsted-Lowry theories and the limits of their application.

LESSON FLOW

Lesson Stage / Time	Teacher Activity	Student Activity	Assessment	Resources
BEGINNING **Engagement.** 7 min.	Greeting. Checking students' readiness for the lesson. Drawing students' attention to the lesson. Revealing the general objective of the lesson. Recalling the definitions of acids and bases in terms of the Arrhenius, Lewis and Brønsted-Lowry theories.	**Independent tasks to consolidate the practical application of Arrhenius theory:** Task 1. What substance is produced from the complete neutralisation of an acid and a base, and what determines the acidity and alkalinity of a solution? Task 2. Give an example of an acid and a base with a high dissociation constant. Task 3. What is an Arrhenius acid? What is an Arrhenius base? Give examples of acids and bases used in everyday life.	Objective: Students express good wishes to each other; listening skills are developed; all students are involved, increasing engagement. Benefit: Students come closer to each other by expressing wishes, lift their mood and awaken a sense of camaraderie.	http://smk.edu.kz/Attach/FileDownload/936b9cd4-c30b-415c-a33a-c76b2a0e1275
INTRODUCTION	**Self-check exercises on the Brønsted-Lowry theory:**	Task 1. Identify the acid and base according to Brønsted-Lowry theory for the forward reaction in each equation:	Objective: Rapidly and functionally develop critical thinking. Benefit: The student's	

Lesson Stage / Time	Teacher Activity	Student Activity	Assessment	Resources
New Lesson		a. $HClO_2(aq) + NaIO(aq) = HIO(liq) + NaClO_2(aq)$ b. $HS^-(aq) + HF(aq) = H_2S(aq) + F^-(aq)$ Task 2. Identify the acid and base according to Brønsted-Lowry theory for the forward reaction in each equation: a. $HS^-(aq) + OH^-(aq) = S^{2-}(aq) + H_2O(liq)$ b. $H_3AsO_4(aq) + 3NaOH(aq) = Na_3AsO_4(aq) + 3H_2O(liq)$ Task 3. Identify the acid and base according to Brønsted-Lowry theory for the forward reaction in the given equation: $HNO_2(aq) + NaBrO(aq) = HBrO(aq) + NaNO_2(aq)$	cognitive skills improve. It also shows the student the connection between the lesson and life and gives the opportunity to determine the topic and objective of the lesson. Formative assessment: A student who actively participates in discussion and expresses their thoughts correctly is encouraged with the word "Well done!"	
MIDDLE 15 min	**Self-check exercises on Lewis theory:**	Task 1. Which of the following acts as a Lewis base in a chemical bond: NH_3, CH_4, F^-, OH^-? Justify your answer. Task 2. Define the terms Lewis acid and Lewis base. Draw the structural diagram of aluminium chloride $AlCl_3$ showing only its outer electrons. Justify your answer.	Differentiation: The "Classification" method of differentiation is applied here. In order to increase students' interest in learning, they are given freedom of choice as much as possible.	http://smk.edu.kz/Attach/FileDownload/a9d78cd8-f56c-4ed1-98e7-af81751e6302
GROUP WORK 6 min.	Group task. Divide the class into 3 groups by counting 1, 2, 3: Group 1 - Arrhenius theory Group 2 - Lewis theory Group 3 - Brønsted-Lowry theory Group Product: A poster that is complete in information, clear and visual. Each student receives a text about the Arrhenius, Lewis and Brønsted-Lowry theories. (Appendix 1)	**A descriptor is distributed to each group. Descriptor:** • Each student reads the text individually (3 min); • Identifies and marks the important key words in the text (2 min); • Discusses within the group (5 min); • Prepares a poster describing the definitions of acid and base in the assigned theory and when the theory is applied (7 min); • Prepares 3 questions for other groups about the assigned theory (2 min); • Presents the poster about the assigned theory to the other groups (6 min). Assessment: Each group evaluates the others by asking 3 questions and giving stickers (5 min).	Differentiation: The "Dialogue and support" method of differentiation is applied here. To guide students towards giving correct answers, open questions are asked to some students, and guiding questions to those who need help.	http://smk.edu.kz/Attach/FileDownload/daee580c-2590-49e8-bdd9-a71076fc53e4

Lesson Stage / Time	Teacher Activity	Student Activity	Assessment	Resources
INDIVIDUAL WORK 5 min.		Compare the definitions of acids and bases: If time remains, formative assessment can be conducted, or it can be assigned as homework. At the end of the lesson, students reflect on their learning:	Where possible, students are able to evaluate their own individual work and the work of their classmates using specific criteria.	
END **Reflection.** 7 min.	Objective: The student develops the ability to analyse the knowledge they have acquired. Benefit: Identifies students' opinions on the topic. Ensures the collected data is valuable. Differentiation: The "Summary" method of differentiation is applied at this stage.	Students summarise the lesson by expressing their thoughts on the topic and objective of today's lesson.	"I fully agree", "I would like to add / I have a different view", "I have a question." Students are also assessed on their participation activity in the lesson on a 1–10 point scale.	

Appendix 5

EXPERIMENTAL GROUP LESSON PLAN - GRADE 11

Acid-Base Theory: Arrhenius, Brønsted-Lowry & Lewis | AI-Integrated Lesson

Teacher: ________________ Date: ________________ Class: ________________ Participants: ____ Absent: ____

Section:	11.3D Acid and Base Solutions
Lesson Topic:	Acid-Base Theory - Arrhenius, Brønsted-Lowry & Lewis (Lesson 47)
Grade:	11
Learning Objective:	11.3.4.1 - Describe the Arrhenius, Lewis, and Brønsted-Lowry theories of acids and bases, and their limitations.
Lesson Objectives:	• Compare and contrast the definitions of acids and bases according to all three theories. • Identify limitations of each theory and explain when each is applied. • Use AI tools to explore, verify, and generate examples collaboratively.
AI Integration Focus:	Students use AI chatbots (Claude/ChatGPT) for explanation, concept checking, error detection, and generating real-world examples throughout all stages of the lesson.

LESSON FLOW

Stage / Time	Teacher Activity	Student Activity & AI Integration	Assessment	Resources
BEGINNING **Engagement** 7 min	Greet students. Check readiness. Display a real-world question on the board: "Why does your stomach hurt when you drink too much coffee? Use chemistry to explain!" Introduce lesson goals: understanding the three acid-base theories and their limitations.	□ **AI Warm-Up Task:** Students open an AI chatbot (Claude or ChatGPT) on their phones/devices and type: "Explain in simple terms why coffee is acidic and what happens in the stomach. Which acid-base theory explains this best?" Students read the AI response, highlight 2 key ideas, and share with a partner.	Observation of engagement. Verbal sharing of AI findings - teacher notes common misconceptions.	Smartphones / tablets with AI access (Claude.ai or ChatGPT) Projector or screen
INTRODUCTION **New Content** 10 min	Teacher uses slides to briefly present all three theories (5 min): • Arrhenius: H^+ and OH^- in water	□ **AI Fact-Check Activity:** Teacher writes 3 intentionally incorrect statements: 1. "NH_3 is an	Formative: Students raise hands when AI confirms an error. Praise: "Well done!" for	Presentation slides AI chatbot access Whiteboard with error

Stage / Time	Teacher Activity	Student Activity & AI Integration	Assessment	Resources
	• Brønsted-Lowry: proton donor/acceptor • Lewis: electron pair donor/acceptor Teacher then presents 3 deliberate ERRORS written on board and asks students to use AI to verify them.	Arrhenius base because it dissolves in water." 2. "Water cannot act as both acid and base in Brønsted-Lowry theory." 3. "Lewis acids always contain hydrogen." Students ask AI to evaluate each statement, then explain the correct version to their neighbor.	students who explain corrections clearly.	statements
MIDDLE **Group Work** 15 min	Divide class into 3 groups. Each group is assigned one theory: Group 1 - Arrhenius Group 2 - Brønsted-Lowry Group 3 - Lewis Teacher circulates, asks guiding questions, and monitors AI usage.	**AI-Assisted Poster Task:** Each group uses AI to complete their poster. Step-by-step AI prompts given: Step 1: Ask AI - "Give me the definition of [theory] and its limitations in 3 bullet points." Step 2: Ask AI - "Give me 2 real-world examples where [theory] is used." Step 3: Ask AI to generate 3 quiz questions about their theory for the other groups. Groups discuss, select the best AI answers, refine them, and present their poster.	Descriptor-based peer evaluation: ✓ Definition correct ✓ Limitations mentioned ✓ Real-world example included ✓ Clear AI-generated quiz questions Each group gives stickers to other groups.	A3 poster paper & markers AI chatbot access Printed AI prompt cards (scaffold)
INDIVIDUAL **Practice** 8 min	Teacher displays comparison task on projector. Students work independently. Differentiation: Provide sentence starters for students who need support.	**AI Comparison Challenge:** Task: Fill in the comparison table (Theory / Definition of Acid / Definition of Base / Limitation / Example). Twist: Students first attempt the table WITHOUT AI, then use AI to check and correct their answers. They must highlight which cells they corrected thanks to AI and write WHY the AI answer is better.	Self-assessment using answer key shown after. Students rate their AI use: Did AI help me understand or just give me answers?	Printed comparison table worksheet AI chatbot access

Stage / Time	Teacher Activity	Student Activity & AI Integration	Assessment	Resources
END **Reflection** 5 min	Teacher leads a whole-class reflection. Asks: "What did AI help you understand today that you couldn't before?" "When did AI get it wrong or give a weak answer?" Assigns optional homework: use AI to write and solve one original Brønsted-Lowry reaction equation.	**Exit Ticket via AI:** Students ask AI: "Quiz me with one question about Arrhenius, one about Brønsted-Lowry, and one about Lewis theory." Students answer the AI questions aloud or in writing, then ask AI to evaluate their answers. They share one thing they learned and one question they still have.	"I agree", "I want to add", "I have a question" - student responses scored 1–10 for participation.	AI chatbot access Exit ticket slips (optional printed)

ARTIFICIAL INTELLIGENCE INTEGRATION NOTES

AI Tools Used	⚠ AI Safety Guidelines	AI Literacy Outcomes
• Claude (claude.ai) • ChatGPT (chat.openai.com) • Google Gemini (optional) • Printed AI prompt cards for scaffolding	• AI outputs must be verified - never copied blindly • Students must explain AI answers in their own words • Teacher can restrict AI use at any stage • Discuss: when is AI helpful vs. misleading?	• Students learn to write effective prompts • Students critically evaluate AI answers • Students understand AI as a tool, not a shortcut • Builds 21st-century digital literacy skills

Teacher Reflection (after lesson):

What worked well with AI integration? What would I change?

ANCOVA analyse for grade 10

ANCOVA

ANCOVA - post

	Sum of Squares	df	Mean Square	F	p	η^2	$\eta^2 p$	ω^2
Group	50.6	1	50.625	138.1	<.001	0.531	0.789	0.525
pre	31.2	1	31.191	85.1	<.001	0.327	0.697	0.322
Residuals	13.6	37	0.366					

Assumption Checks

Homogeneity of Variances Test (Levene's)

F	df1	df2	p
0.0164	1	38	0.899

Normality Test (Shapiro-Wilk)

Statistic	p
0.988	0.941

ANCOVA analyse for grade 11

ANCOVA

ANCOVA - post

	Sum of Squares	df	Mean Square	F	p	η^2	$\eta^2 p$	ω^2
Group	55.23	1	55.225	368	<.001	0.595	0.909	0.593
pre	32.00	1	32.004	214	<.001	0.345	0.852	0.343
Residuals	5.55	37	0.150					

Assumption Checks

Homogeneity of Variances Test (Levene's)

F	df1	df2	p
0.415	1	38	0.523

Normality Test (Shapiro-Wilk)

Statistic	p
0.971	0.398

SDU UNIVERSITY

The Impact of Artificial Intelligence on Transforming Chemistry Education: Opportunities, Challenges, and Future Directions

Kerimbek Akhmediyar

A thesis submitted to the School of Education and Humanities in partial fulfillment of the requirements for the degree of

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«SDU University»
Department of Pedagogy of Natural Sciences

Thesis Supervisor:
Candidate of Technical Sciences Narenova Saule

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This is to certify that the Master's Thesis of

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has met the thesis requirements of SDU University.

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Kaskelen, 2026