Transforming Chemistry Education by Engaging Students Actively and Experientially to foster Deeper Understanding and Lasting Scientific Curiosity

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Abstract

The study explores innovative teaching methodologies that enhance student engagement and comprehension of complex scientific concepts in chemistry. Conventional learning approaches often fail to connect abstract ideas to real-world applications, leading to significant gaps in understanding key concepts of the subject. The study concentrated on those active learning-interactive and technology-driven techniques, such as virtual simulations, problem-based learning, and collaborative projects, which promote critical thinking, teamwork, and problem-solving skills. These active learning strategies cater to diverse learning styles and abilities, fostering an inclusive educational environment. The research highlights the significance of experiential learning through hands-on laboratory experiments, fieldwork, and internships, which deepen students' understanding by linking theoretical knowledge to practical applications. Moreover, the study emphasizes the role of digital platforms in providing customized learning experiences, ensuring equal access to quality education. Integrating contemporary methods can revitalize chemistry education, making it more engaging and impactful for students pursuing academic or professional careers in science. Finally, the study indicates the necessity of evolving teaching practices to meet the demands of modern education and to better equip students for the challenges of the 21st century.

Keywords: Active Learning, Experiential Learning, Chemistry Education, Student Engagement, Problem-Based Learning

Introduction

Nowadays, effective teachers strive to modernize their chemistry instruction to enhance student engagement and understanding in order to be productive problem-solvers after graduating. This transformation is necessary because, conventional teaching methods, as Jofrishal & Munandar (2021) highlight, struggles to make abstract concepts relatable, hindering comprehension of vital concepts. In contrast, interactive and technology-driven methods like virtual simulations and augmented reality provide immersive experiences, fostering deeper understanding. In similar vein, active learning approaches, such as problem-based learning, flipped classrooms, and collaborative experiments (Stenseth *et al.,* 2022), encourage critical thinking, teamwork, and real-world application. These methods also promote inclusivity by catering to diverse learning styles and abilities. Moreover, digital platforms and resources offer personalized learning experiences, ensuring equitable access to quality education. These contemporary approaches empower students with the knowledge and skills for academic and scientific success by making chemistry education dynamic, engaging, and relevant (Gligorea *et al.,* 2023).

Active and experiential learning methods, as emphasized by Macaluso *et al.* (2020), enhance student engagement by encouraging active participation. These approaches, which include discussions, problem-solving, simulations, and projects, foster critical thinking, collaboration, and the application of knowledge to real-world situations. Technology-driven active learning, deepens understanding and improves information retention by stimulating multiple senses and cognitive processes (Chitti *et al.,* 2020). Whereas experiential learning is a significant component of active learning that follows a cyclical process with concrete experience, reflective observation, abstract conceptualization, and active experimentation (Nguyễn *et al.,* 2023; Sewagegn & Diale, 2019). This cyclical nature allows students to connect theory to practice, reflect on their actions, and refine their understanding. These approaches offer numerous benefits, including the development of critical thinking, teamwork, and communication skills, the ability to cater to diverse learning styles, and the fostering of intrinsic motivation and curiosity.

Active learning is an educational approach that emphasizes student engagement and participation. Unlike traditional passive learning, which relies on lectures and rote memorization, active learning encourages students to actively engage with material through critical thinking, problem-solving, and collaborative activities (Chitti *et al.,* 2020). Basic characteristics include student-centered instruction, frequent discussions, and engaging hands-on activities. This approach promotes deeper understanding, enhances information retention, and fosters critical thinking skills. Research consistently demonstrates that active learning improves academic performance, particularly in STEM fields, by connecting theoretical concepts to real-world applications (Gin *et al.,* 2020; Macaluso *et al.,* 2020; Sewagegn & Diale, 2019; Yannier *et al.,* 2020). In the context of chemistry, active learning techniques such as group discussions, laboratory experiments, problem-based learning, molecular modeling software, and concept mapping (Macaluso *et al.,* 2020) make abstract concepts more accessible and meaningful for students.

Experiential learning, a holistic approach developed in 1984 by David Kolb, emphasizes direct experiences and reflection to foster knowledge, skills, and values (Nguyễn *et al., 2023*). By connecting theory with practice, it makes abstract chemical concepts tangible and memorable. In chemistry education, real-world applications are crucial for fostering deeper understanding and appreciation of the subject (Inguva et al., 2021). These applications enhance problem-solving and critical thinking skills while preparing students for careers in chemistry and related fields. By demonstrating the vital role of chemistry in addressing societal challenges, real-world applications can motivate students, inspiring them to contribute to the world through the practical application of their theoretical knowledge.

As experiential learning directs experiences and reflection to gain knowledge, skills, and values, it connects theory with practice, making abstract concepts tangible and memorable (Nguyễn *et al.,* 2023). In chemistry education, real-world applications are crucial for fostering deeper understanding and appreciation of the subject (Inguva *et al.,* 2021). These tasks enhance problem-solving skills and critical thinking, and prepare students for careers in chemistry and related fields. Incorporating real-world applications can motivate students by demonstrating chemistry's vital role in addressing societal challenges, inspiring them to contribute to the world through the practical application of their theoretical knowledge.

Difference between Experiential and Active Learning

While experiential and active learning share similarities, they are distinct in focus and scope. Active learning refers to any strategy that actively engages students in the learning process, such as discussions, problem-solving, or interactive tasks (Chitti *et al.,* 2020). On the other hand, experiential learning specifically emphasizes learning through experience, requiring learners to engage in authentic tasks that mirror real-world challenges (Dernova, 2015). For example, an active learning activity in a chemistry class might involve solving equations collaboratively, whereas an experiential learning task could involve designing an experiment to test a hypothesis. While both methods encourage participation, experiential learning often provides deeper engagement with practical, context-rich situations.

Benefits of Active and Experiential Learning in Chemistry

Active and experiential learning in chemistry significantly enhances student engagement and retention by involving students directly in the learning process. Conventional lecture-based methods can often leave students passive and disengaged, but active strategies such as group discussions, hands-on experiments, and interactive simulations capture their attention and foster deeper understanding. Experiential activities make abstract concepts tangible, allowing students to connect theoretical knowledge with practical experiences. This heightened engagement not only improves their interest in the subject but also strengthens their memory retention, as students are more likely to recall concepts they have actively explored (Silalahi *et al.,* 2022).

Moreover, these methods promote enhanced problem-solving and critical thinking skills. Experiments, case studies, and collaborative projects provide students with valuable opportunities to develop critical thinking, problem-solving, and data analysis skills while working towards innovative solutions (Zhang & Ma, 2023). These activities often mimic the iterative nature of real-world scientific research, requiring students to think critically about their approaches and consider alternative methods. According to Zhanqiang (2023), this kind of learning environment challenges students to apply their knowledge in dynamic and unpredictable scenarios, preparing them to tackle unfamiliar problems with confidence and adaptability.

Finally, active and experiential learning prepares students for real-world applications by bridging the gap between academic theory and practical implementation. Chemistry, being a highly applied science, requires skills that extend beyond textbook knowledge. Activities such as designing experiments, using modern laboratory equipment, and solving real-life chemical challenges help students develop competencies that are directly transferable to industry, academia, and other professional settings (Jofrishal & Munandar, 2021). This hands-on preparation ensures that students are not only knowledgeable but also equipped to contribute meaningfully to their fields upon graduation. In this way, experiential learning cultivates a sense of professional readiness and adaptability in students, essential for their future success.

Theoretical Framework

Active and experiential learning in chemistry emphasizes student engagement through hands-on, participatory methods that align with constructivist theories.

This approach, rooted in the work of Piaget and Vygotsky, recognizes that students construct knowledge through active participation and experiences that challenge their thinking. In this framework, students in chemistry not only receive information but also actively interact with materials, conduct experiments, and reflect on their findings. Techniques like problem-based learning, inquiry-based learning, and collaborative group work encourage students to take responsibility for their learning by engaging in tasks that require them to analyze, synthesize, and apply chemical principles to real-world scenarios (Nurdini *et al.,* 2021). This shift in teaching focuses on student engagement and collaboration, with the teacher acting as a facilitator guiding the learning process (Prastiwi & Laksono, 2018).

Experiential learning is a foundation for active learning in chemistry, emphasizes direct experience in knowledge acquisition, aligning with Kolb's cyclical model of learning. This approach, encompassing laboratory experiments, encourages students to engage in hands-on activities, reflect on their observations, and actively experiment, fostering deeper understanding and developing critical thinking, problem-solving, and scientific reasoning. Active and experiential learning enhances student engagement and comprehension by providing diverse learning opportunities that cater to different learning styles, allowing students to choose methods that best suit their individual needs. Furthermore, these methodologies promote the development of transferable skills crucial for future success, such as teamwork, communication, and adaptability, by mirroring the collaborative nature of scientific research.

David Kolb's (1984) Experiential Learning Theory posits that learning is a cyclical process involving four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation. This cyclical nature encourages active student engagement in the learning process, moving beyond passive learning. In chemistry education, applying Kolb's theory can enhance learning by incorporating hands-on experiments, encouraging reflection on observations, developing and testing hypotheses, and applying concepts to real-world scenarios. This approach caters to diverse learning styles and promotes a more student-centered, practical, and effective learning environment that aligns with the nature of scientific inquiry.

Popular Active Learning Strategies in Chemistry

Active learning is a method that involves students directly in the learning process, enhancing comprehension and retention (Rasyid & Khoirunnisa, 2021). Popular active learning strategies in chemistry include problem-based learning (PBL), Inquiry-Based Learning (IBL), and collaborative group work. PBL involves presenting students with complex problems, encouraging critical thinking and application of chemical principles (Dibyantini *et al.,* 2021). Inquiry-based experiments involve students designing and conducting experiments to explore chemical phenomena, enhancing their understanding of scientific methodology and fundamental concepts like reaction kinetics or thermodynamics (Selco, 2018). Collaborative group work, where students work in teams to solve complex problems, analyze case studies, or discuss challenging concepts, encourages peer learning, communication skills, and diverse perspectives (Stefaniak *et al.,* 2020). These activities build a community of learners and help students articulate and refine their understanding of chemistry concepts.

Think-Pair-Share Technique in Chemistry Education

The Think-Pair-Share (TPS) technique is a collaborative learning strategy in chemistry education that enhances student engagement and understanding (Sweeder *et al.,* 2023). In the "Think" phase, students consider a question or problem individually, allowing them to process information, recall prior knowledge, and apply newly learned concepts independently. In the "Pair" phase, students collaborate with a partner to discuss their thoughts and solutions, fostering peer-to-peer learning and enhancing communication and teamwork skills. In the "Share" phase, pairs present their ideas to the larger group, facilitating a broader discussion and deeper exploration of the topic. This approach addresses common misconceptions, reinforces key concepts, and guides the class toward a comprehensive understanding (Prahl, 2016). TPS promotes active learning and ensures that students at all levels can engage meaningfully with challenging chemistry concepts.

Peer Teaching and Collaborative Learning in Chemistry Education

Peer teaching and collaborative learning are essential strategies in chemistry education, fostering an interactive and supportive learning environment (Jofrishal & Munandar, 2021; Leopold & Smith, 2019; Rahmawati *et al.,* 2020). Peer teaching involves students taking turns as instructors, enhancing comprehension by breaking down complex concepts into simpler terms. This approach builds confidence, communication skills, and a sense of shared responsibility among learners. Moreover, collaborative learning emphasizes group work and shared exploration of chemistry concepts and problems, promoting critical thinking and exposure to diverse perspectives (Luján & Payá, 2020). Both methods address diverse learning needs, benefiting students struggling with specific topics and high-performing students. They foster a sense of community, reduce isolation, and enhance motivation by creating a supportive environment where mistakes are viewed as learning opportunities. Finally, these approaches significantly enhance academic performance and interpersonal skills, making them invaluable in modern chemistry education.

Inquiry-Based Learning in Chemistry Education

According to Juniar *et al.,* (2021), Inquiry-Based Learning (IBL) is a teaching approach that encourages students to actively explore scientific concepts through questioning, investigation, and critical thinking. It is particularly beneficial in chemistry education, where it shifts the focus from rote memorization to hands-on experimentation and problem-solving. Students develop their own hypotheses, design experiments, collect data, and analyze results to draw meaningful conclusions. IBL fosters essential skills such as creativity, teamwork, and scientific literacy, making chemistry a dynamic field of discovery (Dibyantini *et al.,* 2021). It enhances student engagement and motivation by providing opportunities to explore real-world applications of chemistry. However, implementing IBL presents challenges, such as designing experiments that align with curriculum objectives and allowing student-driven exploration. Consequestly, Shin *et al.,* (2021) emphasized that teachers must also provide additional preparation, resources, and a willingness to embrace uncertainty. Effective implementation requires professional development, a supportive learning environment, and gradual introduction of inquiry-based techniques.

Problem-Based Learning (PBL) in Chemistry Education

Problem-Based Learning (PBL) is a teaching method that focuses on student-centered learning by solving real-world problems (Dibyantini *et al.,* 2021). In chemistry education, PBL presents complex, open-ended problems that require critical thinking and application of chemical concepts. This approach shifts the focus from memorization to deep understanding and integration of knowledge across various topics. According to Dotimineli & Mawardi (2021) PBL in chemistry develops essential 21st-century skills like collaboration, communication, and self-directed learning. Students work in teams, researching, hypothesizing, experimenting, and analyzing data to solve problems, mirroring professional chemist practices. This hands-on approach connects abstract chemical theories to practical applications, improving retention and conceptual understanding (Rodríguez *et al.,* 2020). However, implementing PBL in chemistry education can present challenges, such as designing meaningful problems that align with curriculum standards, providing scaffolding and guidance for students, and assessing student performance in PBL settings (Dibyantini *et al.,* 2021). Despite these challenges, PBL can transform chemistry education into an engaging and effective learning experience.

Concept Mapping in Chemistry Education

Concept mapping is a powerful tool in chemistry education that visually organizes and represents relationships among concepts, enhancing students' understanding of complex concepts like molecular interactions and elements' properties (Pedrajas & Varo-Martínez, 2014). It breaks down these complexities into interconnected nodes, identifying prior knowledge gaps and providing a deeper understanding of the subject matter. Concept mapping fosters critical thinking and active learning, encouraging students to analyze and synthesize information rather than passively memorizing it (Hariyanti *et al.,* 2020). It supports diverse learning styles, particularly for visual learners, and can be used to assess students' understanding of key ideas. Concept mapping also enhances long-term retention and application of knowledge, especially in problem-solving scenarios. It serves as cognitive scaffolds, helping students recall foundational principles and their interrelations (Alsuraihi, 2022). For example, a concept map of reaction kinetics might include nodes for rate law, activation energy, and catalysts, guiding students in applying these concepts to experimental data.

Experiential Learning in Chemistry Education

Experiential learning in chemistry education involves hands-on, real-world applications of chemical concepts, focusing on active participation through laboratory experiments, fieldwork, and collaborative projects (Davenport *et al.,* 2018; Edelsztein *et al.,* 2020; Inguva *et al.,* 2021; Jofrishal & Munandar, 2021; Nguyen *et al.,* 2021; Pherson-Geyser *et al.,* 2020). This approach deepens understanding by connecting abstract theories to tangible results, cultivating critical thinking and problem-solving skills. According to Hardy *et al.* (2021) it encourages collaboration and interdisciplinary exploration, aligning chemistry with broader societal applications. Project-based learning helps students tackle challenges like water quality analysis, sustainable energy solutions, and pharmaceutical development, inspiring innovation and creativity. Field trips to industrial labs or research facilities further enhance this approach, bridging classroom learning with career readiness. Experiential learning fosters a deeper appreciation for chemistry's role in addressing global challenges, such as renewable energy (Mutambuki *et al.,* 2019). This approach accommodates diverse learning styles, making chemistry accessible and engaging for all students. By actively participating in their education, learners develop essential skills such as collaboration, creativity, and adaptability, preparing them for success in academic, professional, and societal contexts.

Laboratory Experiments and Hands-On Activities in Chemistry Education

Laboratory experiments and hands-on activities are crucial in chemistry education, allowing students to apply theoretical knowledge in practical scenarios (Faiza & Aznam, 2021). These activities, according to Reith & Nehring (2022), provide a dynamic environment for students to observe chemical phenomena firsthand, fostering a deeper understanding of fundamental principles like reaction kinetics, equilibrium, and thermodynamics. They also develop critical thinking and problem-solving skills, sparking curiosity and enthusiasm. According to Reith & Nehring (2022), laboratory experiments also help develop technical and procedural skills, such as handling equipment, following safety protocols, and conducting systematically. These experiential learning methods help students cultivate a scientific mindset, preparing them for future research endeavors and building confidence in exploring scientific questions independently (Leopold & Smith, 2019).

Relevance of Field Studies and Industrial Visits in Chemistry Education

Field studies and industrial visits are essential in chemistry education, providing students with practical exposure to real-world applications of theoretical knowledge. Field studies allow students to explore natural settings and understand chemical processes, such as water purification and pollution control (Pamenang *et al.,* 2020). For example, industrial visits offer insights into operational dynamics of chemical industries, such as chemical synthesis and pharmaceutical production. These experiences help students appreciate practical challenges and innovations in the field, as well as interact with professionals and understand ethical and environmental considerations (Pagliaro, 2019). Incorporating these activities into the chemistry curriculum enriches the educational experience, instilling essential skills like teamwork, observation, and problem-solving, and inspiring students to pursue research and innovation. A deeper appreciation for chemistry's practical applications equips students with the confidence and competence to effectively address real-world challenges.

The Role of Simulations and Virtual Labs in Chemistry Education

Simulations and virtual labs have revolutionized chemistry education by providing interactive and immersive learning environments. These methods address challenges like safety hazards, limited access to expensive equipment, and material constraints by offering digital replicas of laboratory setups. This approach enhances accessibility and inclusivity, making quality education accessible to a broader audience. Virtual labs offer flexibility and scalability, allowing students to learn at their own pace and experiment with scenarios not feasible in physical settings (Rahman *et al.,* 2022). They often incorporate gamification elements, visualizations, and step-by-step guides, making learning engaging and intuitive. However, simulations and virtual labs may lack tactile experience and hands-on skills, hindering the development of practical skills. A blended approach combining physical labs with virtual tools is recommended by (Schnieder *et al.,* 2022) to ensure students gain both conceptual understanding and practical competence in chemistry.

Incorporation of Research Projects and Internships in Chemistry Education

Research projects and internships in chemistry education are vital for improving teaching methodologies and students' learning experiences. Projects, according to Prasetya *et al.* (2019) help educators refine their instructional strategies and promote deeper understanding among students. Internships provide opportunities for pre-service teachers and graduate students to apply theoretical knowledge in real-world educational settings, often involving collaboration with secondary schools or community organizations (Bawica, 2021). Interns gain insights into classroom management, curriculum development, and meeting diverse learners' needs. Both research projects and internships contribute to the broader field of chemistry education by fostering a community of practice among educators, promoting the exchange of ideas and strategies, generally enhancing the quality of chemistry education and making it more engaging and effective for students at all levels.

Incorporating Technology in Active and Experiential Learning

Incorporating technology into active and experiential learning has transformed education across disciplines, especially in fields like chemistry. For example, digital tools and platforms facilitate dynamic learning experiences that engage students in hands-on experimentation, data collection, and collaborative projects. Moreover, technologies such as Learning Management Systems (LMS), Virtual Reality (VR), and mobile applications provide students with diverse opportunities to interact with content in meaningful ways. Integrating these tools allows educators to create immersive learning environments that go beyond the traditional classroom, providing students with opportunities to explore complex concepts in depth and ultimately improve their understanding and retention (Liang *et al.,* 2023).

In chemistry education specifically, various digital platforms have demonstrated significant potential for improving learning outcomes. For example, simulation software like PhET Interactive Simulations allows students to conduct virtual experiments, visualize chemical reactions, and manipulate variables, all while receiving immediate feedback. These simulations make it possible to explore phenomena that may not be feasible in a standard laboratory setting due to safety, cost, or resource constraints. Furthermore, laboratory management systems can streamline data collection and analysis, fostering a collaborative atmosphere where students can work together on projects that require critical thinking and problem-solving skills.

Moreover, digital tools can facilitate engagement beyond the classroom through platforms like YouTube and social media, where educators share instructional videos, experiments, and student projects. Online forums and collaborative software like Google Classroom enable real-time communication and teamwork, encouraging peer-to-peer learning and support. Integrating technology in these ways not only enriches the educational experience but also prepares students for the digital landscapes they will encounter in their future professional environments (Camilleri & Camilleri, 2022). Technology-enabled active and experiential learning opportunities empower students to develop essential skills like adaptability, critical thinking, and creativity, preparing them for success in the evolving fields of chemistry and beyond (Neiles & Mertz, 2020).

How can educators implement active learning in large classrooms?

Implementing active learning in large classrooms presents unique challenges due to the size and diversity of the student group, but with the right strategies, it can be highly effective. A crucial strategy is to facilitate small group activities within the larger class setting. Techniques like "think-pair-share" and small group discussions can effectively engage students in large classes, allowing them to actively process the material in a more manageable setting (Lynch & Pappas, 2017). These group activities can include solving problems, discussing case studies, or brainstorming ideas, which not only fosters deeper learning but also helps students learn from their peers. The instructor can then circulate among the groups, providing guidance and answering questions, while students can collaborate and share their insights with one another.

Another effective method for active learning in large classrooms is the use of technology. Tools like clickers or polling software enable instructors to ask questions in real-time and gather immediate feedback from all students. This helps create an interactive environment where students can participate without needing to speak out in front of a large crowd. It also provides instructors with valuable data on student understanding, allowing them to adjust the pace or focus of the lesson based on the responses. Moreover, online platforms can support collaborative learning outside of class time, with students working on projects, assignments, or discussions in virtual spaces, enhancing both in-class and out-of-class engagement (Brođanac & Novak, 2023; Tawalbeh & Al-husban, 2023).

To further foster active learning in large classrooms, educators can incorporate Problem-Based Learning (PBL) into their teaching. In PBL, students are presented with real-world problems that require them to apply their knowledge and work collaboratively to find solutions (Liu & Liu, 2021). In large classes, this can be done by dividing the students into smaller teams and assigning each team a specific aspect of the problem. Real-world scenarios actively engage students in critical thinking and analysis, providing them with valuable hands-on experience (Gitinabard *et al.,* 2022). The instructor can then facilitate the learning by guiding the groups' discussions and providing additional resources, ensuring that all students are actively engaged and developing problem-solving skills.

Instructors can also use active learning through flipped classrooms, where students engage with course material outside of class through videos, readings, or online activities. In-class time can then be devoted to interactive discussions, hands-on activities, and group work, all aimed at reinforcing the concepts studied. This model allows educators to use large classroom time more effectively by creating a more personalized and engaging environment (Lo & Hew, 2017). Students come to class already familiar with the core material, allowing the educator to focus on higher-order learning activities such as applying, analyzing, and synthesizing the content in a collaborative setting.

Finally, to successfully implement active learning in large classrooms, it's crucial for educators to establish clear expectations and a supportive classroom environment. Large classes often mean greater anonymity, so setting ground rules for participation and encouraging a culture of respect and engagement is essential. Educators should encourage students to ask questions, challenge ideas, and contribute to discussions. Moreover, providing regular feedback on group activities or individual contributions helps maintain motivation and ensures that students are on track. A classroom environment that values participation and collaboration is essential for successful active learning implementation, even in large settings, leading to enhanced student engagement and improved learning outcomes.

What are some cost-effective strategies for implementing these methods?

Implementing active and experiential learning methods can seem resource-intensive, especially in terms of materials and technology, but there are several cost-effective strategies that educators can use to enhance student engagement without incurring significant expenses. One of the most effective and inexpensive approaches is utilizing group work and peer collaboration. Organizing students into small groups enables instructors to facilitate cooperative learning activities, such as problem-solving tasks, case studies, or discussions, with minimal additional resources. According to Xu *et al.,* (2023), group activities foster engagement, critical thinking, and teamwork, and the learning process is often enhanced through peer-to-peer interactions, making this approach both economical and impactful.

Another cost-effective strategy is the use of open educational resources (OERs), which include free or low-cost textbooks, videos, simulations, and other learning materials. Many educational institutions and organizations offer a wealth of OERs that can be easily integrated into active learning and experiential learning activities (Eaton *et al.,* 2022). For example, instead of purchasing expensive textbooks or proprietary simulations, instructors can utilize high-quality, freely accessible materials available online. Many OER platforms also include interactive content that can support experiential learning, allowing students to conduct virtual experiments or simulations in various disciplines without the need for physical lab equipment (Eaton et al., 2022).

Technology, when used strategically, can also be a cost-effective tool for fostering active learning. While high-end technology can be costly, simpler, low-cost tools can still promote engagement. For instance, instructors can use free online polling tools like Kahoot! or Mentimeter to facilitate real-time questions, quizzes, or discussions during class. These tools engage students and provide immediate feedback, helping to maintain interactivity in large or small classrooms. Moreover, platforms like Google Classroom or Moodle can facilitate collaboration and group discussions, offering a virtual space for students to engage with course materials and peers without requiring additional expenditures.

Incorporating active learning through project-based learning (PBL) can be another cost-effective approach, especially when using real-world problems or situations relevant to students' lives. For example, students might work on projects related to local community issues or explore real-world applications of course concepts using inexpensive or readily available materials. This hands-on approach allows students to directly apply their knowledge and engage in experiential learning (Tanious *et al.,* 2023), while the costs of materials can often be minimized by repurposing everyday items or seeking low-cost alternatives. Furthermore, project-based learning often emphasizes creativity and resourcefulness, which can make it a valuable tool for enhancing learning while keeping costs low.

Finally, implementing flipped classroom models can be a highly cost-effective way to incorporate active and experiential learning. In a flipped classroom, students access course content—such as lecture videos, readings, or online tutorials—outside of class, freeing up in-class time for interactive activities like discussions, problem-solving sessions, and collaborative projects. This method reduces the need for expensive classroom equipment or additional materials because much of the instruction occurs outside of class, and the active learning component is focused on application rather than traditional lecture-based delivery. Moreover, instructors can use free video-editing software to create engaging content or leverage pre-existing materials from educational platforms. A thoughtful combination of these strategies allows for the successful implementation of active and experiential learning methods in a cost-effective manner, fostering a dynamic and engaging learning environment for students.

Challenges and Solutions in Implementing Active Learning

Implementing active learning in the classroom can significantly enhance student engagement and understanding, yet educators often encounter various challenges when trying to integrate these methods into their teaching strategies. One prominent barrier is resistance to change, particularly from educators who are accustomed to traditional lecture-based approaches. Some may fear that active learning requires more preparation time or that it could lead to classroom chaos if not managed properly (Dancy *et al.,* 2022). Moreover, large class sizes can complicate the logistics of implementing small group activities, making it difficult for instructors to facilitate interactions effectively and assess student participation.

To address these challenges, teachers can adopt practical strategies that gradually ease the transition to active learning. For instance, starting with small-scale active learning techniques, such as think-pair-share or quick polls, can help acclimate both teachers and students to the new approach without overwhelming either party. Teachers can also seek training and professional development opportunities focused on active learning strategies, which can provide valuable insights and tools to enhance their instructional practices. Moreover, using technology tools—like discussion boards and collaborative platforms—can facilitate group interactions and manage communication among large classes, making it easy for every student to contribute (Kerimbayev *et al.,* 2023).

Another significant barrier is the perception of assessment in an active learning environment. Many teachers worry that traditional assessment methods may not accurately reflect students' understanding in active learning settings (Sewagegn & Diale, 2019). To overcome this hurdle, instructors can develop alternative assessment methods that align with active learning, incorporating formative assessments such as peer evaluations, group projects, or reflective journals. This not only provides a more comprehensive view of student learning but also encourages collaboration and self-assessment among students. Teachers can successfully implement active learning by cultivating a supportive environment that embraces flexibility and continuous improvement, thereby fostering deeper student engagement and achieving superior learning outcomes.

Successful Implementation of Experiential Learning

Experiential learning in high school chemistry labs has proven effective in enhancing student engagement and understanding (Castellanos *et al.,* 2021; Mutambuki *et al.,* 2019; Nguyen *et al.,* 2021; Osorio & Aliazas, 2022; Pamungkas *et al.,* 2019; Rahmawati *et al.,* 2021). Project-based learning, where students investigate real-world problems through hands-on experiments, has been successful in fostering critical thinking, teamwork, and communication skills (McKinney, 2023; Rasyid & Khoirunnisa, 2021). Similarly, incorporating technology into chemistry labs has also proven successful (Rahmawati *et al.,* 2021), allowing students to conduct real-time experiments and gain valuable experience in scientific data analysis and interpretation (Winkelmann *et al.,* 2020). Collaborative learning environments, such as a cooperative lab project in New York, have shown promise in fostering responsibility and innovation in addressing environmental issues (Samsonau *et al.,* 2022). These case studies demonstrate the potential of experiential learning in producing engaged, informed, and innovative learners in chemistry.

However, experiential learning, particularly through undergraduate research programs, has been shown to significantly improve student engagement and learning outcomes. Institutions like the University of California, Berkeley and Oberlin College have implemented programs that encourage students to participate in hands-on research projects, fostering critical thinking skills and real-world experience (Kohrs *et al.,* 2023; Ye & Xu, 2023). These programs also promote interdisciplinary collaboration, allowing students to work on projects that address societal challenges. This holistic educational experience encourages teamwork and collaborative problem-solving skills essential in today's job market.

The success of experiential learning through these programs is often reflected in increased retention rates, greater academic achievement, and improved career preparedness. Students report higher levels of satisfaction with their educational experience and feel more connected to their institutions (Acut *et* *al.,* 2021; DeLuca & Fornatora, 2020). Institutions that actively promote these programs also enhance their reputation as leaders in innovative education, attracting prospective students and faculty members who prioritize hands-on learning experiences.

In more advanced case, experiential learning, particularly through corporate partnerships and internships, has been shown to have transformative effects on students, educational institutions, and industry partners. Universities and local businesses can create internship opportunities for students, providing hands-on learning experiences and fostering essential skills like problem-solving and teamwork. This approach also allows students to apply theoretical knowledge to practical situations, enhancing their understanding of the subject matter (Bawica, 2021; Minnes et al., 2021). For example, engineering students can collaborate with a manufacturing firm to develop a sustainable product design, learning about project management and collaboration in a business context. This experience boosts student engagement and motivation, providing valuable insights into industry standards and expectations. The successful implementation of experiential learning leads to improved outcomes for all stakeholders involved, including students, companies, educational institutions, and the job market. Institutions can inspire other programs to adopt similar partnerships by documenting and sharing successful case studies, thereby ensuring the educational realm evolves to meet the dynamic needs of the job market.

Thus, the experiential learning in chemistry labs equips students with valuable skills for future scientific pursuits. Moreover, it plays a leading role in cultivating the next generation of critical thinkers, innovators, and leaders.

Future of Active and Experiential Learning in Chemistry

The future of active and experiential learning in chemistry is being shaped by innovative teaching methodologies that emphasize participation and real-world relevance. Traditional lecture formats are being replaced by collaborative projects, laboratory work, and problem-based learning scenarios. Technologies like simulations, virtual reality, and augmented reality are paving the way for immersive learning experiences. These trends are transforming the classroom experience and influencing the curriculum to better align with the skills required in today's fast-evolving job market (Ahmad *et al.,* 2023). It could be the reason that inspire Isaacs (2023) to conclude that experiential learning opportunities, such as internships, research projects, and field studies, are becoming integral components of chemistry education. This aligns with industry needs, preparing students for the workforce and fostering a new generation of knowledgeable and versatile chemists. The shift towards active learning has significant implications for both education and industry, leading to improved student engagement, retention, and advancements in research and development.

Conclusion

Active and experiential learning are educational methods that enhance student engagement and understanding by involving students directly in the learning process. These methods move away from traditional lecture-based formats, encouraging active participation and critical thinking. Research shows that active engagement improves retention and comprehension, leading to a deeper understanding of the subject matter. Experiential learning emphasizes real-world application, making learning more relevant and motivating. For example, conducting experiments or fieldwork in science education helps develop skills essential in today's job market. Active and experiential learning promote a sense of ownership and responsibility, leading to improved academic performance and higher satisfaction. These methods also foster a collaborative classroom environment, fostering a culture of mutual respect and support. Finally, active and experiential learning prepare students for lifelong learning and personal growth.

Active and experiential learning strategies are crucial for creating engaging and effective learning environments. Active learning involves students actively participating in their education, enhancing critical thinking and knowledge retention. Techniques like problem-based learning, case studies, and collaborative learning help connect classroom discussions to real-world applications. Experiential learning, which emphasizes learning through experience, connects academic concepts with real-life contexts. Benefits include increased student motivation, improved skill retention, and enhanced capacity for critical reflection.

Professional development opportunities and resources should be made available to educators to promote these innovative teaching approaches. Workshops, training sessions, and collaborative networks can equip teachers with the necessary tools and strategies. Celebrating successful case studies and sharing positive outcomes can motivate educators to experiment with these methods. A supportive environment encourages continuous improvement, benefiting students and enhancing overall educational quality.

Reference

Acut, D. P., Curaraton, E. P., Latonio, G. C., & Latonio, R. A. C. (2021). Work immersion performance appraisal and evaluation of Grade 12 STEM students in science and technology-based industries. *Journal of Physics Conference Series*, 1835(1). p. 12013). IOP Publishing. https://doi.org/10.1088/1742-6596/1835/1/012013

Ahmad, S., Umirzakova, S., Mujtaba, G., Amin, M., & Whangbo, T. K. (2023). Education 5.0: Requirements, Enabling Technologies, and Future Directions. *arXiv (Cornell University)*. Cornell University. https://doi.org/10.48550/arxiv.2307.15846

Alsuraihi, A. A. (2022). The effect of implementing mind maps for online learning and assessment on students during COVID-19 pandemic: a cross-sectional study. *BMC Medical Education,* 22(1). BioMed Central. https://doi.org/10.1186/s12909-022-03211-2

Bawica, I. (2021). The University Internship Program and its Effects on Students' Employability Readiness. *International Journal of Academe and Industry Research*, 2(3). p. 86-95. https://doi.org/10.53378/348731

Brođanac, P., & Novak, J. (2023). What Form of Online Teaching Do High School Students Prefer? *International Journal of Technology in Education and Science,* 7(3). p. 386-394. https://doi.org/10.46328/ijtes.505

Camilleri, M. A., & Camilleri, A. C. (2022). Remote learning via video conferencing technologies: Implications for research and practice. *Technology in Society,* 68(1). p. 101881). Elsevier BV. https://doi.org/10.1016/j.techsoc.2022.101881

Castellanos, J. L. G., Leon, A. R., Reed, C., Lo, J. Y., Ayson, P., Garfield, J. M., Alva, M., Moreno, M. U., Drake, M., Gordon, M. E., Phillips, S. A., & Alemán, E. A. (2021). Chemistry in Our Community: Strategies and Logistics Implemented to Provide Hands-On Activities to K–12 Students, Teachers, and Families. *Journal of Chemical Education,* 98(4). p. 1266-1273. American Chemical Society. https://doi.org/10.1021/acs.jchemed.0c01120

Chitti, S., Kumar, J. T., Rao, P. R., Padmaja, Ch., & Shilpa, N. (2020). Successful strategies implemented in active learning: ECE Perspective. *IOP Conference Series Materials Science and Engineering,* 981(3). p. 32050. IOP Publishing. https://doi.org/10.1088/1757-899x/981/3/032050

Dancy, M., Henderson, C., Apkarian, N., Johnson, E., Stains, M., Raker, J. R., & Lau, A. (2022). Physics instructors' knowledge and use of active learning has increased over the last decade but most still lecture too much. *arXiv (Cornell University).* Cornell University. https://doi.org/10.48550/arxiv.2211.13082

Davenport, J. L., Rafferty, A. N., & Yaron, D. (2018). Whether and How Authentic Contexts Using a Virtual Chemistry Lab Support Learning. *Journal of Chemical Education,* 95(8). p. 1250). American Chemical Society. https://doi.org/10.1021/acs.jchemed.8b00048

DeLuca, J. R., & Fornatora, E. (2020). Experiential Learning from a Classroom Desk: Exploring Student Perceptions of Applied Coursework. *Sport Management Education Journal* (Vol. 14, Issue 2, p. 142). Human Kinetics. https://doi.org/10.1123/smej.2019-0015

Dernova, M. (2015). Experiential Learning Theory as One of the Foundations of Adult Learning Practice Worldwide. *Comparative Professional Pedagogy* (Vol. 5, Issue 2, p. 52). De Gruyter Open. https://doi.org/10.1515/rpp-2015-0040

Dibyantini, R. E., Suyanti, R. D., & Silaban, R. (2021). The Effectiveness of Problem Based Learning Model Through Providing Generic Science Skill in Organic Chemistry Reaction Subject. *Journal of Physics Conference Series* (Vol. 1819, Issue 1, p. 12073). IOP Publishing. https://doi.org/10.1088/1742-6596/1819/1/012073

Dotimineli, A., & Mawardi, M. (2021). Development of STEM Integrated PBL-Based Student Worksheets in Energetic Materials of First-Year Students. *Journal of Physics Conference Series* (Vol. 1788, Issue 1, p.

12045). IOP Publishing. https://doi.org/10.1088/1742-6596/1788/1/012045

Eaton, C. D., Bonner, K., Cangialosi, K., Dewsbury, B. M., Diamond-Stanic, M. K., Douma, J., Smith, M. K., Taylor, R., Wojdak, J. M., & Wilfong, K. (2022). Sustainability and Justice: Challenges and Opportunities for an Open STEM Education. *CBE—Life Sciences Education* (Vol. 21, Issue 3). American Society for Cell Biology. https://doi.org/10.1187/cbe.20-08-0180

Edelsztein, V. C., Tarzi, O. I., & Galagovsky, L. R. (2020). Chemical senses: a context-based approach to chemistry teaching for lower secondary school students. *Chemistry Teacher International* (Vol. 2, Issue 2). De Gruyter. https://doi.org/10.1515/cti-2019-0003

Faiza, N. I., & Aznam, N. (2021). Perceptions of Pre-Service Teachers to Chemistry Laboratory Activities Based on Learning Experiences in the Laboratory. In *Advances in Social Science, Education and Humanities Research/Advances in social science, education and humanities research*. https://doi.org/10.2991/assehr.k.210326.036

Gin, L. E., Guerrero, F. A., Cooper, K. M., & Brownell, S. E. (2020). Is Active Learning Accessible? Exploring the Process of Providing Accommodations to Students with Disabilities. *CBE—Life Sciences Education* (Vol. 19, Issue 4). American Society for Cell Biology. https://doi.org/10.1187/cbe.20-03-0049

Gitinabard, N., Heckman, S., Barnes, T., & Lynch, C. F. (2022). Designing a Dashboard for Student Teamwork Analysis. *In Proceedings of the 53rd ACM Technical Symposium on Computer Science Education* (p. 446). https://doi.org/10.1145/3478431.3499377

Gligorea, I., Cioca, M., Oancea, R., Gorski, A.-T., Gorski, H., & Tudorache, P. (2023). Adaptive Learning Using Artificial Intelligence in e-Learning: A Literature Review [Review of Adaptive Learning Using Artificial Intelligence in e-Learning: A Literature Review]. *Education Sciences*, 13(12), 1216. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/educsci13121216

Hardy, J. G., Sdepanian, S., Stowell, A., Aljohani, A. D., Allen, M. J., Anwar, A., Barton, D. R., Baum, J. V., Bird, D., Blaney, A., Brewster, L., Cheneler, D., Ефремова, O. A., Entwistle, M., Esfahani, R. N., Fırlak, M., Foito, A., Forciniti, L., Geissler, S. A., … Wright, K. L. (2021). Potential for Chemistry in Multidisciplinary, Interdisciplinary, and Transdisciplinary Teaching Activities in Higher Education. *Journal of Chemical Education* (Vol. 98, Issue 4, p. 1124). American Chemical Society. https://doi.org/10.1021/acs.jchemed.0c01363

Hariyanti, H., Indrawan, G., Dantes, G. R., & Divayana, D. G. H. (2020). Application of mind mapping learning method to improve learning outcomes of grade 10 students of information and communication technology at SMK Wira Harapan, Bali, Indonesia. *Journal of Physics Conference Series* (Vol. 1516, Issue 1, p. 12050). IOP Publishing. https://doi.org/10.1088/1742-6596/1516/1/012050

Inguva, P., Shah, P., Shah, U. V., & Brechtelsbauer, C. (2021). How to Design Experiential Learning Resources for Independent Learning. *Journal of Chemical Education* (Vol. 98, Issue 4, p. 1182). American Chemical Society. https://doi.org/10.1021/acs.jchemed.0c00990

Isaacs, A. K. (2023). How to attract the next generation of chemists [Review of How to attract the next generation of chemists]. *Nature Reviews Chemistry*, 7(6), 375. Nature Portfolio. https://doi.org/10.1038/s41570-023-00503-z

Jofrishal, J., & Munandar, H. (2021). Analysis of Problem in Utilizing School Laboratories in the Chemistry Learning. In Advances in Social Science, Education and Humanities Research/Advances in social science, education and humanities research. https://doi.org/10.2991/assehr.k.210909.025

Juniar, A., Fardilah, R. D., & Tambunan, P. M. (2021). The Distinction of Students' Science Process Skill and Learning Activities between Guided Inquiry and Conventional Learning with Experiment. *Journal of Physics Conference Series* (Vol. 1788, Issue 1, p. 12043). IOP Publishing. https://doi.org/10.1088/1742-6596/1788/1/012043

Kerimbayev, N., Umirzakova, Z., Shadiev, R., & Jotsov, V. (2023). A student-centered approach using modern technologies in distance learning: a systematic review of the literature. *Smart Learning Environments*, 10(1). Springer Nature. https://doi.org/10.1186/s40561-023-00280-8

Kohrs, F. E., Auer, S., Bannach-Brown, A., Fiedler, S., Haven, T., Heise, V., Holman, C., Azevedo, F., Bernard, R., Bleier, A., Bössel, N., Cahill, B., Castro, L. J., Ehrenhofer, A., Eichel, K., Frank, M., Frick, C., Friese, M., Gärtner, A., … Weissgerber, T. L. (2023). Eleven strategies for making reproducible research and open science training the norm at research institutions. *eLife* (Vol. 12). eLife Sciences Publications Ltd. https://doi.org/10.7554/elife.89736

Leopold, H., & Smith, A. C. (2019). Implementing Reflective Group Work Activities in a Large Chemistry Lab to Support Collaborative Learning. *Education Sciences* (Vol. 10, Issue 1, p. 7). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/educsci10010007

Liang, J., Wang, L., Luo, J., Yan, Y., & Fan, C. (2023). The relationship between student interaction with generative artificial intelligence and learning achievement: serial mediating roles of self-efficacy and cognitive engagement. *Frontiers in Psychology* (Vol. 14). Frontiers Media. https://doi.org/10.3389/fpsyg.2023.1285392

Liu, G., & Liu, Y. (2021). Problem Based Learning: Its Advantages, Current Situations and Future Development. In Advances in Social Science, Education and Humanities Research/Advances in social science, education and humanities research. https://doi.org/10.2991/assehr.k.211220.060

Lo, C. K., & Hew, K. F. (2017). A critical review of flipped classroom challenges in K-12 education: possible solutions and recommendations for future research. *Research and Practice in Technology Enhanced Learning*, 12(1). Springer Nature. https://doi.org/10.1186/s41039-016-0044-2

Luján, J. F. G., & Payá, E. (2020). Direct Instruction vs. Cooperative Learning in Physical Education: Effects on Student Learning, Behaviors, and Subjective Experience. *Sustainability* (Vol. 12, Issue 12, p. 4893). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su12124893

Lynch, R. P., & Pappas, E. (2017). A Model for Teaching Large Classes: Facilitating a "Small Class Feel." *International Journal of Higher Education* (Vol. 6, Issue 2, p. 199). Sciedu Press. https://doi.org/10.5430/ijhe.v6n2p199

Macaluso, R. T., Amaro-Jiménez, C., Patterson, O. K., Martinez-Cosio, M., Veerabathina, N., Clark, K., & Luken-Sutton, J. (2020). Engaging Faculty in Student Success: The Promise of Active Learning in STEM Faculty in Professional Development. *College Teaching* (Vol. 69, Issue 2, p. 113). Taylor & Francis. https://doi.org/10.1080/87567555.2020.1837063

McKinney, L. (2023). Effectiveness of project-based learning in a junior high science classroom. *Interdisciplinary Journal of Environmental and Science Education* (Vol. 19, Issue 3). https://doi.org/10.29333/ijese/13678

Minnes, M., Serslev, S. G., & Padilla, O. (2021). What Do CS Students Value in Industry Internships? *ACM Transactions on Computing Education* (Vol. 21, Issue 1, p. 1). Association for Computing Machinery. https://doi.org/10.1145/3427595

Mutambuki, J. M., Fynewever, H., Douglass, K. O., Cobern, W. W., & Obare, S. O. (2019). Integrating Authentic Research Experiences into the Quantitative Analysis Chemistry Laboratory Course: STEM Majors' Self-Reported Perceptions and Experiences. *Journal of Chemical Education* (Vol. 96, Issue 8, p. 1591). American Chemical Society. https://doi.org/10.1021/acs.jchemed.8b00902

Neiles, K. Y., & Mertz, P. (2020). Professional Skills in Chemistry and Biochemistry Curricula: A Call to Action. *ACS symposium series* (p. 3). American Chemical Society. https://doi.org/10.1021/bk-2020-1365.ch001

Nguyen, H. T. T., Luong, V. T. T., Pham, T. T. H., & Nguyen, H. T. (2021). Organizing experiences - based learning activities "making bio-products for environmental protection" in STEM Education in high schools. *Journal of Physics Conference Series* (Vol. 1835, Issue 1, p. 12059). IOP Publishing. https://doi.org/10.1088/1742-6596/1835/1/012059

Nguyễn, T. T. H., Huyen, B. T. T., & Huyen, T. (2023). Developing Scientific Competence for Primary School Students through Experiential Learning. *International Journal of Education and Social Science Research* (Vol. 6, Issue 3, p. 1). https://doi.org/10.37500/ijessr.2023.6301

Nurdini, I. S., Sutoyo, S., & Setiarso, P. (2021). The Effectiveness of Learning Tools Using the 5E Learning Cycle Model to Improve Mastery of Concepts and Generic Science Skills. *Jurnal Penelitian Pendidikan IPA*, (Vol. 7, Issue 2, p. 184). https://doi.org/10.29303/jppipa.v7i2.672

Osorio, R., & Aliazas, J. V. (2022). Integrating Android-Based Applications in Teaching Chemistry for Improved Experiential Learning. *International Journal of Science Technology Engineering and Mathematics,* (Vol. 2, Issue 4, p. 132). https://doi.org/10.53378/352943

Pagliaro, M. (2019). An Industry in Transition: The Chemical Industry and the Megatrends Driving Its Forthcoming Transformation. *Angewandte Chemie International Edition*, 58(33), 11154. Wiley. https://doi.org/10.1002/anie.201905032

Pamenang, F. D. N., Harta, J., Listyarini, R. V., Wijayanti, L. W. R., Ratri, M. C., Hapsari, N. D., Asy'ari, M., & Lee, W. (2020). Developing chemical equilibrium practicum module based on guided inquiry to explore students' abilities in designing experiments. *Journal of Physics Conference Series* (Vol. 1470, Issue 1, p. 12097). IOP Publishing. https://doi.org/10.1088/1742-6596/1470/1/012097

Pamungkas, S. F., Widiastuti, I., & Suharno, S. (2019). Kolb's experiential learning for vocational education in mechanical engineering: A review. *AIP Conference Proceedings. American Institute of Physics*. https://doi.org/10.1063/1.5112427

Pedrajas, A. P., & Varo-Martínez, M. (2014). Educative Experience of the Use of Concept Mapping in Science and Environmental Teacher Training Programmes. *Journal of Teacher Education for Sustainability* (Vol. 16, Issue 1, p. 102). De Gruyter. https://doi.org/10.2478/jtes-2014-0006

Pherson-Geyser, G. M., Villiers, R. de, & Kavai, P. (2020). The Use of Experiential Learning as a Teaching Strategy in Life Sciences. In

International Journal of Instruction (Vol. 13, Issue 3, p. 877). Osmangazi University. https://doi.org/10.29333/iji.2020.13358a

Prahl, K. (2016). Best Practices for the Think-Pair-Share Active-Learning Technique. *The American Biology Teacher* (Vol. 79, Issue 1, p. 3). University of California Press. https://doi.org/10.1525/abt.2017.79.1.3

Prasetya, A. T., Haryani, S., Cahyono, E., & Sudarmin. (2019). Review challenges and constraints of project-based learning in chemical instrumentation to enhance competence and life skills. *Journal of Physics Conference Series* (Vol. 1321, Issue 3, p. 32055). IOP Publishing. https://doi.org/10.1088/1742-6596/1321/3/032055

Prastiwi, M. N. B., & Laksono, E. W. (2018). The ability of analytical thinking and chemistry literacy in high school students learning. *Journal of Physics Conference Series* (Vol. 1097, p. 12061). IOP Publishing. https://doi.org/10.1088/1742-6596/1097/1/012061

Rahman, F., Mim, M. S., Baishakhi, F. B., Hasan, M., & Morol, Md. K. (2022). A Systematic Review on Interactive Virtual Reality Laboratory. *arXiv (Cornell University)*. Cornell University. https://doi.org/10.48550/arXiv.2203.

Rahmawati, Y., Hadinugrahaningsih, T., Ridwan, A., Palimbunga, U. S., & Mardiah, A. (2021). Developing the critical thinking skills of vocational school students in electrochemistry through STEM - project-based learning (STEM-PjBL). *AIP conference proceedings* (Vol. 2331, p. 40002). American Institute of Physics. https://doi.org/10.1063/5.0041915

Rahmawati, Y., Ramadhani, S. F., & Afrizal, A. (2020). Developing Students' Critical Thinking: A STEAM Project for Chemistry Learning. In Universal Journal of Educational Research (Vol. 8, Issue 1, p. 72). Horizon Research Publishing. https://doi.org/10.13189/ujer.2020.080108

Rasyid, M. A., & Khoirunnisa, F. (2021). The Effect Of Project-Based Learning On Collaboration Skills Of High School Students. *Jurnal Pendidikan Sains (JPS)* (Vol. 9, Issue 1, p. 113). Unimus press. https://doi.org/10.26714/jps.9.1.2021.113-119

Reith, M., & Nehring, A. (2022). Fostering Scientific Reasoning Competencies in Undergraduate Laboratories Using "Classical" Kinetics Experiments. *Journal of Chemical Education* (Vol. 99, Issue 12, p. 3915). American Chemical Society. https://doi.org/10.1021/acs.jchemed.2c00340

Rodríguez, J., Cáceres-Jensen, L., Díaz, T., Ibáñez, S. D., Padilla, V. B., Pernaa, J., & Aksela, M. (2020). Developing technological pedagogical science knowledge through educational computational chemistry: a case study of pre-service chemistry teachers' perceptions. *Chemistry Education Research and Practice* (Vol. 21, Issue 2, p. 638). Royal Society of Chemistry. https://doi.org/10.1039/c9rp00273a

Samsonau, S. V., Kurbonova, A., Jiang, L., Lashen, H., Bai, J., & Merchant, T. (2022). Scalable authentic research education framework. *arXiv (Cornell University)*. Cornell University. https://doi.org/10.48550/arXiv.2210.

Schnieder, M., Williams, S. R., & Ghosh, S. (2022). Comparison of In-Person and Virtual Labs/Tutorials for Engineering Students Using Blended Learning Principles. *Education Sciences* (Vol. 12, Issue 3, p. 153). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/educsci12030153

Selco, J. I. (2018). Designing an Active Learning Physical Chemistry Course Using Best Practices. *ACS symposium series* (p. 115). American Chemical Society. https://doi.org/10.1021/bk-2018-1279.ch008

Sewagegn, A. A., & Diale, B. M. (2019). Empowering Learners Using Active Learning in Higher Education Institutions. Intech Open eBooks. IntechOpen. https://doi.org/10.5772/intechopen.80838

Shin, N., Bowers, J., Krajcik, J., & Damelin, D. (2021). Promoting computational thinking through project-based learning. *Disciplinary and Interdisciplinary Science Education Research,* 3(1). Springer Nature. https://doi.org/10.1186/s43031-021-00033-y

Silalahi, S. A., Zainal, A., & Sagala, G. H. (2022). The Importance of Deep Learning on Constructivism Approach. In Advances in economics, business and management research/Advances in Economics, Business and Management Research. Atlantis Press. https://doi.org/10.2991/aebmr.k.220104.036

Stefaniak, K. R., Winfrey, M. K., Curtis, A. C., & Kennedy, S. (2020). Implementing an Iterative and Collaborative Approach to Inclusive First-Semester General Chemistry Laboratory Redesign. *Journal of Chemical Education* (Vol. 98, Issue 2, p. 340). American Chemical Society. https://doi.org/10.1021/acs.jchemed.0c00487

Stenseth, H. V., Steindal, S. A., Solberg, M. T., Ølnes, M. A., Mohallem, A. G. da C., Sørensen, A. L., Strandell-Laine, C., Olaussen, C., Aure, C. F., Riegel, F., Pedersen, I., Zlámal, J., Martini, J. G., Bresolin, P., Linnerud, S. C. W., & Nes, A. A. G. (2022). Simulation-Based Learning Supported by Technology to Enhance Critical Thinking in Nursing Students: Protocol for a Scoping Review. *JMIR Research Protocols*, 11(4). JMIR Publications. https://doi.org/10.2196/36725

Sweeder, R. D., Herrington, D. G., & Crandell, O. M. (2023). Chemistry Education Research at a Crossroads: Where Do We Need to Go Now? *Journal of Chemical Education* (Vol. 100, Issue 5, p. 1710). American Chemical Society. https://doi.org/10.1021/acs.jchemed.3c00091

Tanious, R., Gérain, P., Jacquet, W., & Hoof, E. V. (2023). A scoping review of life skills development and transfer in emerging adults [Review of A scoping review of life skills development and transfer in emerging adults]. *Frontiers in Psychology*, 14(1). Frontiers Media. https://doi.org/10.3389/fpsyg.2023.1275094

Tawalbeh, M., & Al-husban, N. (2023). EFL Students' Perspectives on Activities Designed for Asynchronous Discussion Forums: Transformative Practices. In International Journal of Technology in Education (Vol. 6, Issue 3, p. 507). https://doi.org/10.46328/ijte.519

Winkelmann, K., Keeney-Kennicutt, W., Fowler, D., Macik, M. L., Guarda, P. P., & Ahlborn, C. J. (2020). Learning gains and attitudes of students performing chemistry experiments in an immersive virtual world. *Interactive Learning Environments* (Vol. 28, Issue 5, p. 620). Taylor & Francis. https://doi.org/10.1080/10494820.2019.1696844

Xu, E., Wang, W., & Wang, Q. (2023). The effectiveness of collaborative problem solving in promoting students' critical thinking: A meta-analysis based on empirical literature. *Humanities and Social Sciences Communications* (Vol. 10, Issue 1). Palgrave Macmillan. https://doi.org/10.1057/s41599-023-01508-1

Yannier, N., Hudson, S. E., & Koedinger, K. R. (2020). Active Learning is About More Than Hands-On: A Mixed-Reality AI System to Support STEM Education. *International Journal of Artificial Intelligence in Education* (Vol. 30, Issue 1, p. 74). Springer Science+Business Media. https://doi.org/10.1007/s40593-020-00194-3

Ye, P., & Xu, X. (2023). A case study of interdisciplinary thematic learning curriculum to cultivate "4C skills." *Frontiers in Psychology* (Vol. 14). Frontiers Media. https://doi.org/10.3389/fpsyg.2023.1080811

Zhang, L., & Ma, Y. (2023). A study of the impact of project-based learning on student learning effects: a meta-analysis study. *Frontiers in Psychology*, 14. Frontiers Media. https://doi.org/10.3389/fpsyg.2023.1202728

Zhanqiang, M. (2023). Strategies for Cultivating Creative Thinking Ability of Students Majoring in Educational Technology. *Frontiers in Educational Research* (Vol. 6, Issue 19). https://doi.org/10.25236/fer.2023.061911