

The Metaverse-Enabled Chemistry Classroom: Immersive Virtual Environments for Conceptual Understanding, Experimental Learning, and Laboratory Safety

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Abstract — Chemistry education presents distinctive pedagogical challenges because learners must interpret observable phenomena, infer processes occurring at the molecular and atomic levels, and represent these processes through chemical symbols, equations, and models. Conventional instructional approaches do not always provide sufficient opportunities to integrate these different forms of representation or to engage in repeated, exploratory experimentation. Immersive virtual environments offer an alternative learning space in which students can manipulate three-dimensional molecular structures, investigate chemical reactions, rehearse laboratory procedures, and collaborate in simulated scientific settings. This article reveals the educational potential of metaverse-enabled chemistry education through a thematic synthesis of published research on virtual reality (VR), augmented reality (AR), and virtual chemistry laboratories. The discussion is organised around five major themes. The first explores how immersive virtual environments help students visualise molecular structures and understand chemical concepts through different representations. The second examines how virtual experiments provide opportunities for hands-on-style learning, exploration, and scientific investigation. The third focuses on the role of virtual environments in developing laboratory safety awareness and understanding experimental procedures. The fourth considers how these technologies can promote student interest, active participation, teamwork, and collaborative learning. The fifth discusses the practical and ethical challenges of implementing these technologies, including teaching methods, data privacy, accessibility, equipment availability, and infrastructure requirements. Existing evidence indicates that immersive technologies can support selected learning outcomes, even though their effectiveness varies according to instructional design, learning objectives, learner characteristics, and the comparison method employed. Research comparing virtual and physical chemistry laboratories also suggests that virtual environments can support aspects of conceptual learning and procedural practice, but they do not automatically reproduce all the behavioural demands of laboratory work. The article therefore advances a pedagogically integrated model in which immersive environments complement physical experiments, guided inquiry, teacher facilitation, and evidence-based assessment. It concludes that the educational value of the metaverse depends less on technological novelty than on its capacity to make chemical phenomena intellectually accessible, experimentally meaningful, and educationally inclusive.

Keywords— metaverse, immersive virtual environments, virtual reality, augmented reality, molecular visualisation, virtual laboratories, laboratory safety

I. INTRODUCTION

Chemistry is concerned with phenomena that learners can observe directly and processes that cannot be seen without theoretical models, experimental techniques, or specialised instruments. The change in colour during a reaction, the formation of a precipitate, or the release of a gas may be observable, but explaining these events requires learners to reason about particles, chemical bonds, energy changes, and molecular interactions. Students must also connect these explanations with formulae, equations, graphs, and structural representations. Johnstone (1991) identified the relationship

between macroscopic, submicroscopic, and symbolic levels as a central challenge in chemistry learning.

This representational demand has important implications for teaching. A learner may memorise a chemical equation without understanding the particle-level changes it represents. Similarly, a student may identify a molecular structure from a diagram without being able to interpret its three-dimensional geometry. These difficulties suggest that chemistry education requires learning environments that support the interpretation and coordination of different forms of representation rather than the presentation of information alone.

The emergence of immersive technologies provides new possibilities for addressing these challenges. Virtual reality (VR) enables learners to interact with computer-generated environments, whereas augmented reality (AR) overlays digital information onto the physical world. When integrated with shared virtual spaces, avatars, interactive objects, and synchronous communication, these technologies may contribute to a broader metaverse-enabled learning environment. However, VR, AR, and the metaverse should not be treated as interchangeable concepts. A standalone molecular visualisation application may use VR without providing a persistent, socially interactive virtual world. The term metaverse-enabled chemistry education is therefore most appropriately used when immersive technologies form part of an interactive environment supporting scientific exploration, communication, and shared learning.

Early research on immersive learning has documented the potential of virtual environments to influence learning performance, engagement, and emotional experience (Allcoat & von Mühlengen, 2018). More specifically, Amirbekova et al. (2023) investigated VR- and AR-supported chemistry teaching with 236 first-year undergraduate students. Their study examined motivation, self-actualisation, and self-management alongside chemistry instruction, offering evidence relevant to the educational possibilities of immersive environments. Research comparing virtual and real-life chemistry laboratories has also examined conceptual knowledge, procedural understanding, and laboratory safety behaviours (Hu-Au & Okita, 2021).

Technological immersion should not be confused with educational effectiveness. A virtual environment can attract attention without producing durable understanding, and a visually impressive simulation may fail to develop the experimental judgement required in a real laboratory. The relevant question is not simply whether chemistry can be taught in the metaverse, but under what conditions immersive environments improve the quality of chemistry learning. This article examines the pedagogical potential, empirical support, implementation challenges, and future research directions associated with metaverse-enabled chemistry education. It approaches immersive technology as a means of addressing identifiable learning difficulties rather than as an end in itself.

II. UNDERSTANDING THE METAVERSE AS A LEARNING ENVIRONMENT

The metaverse can be understood, for educational purposes, as a digitally mediated environment in which users interact with

virtual spaces, objects, and other participants. Its educational significance lies in the combination of spatial interaction, simulation, communication, and opportunities for collaborative activity. Mystakidis (2022) discussed the metaverse as an emerging environment for social connection and immersive interaction, while Amirbekova et al. (2023) examined its relevance to chemistry education through VR and AR technologies.

In chemistry education, metaverse-enabled environments provide opportunities for students to explore chemical concepts in ways that textbooks alone may not offer. Students can examine three-dimensional molecular structures, conduct virtual experiments, change experimental conditions, and share their observations with classmates. These activities can help students understand abstract chemical concepts and encourage active learning (Johnstone, 1991; Hu-Au & Okita, 2021). However, the use of immersive technology does not automatically improve learning. Its effectiveness depends on how teachers design and guide the activities. Students should be encouraged to ask questions, analyse experimental results, explain chemical processes, and draw conclusions based on evidence. Therefore, the metaverse can support chemistry learning when it is used purposefully to develop conceptual understanding, scientific inquiry, and critical thinking (de Jong et al., 2013).

The representational challenge in chemistry

Johnstone (1991) explained that learning chemistry involves understanding three interconnected levels: the macroscopic level, which includes observable changes such as colour changes, temperature variations, and precipitate formation; the submicroscopic level, which concerns atoms, ions, molecules, and chemical interactions; and the symbolic level, which involves chemical formulae, equations, and structural diagrams. Students need to connect these three levels to understand chemical concepts effectively. For example, when studying a neutralisation reaction, they must observe the reaction, understand the interactions between the particles, and represent the process using a chemical equation. Immersive virtual environments can help students make these connections by allowing them to explore three-dimensional molecular structures and relate them to chemical symbols and equations. However, virtual models should be supported by clear explanations from teachers, as these models are simplified representations of chemical structures rather than exact images of particles as they exist in nature. Such guidance helps students interpret the models correctly and develop a deeper understanding of chemical concepts (Johnstone, 1991).

Theoretical perspectives informing immersive learning

Three theoretical perspectives provide a useful foundation for designing metaverse-enabled chemistry education. First, experiential learning theory, proposed by Kolb (1984), emphasises learning through experience, reflection, understanding, and further experimentation. In a virtual laboratory, students can conduct simulated experiments and observe the results; however, meaningful learning occurs when they reflect on their observations and use them to explain chemical processes. Second, constructivist learning emphasises that students develop understanding through active participation, prior knowledge, problem-solving, and interaction with others. Virtual chemistry activities can support this approach by encouraging students to make predictions, change experimental conditions, compare results, and explain their conclusions rather than simply follow instructions. Third, the cognitive theory of multimedia learning, discussed by Mayer (2021), explains that students learn more effectively when they can organise and connect visual and verbal information meaningfully. Although immersive environments can provide useful three-dimensional representations of chemical structures, excessive animation, unnecessary visual effects, and too much information at once may distract students from the main concepts. Therefore, metaverse-enabled chemistry lessons should focus on meaningful activities, reflection, clear explanations, and connections between molecular models and chemical symbols. Integrating these three perspectives can help teachers design immersive learning experiences that promote conceptual understanding and scientific inquiry.

Making the Invisible Accessible Through Molecular Visualisation

One of the major advantages of immersive virtual environments in chemistry education is their ability to help students understand chemical structures that cannot be observed directly. Concepts such as molecular geometry, stereochemistry, atomic orbitals, and chemical bonding often require students to imagine three-dimensional structures from two-dimensional diagrams, which can be difficult for some learners. Virtual reality (VR) allows students to rotate, enlarge, and examine molecular structures from different angles, while augmented reality (AR) enables them to view digital molecular models within their physical surroundings. These technologies may help students understand the spatial arrangement of atoms and relate molecular structures to their chemical properties. Research by Amirbekova et al. (2024) examined the use of VR and AR in undergraduate chemistry education, while Allcoat and von Mühlengen (2018) explored the effects of virtual reality on learning performance, emotions, and engagement. Similarly,

Conrad et al. (2024) reported that the learning benefits of immersive virtual reality varied according to the learning objectives and instructional approaches used. These findings suggest that immersive visualisation can support chemistry learning, although three-dimensional models do not automatically guarantee conceptual understanding. Students learning molecular geometry can use virtual models to examine methane, ammonia, and water, compare their molecular shapes and bond angles, and explain the differences using the principles of electron-pair repulsion. Teachers should connect these visual experiences with structural formulae, chemical equations, and theoretical explanations to help students develop accurate scientific understanding. Thus, the educational value of immersive visualisation lies not simply in displaying molecular structures but in helping students connect three-dimensional models with chemical concepts and scientific reasoning (Johnstone, 1991)

III. VIRTUAL EXPERIMENTATION AS EXPERIENTIAL CHEMISTRY LEARNING

Laboratory work plays an important role in chemistry education because it enables students to connect theoretical knowledge with observation, measurement, experimentation, and scientific reasoning. However, limited laboratory facilities, equipment costs, large class sizes, time constraints, and safety concerns can restrict students' opportunities to conduct practical activities. Virtual chemistry laboratories can help address some of these challenges by allowing students to practise experimental procedures, change experimental conditions, observe simulated results, and repeat activities without consuming chemicals or exposing themselves to laboratory hazards. A review by de Jong et al. (2013) discussed the educational potential of physical and virtual laboratories and highlighted the importance of designing laboratory activities that support meaningful learning. For example, students studying reaction kinetics can use a virtual laboratory to investigate how changes in temperature or concentration affect reaction rates. They can predict the outcomes, manipulate variables, record results, interpret graphs, and compare their findings with their initial predictions. Such activities provide opportunities for repeated practice and help students understand relationships that may be difficult to investigate during a single laboratory session. Virtual experiments have limitations because their results depend on the assumptions and parameters built into the software. If simulations do not include measurement errors or unexpected outcomes, students may develop an incomplete understanding of actual scientific experimentation. Teachers should therefore encourage students to examine the conditions of the simulation, interpret the results

critically, and consider whether similar outcomes would occur in a physical laboratory. Research on virtual and physical chemistry laboratories also indicates that virtual environments can support several learning outcomes, although they may not reproduce every aspect of practical laboratory behaviour (Hu-Au & Okita, 2021). Therefore, virtual laboratories are best used to prepare students for physical experiments, provide additional opportunities for practice, and reinforce conceptual understanding rather than replace hands-on laboratory experiences entirely.

Laboratory Safety and Procedural Understanding

Laboratory safety is an essential part of chemistry education because students need to learn how to handle laboratory equipment, identify potential hazards, use protective equipment, and respond appropriately to unsafe situations. Metaverse-enabled environments and virtual reality (VR) laboratories provide opportunities for students to practise these skills in a simulated setting without being exposed to actual chemical hazards. Students can identify unsafe laboratory practices, select appropriate protective equipment, and practise the correct procedures for responding to a simulated chemical spill. They can also receive immediate feedback on incorrect decisions and understand why particular safety measures are necessary. Hu-Au and Okita (2021) compared student learning and behaviour in real-life and VR chemistry laboratories and found comparable outcomes in several areas, including general chemistry knowledge, laboratory skills, and some safety-related procedures. Students demonstrated less frequent clean-up behaviour in the VR environment, suggesting that virtual practice may not develop every aspect of actual laboratory conduct equally well. This finding highlights the importance of distinguishing between knowing laboratory safety rules, practising appropriate procedures in a simulation, and demonstrating safe behaviour in a physical laboratory. For instance, a student may correctly identify a virtual chemical waste container but may still require supervised practice to handle and dispose of actual chemical waste safely. Immersive virtual environments can help students develop safety awareness and prepare for laboratory activities, but practical competence must also be assessed through appropriate hands-on activities. Metaverse-enabled chemistry education should consequently complement supervised laboratory practice rather than replace it entirely (Hu-Au & Okita, 2021).

Motivation, Collaboration, and Scientific Inquiry

Immersive virtual environments can encourage students to participate actively in chemistry learning by allowing them to explore virtual laboratories, manipulate molecular models, investigate chemical problems, and share their findings with

classmates. These activities can make abstract chemical concepts easier to explore and provide opportunities for collaborative learning. Amirbekova et al. (2024) examined VR- and AR-supported chemistry instruction among 236 first-year undergraduate students, providing evidence relevant to the potential of immersive technologies to support student motivation and learning. However, increased interest in technology does not necessarily lead to better academic achievement. Students may enjoy a virtual activity without developing a lasting understanding of the chemical concepts involved. Therefore, teachers should design activities that connect student engagement with scientific inquiry and conceptual understanding. Students can work in groups to investigate how temperature affects the rate of a chemical reaction. One student may change the experimental conditions, another may record the results, and a third may explain the changes in terms of particle movement and collision frequency. The group can then present its findings, discuss the evidence, and respond to questions from classmates. Such activities encourage students to share ideas, interpret results, and develop scientific explanations. However, effective collaboration requires clear instructions, defined responsibilities, and appropriate assessment criteria. Without proper guidance, students may explore the virtual environment without concentrating on the learning objectives. Thus, immersive technologies can promote motivation, collaboration, and scientific inquiry when teachers use them to encourage purposeful investigation, evidence-based reasoning, and meaningful interaction among learners.

Implementation Challenges and Inclusive Access

The effective use of metaverse-enabled environments in chemistry education depends not only on their educational potential but also on the resources and support available for implementation. These technologies require suitable devices, reliable internet connectivity, appropriate software, technical support, and trained teachers, which may create difficulties for institutions with limited financial resources. Students may also experience motion discomfort, visual fatigue, difficulties operating devices, or barriers related to disability and limited digital skills. Therefore, providing immersive technology alone does not guarantee equal learning opportunities. An inclusive approach should offer alternative ways to explore the same chemical concepts, such as desktop simulations, three-dimensional molecular models, augmented reality applications, and conventional diagrams. These alternatives can help students participate according to their needs while working towards the same learning objectives. Teacher preparation is equally important because educators must select scientifically accurate applications, connect virtual activities with curriculum

objectives, guide student investigations, and assess conceptual understanding rather than simply measure enjoyment or participation. Mayer (2021) emphasised the importance of presenting information in ways that support meaningful learning without imposing unnecessary cognitive demands. In addition, institutions must consider student privacy and wellbeing because some immersive applications may collect personal information about users and their interactions. Clear policies are needed to protect student data and promote respectful participation in shared virtual environments. Finally, the financial benefits of virtual laboratories should be evaluated alongside the costs of software licences, equipment maintenance, technical support, and teacher training. As de Jong et al. (2013) discussed, virtual and physical laboratories offer different educational opportunities, and their effectiveness depends on how they are designed and integrated into instruction. Therefore, institutions should adopt immersive technologies when their educational benefits justify the investment and when accessibility, teacher readiness, student wellbeing, and curriculum requirements are adequately addressed.

Metaverse-Enabled Chemistry Education

The proposed instructional framework for metaverse-enabled chemistry education consists of five stages. First, conceptual orientation involves introducing the chemical concept, activating students' prior knowledge, and establishing clear learning objectives. Second, immersive exploration allows students to examine three-dimensional molecular structures, manipulate virtual models, and record relevant observations. Third, guided experimentation encourages students to predict outcomes, change experimental conditions, conduct virtual experiments, and compare results with their predictions. Fourth, reflective interpretation helps students connect their observations with chemical principles, equations, and theoretical models. Finally, transfer and assessment evaluate whether students can apply their understanding to new problems or demonstrate relevant skills in a physical laboratory. Together, these stages connect virtual exploration with scientific reasoning, conceptual understanding, and practical application. The framework is a proposed instructional synthesis informed by experiential learning theory (Kolb, 1984), multimedia learning theory (Mayer, 2021), and research on virtual laboratories (de Jong et al., 2013); it has not yet been independently validated through empirical testing.

Implications for Chemistry Teachers and Educational Institutions

The effective integration of metaverse-enabled environments into chemistry education requires appropriate teaching

strategies, institutional support, and teacher preparation. Chemistry teachers should select immersive technologies according to the learning objectives: virtual reality (VR) can support the exploration of three-dimensional molecular structures and the practice of complex procedures, augmented reality (AR) can connect digital models with physical objects, and desktop simulations can help students investigate variables and interpret experimental results. Teachers should assess learning through pre- and post-activity questions, student explanations, laboratory reports, and practical demonstrations to determine whether these activities improve conceptual understanding. Educational institutions should begin with small, curriculum-based pilot programmes to evaluate learning outcomes, accessibility, technical requirements, and costs before investing in large-scale implementation. They should also establish appropriate arrangements for software selection, equipment maintenance, data protection, and alternative learning resources. Furthermore, teacher education programmes should prepare prospective chemistry teachers to evaluate the scientific accuracy of virtual models, design inquiry-based activities, guide collaborative learning, and assess the transfer of knowledge from virtual to physical laboratories. The primary objective should not be merely to train teachers to operate immersive devices, but to develop their ability to select and use these technologies purposefully. Thus, successful implementation depends on aligning technological resources with curriculum objectives, sound pedagogical practices, inclusive access, and meaningful assessment.

IV. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite growing interest in immersive chemistry education, several areas require further investigation. Longitudinal studies are needed to determine whether students retain the knowledge gained through virtual learning and can apply it to unfamiliar chemical problems. Researchers should also examine learning outcomes separately, including conceptual understanding, spatial reasoning, motivation, experimental skills, and laboratory safety behaviour, as improvements in one area may not necessarily lead to improvements in others. Comparisons between immersive and conventional learning environments should use equivalent content, instructional time, teacher support, and assessment methods to establish whether observed benefits result from immersion or other instructional factors. Further research should explore how equipment costs, internet connectivity, accessibility requirements, and students' digital skills influence participation and learning, particularly in resource-constrained educational institutions. Another important area is the transfer of learning from virtual to

physical laboratories, including whether virtual preparation improves practical performance and whether safety practices developed in simulations are applied during actual experiments. Future studies should also provide clear information about instructional design, software features, participant characteristics, assessment methods, implementation costs, and study limitations. Addressing these research gaps will help establish the educational value of metaverse-enabled chemistry instruction, identify the conditions under which it is most effective, and guide its responsible integration into chemistry curricula.

V. CONCLUSION

Metaverse-enabled chemistry education offers promising opportunities to improve students' understanding of three-dimensional molecular structures, chemical processes, laboratory procedures, and collaborative scientific inquiry. However, its effectiveness depends on purposeful instructional design, appropriate assessment, accessibility, and the learning objectives being addressed. Although virtual laboratories can support conceptual understanding and experimental preparation, they cannot fully replace the practical experience, material handling, and safety skills developed through supervised physical laboratory work. Therefore, immersive technologies should complement conventional teaching through guided exploration, experimentation, reflection, and the application of knowledge to real-world situations. Ultimately, the educational value of the metaverse should be measured not by its technological novelty but by its contribution to meaningful chemistry learning, scientific reasoning, and equitable educational opportunities.

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