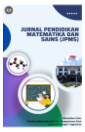

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Immersive and Experiential Learning: A Review of Project-based Learning and Virtual Reality in Chemistry Education

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Abstract

This review explores the integration of Project-based Learning (PjBL) and Virtual/Augmented Reality (VR/AR) in chemistry education. By synthesizing findings from eight peer-reviewed studies published between 2020 and 2025, selected through a systematic search using the Dimensions.ai database with specific inclusion criteria, the review highlights how immersive technologies enhance conceptual understanding, motivation, and engagement in student-centered learning environments. Data were collected using a structured literature search, and the findings were analyzed through thematic synthesis based on educational level, technology used, implementation strategies, and reported outcomes. The review reveals that VR/AR, when effectively embedded in PjBL frameworks, allows learners to simulate experiments, visualize abstract molecular structures, and collaborate in meaningful, inquiry-driven projects. However, challenges remain, including limited access to technology, pedagogical integration issues, and educator resistance. The review concludes with recommendations for future research, emphasizing the need for teacher training, inclusive design, and long-term evaluation of immersive PjBL in chemistry education.

Keywords: *Augmented reality, Chemistry education, Immersive learning, Project-based learning, Virtual reality*

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INTRODUCTION

Chemistry education has long been grounded in a combination of theoretical instruction and laboratory-based experimentation, which together form the backbone of scientific understanding. Traditionally, students learned chemical concepts through textbook explanations and direct manipulation of materials in physical labs an approach considered essential for mastering abstract content such as molecular structures or reaction dynamics (Babinčáková & Bernard, 2020). However, the COVID-19 pandemic in 2020 catalyzed a dramatic shift in science education globally. With schools and universities forced into remote or hybrid learning formats, traditional lab access was restricted, prompting educators to explore virtual experimentation and digital simulations as substitutes for hands-on experiences. This sudden transition accelerated the use of technology-driven solutions, including Virtual and Augmented Reality tools, to preserve engagement and support conceptual understanding in chemistry learning (Kubiliene et al., 2024)

At the same time, the adoption of Project-based Learning (PjBL) has gained momentum as a response to the need for more flexible, student-centered pedagogies. PjBL emphasizes collaborative inquiry, real-world relevance, and critical thinking all essential for cultivating scientific literacy. It encourages learners to take ownership of their learning by solving complex problems through exploration and iterative reflection, making it particularly effective for fostering deeper engagement with chemistry content in digital or blended settings (Han & Fung, 2024; Soroko et al., 2021). In short, chemistry education is undergoing a methodological evolution: from static content delivery and physical labs toward technology-enabled, Project-based models that emphasize active learning and adaptability in a post-pandemic world.

As digital tools become more embedded in education, Virtual Reality (VR) and Augmented Reality (AR) have emerged as transformative technologies for science learning. These tools enable students to interact with three-dimensional models, simulate laboratory procedures, and visualize otherwise invisible chemical processes such as electron transfers or molecular bonding in dynamic, immersive ways. Unlike static diagrams or verbal descriptions, VR and AR environments provide spatial and temporal representations that foster deeper conceptual understanding (Nechypurenko et al., 2023).

Immersive technologies have proven particularly valuable in chemistry education because of the subject's inherently abstract and microscopic nature. Representations of atoms, ions, and molecular interactions can be difficult for students to conceptualize using traditional teaching methods. With AR, for instance, digital overlays can animate reaction mechanisms on physical surfaces or devices, making it easier for learners to grasp complex processes. Studies show that such tools enhance visualization skills and cognitive engagement, particularly among secondary school students involved in science research projects (Soroko et al., 2021).

Furthermore, the incorporation of immersive tools aligns with constructivist learning theories, which emphasize experiential, hands-on learning. Chemistry educators are increasingly using VR labs not merely as replacements for physical labs, but as platforms for simulation-based inquiry, allowing students to explore, test, and revise their ideas within safe and flexible environments (Li et al., 2023). This represents a shift in thinking from using digital tools to supplement lessons, to restructuring entire learning activities around them.

Recent reviews of technology-enhanced science education have also highlighted how immersive environments promote collaborative exploration and creative problem-solving, which are foundational principles of PjBL. For example, virtual chemistry labs embedded within project assignments allow learners to simulate experiments multiple times, manipulate variables, and analyze outcomes as part of real-world problem scenarios (Hasan, 2024). In sum, VR and AR are not just engaging innovations; they serve as cognitive amplifiers in chemistry education. When integrated into PjBL contexts, they allow students to see, do, and understand chemical processes in ways that are both rigorous and personally meaningful.

The convergence of Virtual and Augmented Reality (VR/AR) with Project-based Learning (PjBL) represents a significant evolution in chemistry education. While these methodologies can independently foster engagement and deeper understanding, their integration allows students to conduct projects that are interactive, immersive, and inquiry-driven. In chemistry, where experimental practice is traditionally central, this combination offers students simulated environments to design and explore chemical investigations without the limitations of physical lab access. Recent studies show that when VR tools are embedded within structured project tasks, students are not only more engaged but also more capable of applying scientific thinking (Han & Fung, 2024; Hasan, 2024; Soroko et al., 2021). For example, the use of mobile-based AR in chemistry lab assignments allowed students to manipulate digital representations of lab equipment and chemicals as part of exploratory research tasks, enhancing their problem-solving abilities and conceptual clarity (Luis et al., 2013).

In a broader context of STEM education, immersive technologies have been used to structure interdisciplinary PjBL environments. Students working on science projects using VR such as analyzing optical properties or chemical behaviors were able to formulate hypotheses, test variables in virtual simulations, and present findings using digital visualization tools. These practices mirror authentic scientific processes, and VR made these steps more accessible and less resource-dependent (Alexiou et al., 2005).

Moreover, the pedagogical design of PjBL can be strengthened by VR features such as scenario-based learning, simulated experiments, and interactive 3D environments. In these settings, students are guided through problem-solving tasks that demand the application of chemistry concepts to real-world contexts. This immersive element helps bridge the gap between theory and practice and promotes sustained engagement over time (Paigude & Shaikh, 2019).

Importantly, immersive PjBL in chemistry also supports inclusive education. By enabling remote, digital participation, students who face geographical or physical barriers to traditional labs can still take part in collaborative, Project-based learning experiences that are academically rigorous and socially engaging (Yağcı & Şentürk, 2023). Overall, the integration of VR/AR into PjBL in chemistry fosters a learning ecosystem where students are not just recipients of knowledge but active investigators engaging in meaningful, inquiry-based exploration.

Despite the growing use of Virtual and Augmented Reality in education and the increasing popularity of Project-based Learning as a learner-centered strategy, there remains a notable gap in the literature regarding their combined application in chemistry education. While studies have explored VR or PjBL individually within science contexts, few have systematically examined how these two approaches intersect specifically in the teaching and learning of chemistry.

Recent research has tended to focus on either the technological affordances of VR/AR tools or the general benefits of PjBL for improving student engagement and critical thinking in STEM subjects (Kishoyan & University, 2013). Although there has been some research on the integration of PjBL and VR/AR in science education, the ways in which these immersive technologies specifically enhance Project-based inquiry, experimentation, and collaborative learning in chemistry remain limited and underexplored. This is particularly true for secondary and higher education, where chemistry often involves abstract concepts that are difficult to visualize and require experimental validation.

Moreover, while platforms such as virtual labs and simulation software have become more accessible, studies often fail to assess their integration into structured pedagogical models like PJBL. As a result, there's limited guidance on best practices for educators looking to combine these tools in meaningful, curriculum-aligned ways (Dahlman-Höglund et al., 2022). Furthermore, existing reviews tend to lump chemistry with broader STEM or general science education, overlooking the discipline-specific needs such as chemical safety, visualizing molecular dynamics, or reaction kinetics. Given these gaps, this review seeks to:

1. Analyze how VR/AR technologies have been used within PjBL frameworks specifically in chemistry education;
2. Evaluate the effects of this integration on student engagement, understanding, and motivation;
3. Identify key challenges faced by educators in adopting immersive PJBL approaches in the chemistry classroom.

By focusing on studies published between 2020 and 2025, this review aims to capture the most recent developments in digital pedagogy and post-pandemic education strategies. In doing so, it contributes to a more nuanced understanding of how immersive tools can transform chemistry learning when aligned with inquiry-based and project-driven methods.

METODE

This review was conducted to systematically analyze recent research on the integration of Project-based Learning (PjBL) and Virtual or Augmented Reality (VR/AR) in chemistry education, with a focus on pedagogical design, student outcomes, and implementation challenges. The process followed a transparent and structured protocol for search, selection, and thematic synthesis. This systematic literature review (SLR) was guided by the following research questions:

1. How are Virtual and Augmented Reality (VR/AR) technologies integrated within Project-Based Learning (PjBL) frameworks in chemistry education?
2. What are the reported impacts of immersive PjBL on student engagement, conceptual understanding, and motivation in chemistry?
3. What challenges and limitations do educators face when implementing VR/AR-based PjBL in chemistry classrooms?

Database and Search Strategy

The literature search was conducted using the Dimensions.ai research platform, a comprehensive scientific database with access to peer-reviewed open-access publications. The following Boolean search string was used:

a) Query: "Project-based Learning" AND ("Virtual Reality" OR "Augmented Reality") AND Chemistry
b) Years covered: 2020–2025
c) Filters applied: Open Access, English language, Peer-reviewed publications

This search yielded a total of 16,652 documents matching the criteria broadly.

Inclusion and Exclusion Criteria

To ensure relevance and academic rigor, the following inclusion criteria were applied:

Table 1. Inclusion criteria

Inclusion Factor	Specification
Subject Focus	Chemistry education
Pedagogical Integration	Combines Project-Based Learning (PjBL) with VR or AR
Type of Study	Empirical research, literature review, or documented case study
Education Level	Secondary or higher education
Accessibility	Open access, full-text available
Language	English
Journal Quality	Indexed in reputable databases (e.g., Scopus, DOAJ), verified via Dimensions.ai or journal websites

Exclusion criteria included:

Table 2. Exclusion criteria

Exclusion Factor	Reason for Exclusion
Subject Mismatch	Studies not addressing both PjBL and VR/AR together
Non-Chemistry Context	Articles focused on STEM fields other than chemistry (e.g., physics, biology)
Language Barrier	Non-English publications
Accessibility Issue	Inaccessible or non-open-access full texts

Screening and Final Selection

The search results (n = 16,652) were screened in three stages:

a) Title and abstract review to filter for relevance.
b) Full-text screening for explicit integration of immersive technologies within PJBL in chemistry.
c) Eligibility checks based on the inclusion criteria above.

After this multi-step process, 8 journal articles were selected for inclusion in the final review. These publications represent a range of contexts (secondary and tertiary education), technologies (VR, AR, virtual labs), and implementation models.

Data Extraction and Thematic Analysis

The following information was extracted from each selected study:

a) Author(s), year, and article title
b) Education level (secondary or tertiary)
c) Type of immersive technology (VR/AR)
d) PjBL structure and implementation strategy
e) Reported student outcomes (e.g., motivation, understanding, engagement)
f) Reported educator or systemic challenges

The studies were then grouped and analyzed thematically according to the three guiding research questions, identifying key patterns, gaps, and implications for future practice.

RESULTS AND DISCUSSION

To address the research questions, a total of 8 open-access journal articles published between 2020 and 2025 were selected based on their explicit focus on the integration of Project-based Learning (PjBL) and Virtual or Augmented Reality (VR/AR) in chemistry education. These studies represent a range of educational contexts, from secondary schools to higher education institutions, and explore diverse applications of immersive technologies in Project-based learning environments. The following table summarizes the key characteristics and findings of each article, providing a foundation for the thematic discussion that follows.

Table 3. Selected articles from 2020-2025

Author (Year)	Title	Education Level	Focus / Intervention	Key Findings / Contributions
Nechypurenko et al. (2023)	Cloud technologies of augmented reality as a means of supporting educational and research activities in chemistry	Secondary (Grade 11)	Developed a cloud-based AR chemistry lab using A-Frame and AR.js	AR tools enhanced research-oriented projects by simulating chemical reactions visually
Babinčáková & Bernard (2020)	Online Experimentation during COVID-19	Secondary	Remote chemistry teaching using online platforms during COVID-19	Identified shifts in student motivation and teacher challenges in virtual labs
Kubiliene et al. (2024)	Digital support in chemistry education	Secondary / Tertiary	Reviewed various digital tools including VR and simulations	VR enhanced engagement and understanding; digital literacy was key to success
Soroko et al. (2021)	Using VR tools for the development of STEAM education	Secondary	Teaching chemistry and physics with VR-based projects	VR supported cross-disciplinary projects and improved visualization in complex topics
Han & Fung (2024)	Spatial reality in chemistry education in Singapore	Tertiary	Shared teacher experiences integrating VR and dealing with VR anxiety	Offered best practices for overcoming educator resistance and improving implementation
YAĞCI & ŞENTÜRK (2023)	Metaverse in science education	Secondary	Described immersive VR environments for science (incl. chemistry)	Metaverse tools enabled collaboration, interactivity, and motivation in PJBL
Li et al. (2023)	Innovations in distance learning	Higher Education	Reviewed TLIs including VR, AR, and Project-based science activities	Found VR-based science tasks to be effective in digital environments
Hasan (2024)	Virtual labs in engineering & technology	Tertiary (Engineering)	Promoted sustainable, virtual science labs with PJBL structure	While not chemistry-specific, insights apply to lab simulation and remote access

Integration of VR/AR into Project-based Chemistry Education

The integration of Virtual and Augmented Reality (VR/AR) into Project-based Learning (PjBL) in chemistry education has enabled significant innovation in how students engage with complex scientific concepts, especially in environments with limited access to physical laboratories. Across the selected studies, VR and AR were not used as standalone tools, but as supportive frameworks that enhance student-driven exploration, simulate experiments, and facilitate visual understanding of chemical phenomena within PjBL models.

In secondary education, a prime example is the development of a cloud-based AR chemical lab by Nechypurenko et al., (2023), where students used mobile devices and AR markers to trigger video-based simulations of chemical reactions. This setup allowed learners to interact with virtual reagents and observe outcomes, supporting inquiry-based PjBL tasks even outside the physical classroom. Similarly, Soroko et al., (2021) demonstrated how VR tools supported STEAM-oriented PjBL projects, helping students conceptualize topics such as optics and chemistry through immersive, interdisciplinary activities.

At the tertiary level, Han & Fung, (2024) reported the use of Spatial Reality technologies in university-level chemistry, highlighting how VR-enabled learning environments were integrated into structured research assignments. These experiences offered students not only visual representations of chemical structures and processes but also collaborative tools that mimicked real research workflows key elements of PjBL. Further illustrating this, Zhang & Liu, (2024) designed and implemented over 40 virtual simulation projects across university programs, showing how virtual labs enabled scalable, student-driven experimentation that aligns with sustainability and higher education goals

Beyond specific platforms, the general role of VR in facilitating Project-based engagement is reflected in broader reviews such as Kubiliene et al., (2024) who emphasized that digital simulations and virtual environments help create realistic problem-solving contexts essential for PJBL. The findings also noted that the integration of VR in PjBL was most effective when paired with clear learning goals, guided inquiry, and adequate teacher support.

A notable contextual factor came from the COVID-19 pandemic, which forced educators to rapidly shift to remote learning. Babinčáková & Bernard, (2020) showed that this disruption led to an increase in creative use of online labs and digital tools, often restructured around PjBL principles due to the absence of traditional labs. These adaptations laid a foundation for more permanent incorporation of VR and AR technologies in curriculum design (Asino et al., 2022; Dermott et al., 2023).

Student Engagement, Motivation, and Understanding in Immersive PjBL Environments

The use of Virtual Reality (VR) and Augmented Reality (AR) within Project-based Learning (PjBL) frameworks in chemistry education has shown notable benefits for student engagement, conceptual clarity, and motivation, as evidenced across the selected studies from 2020 to 2025.

A consistent theme across the literature is that immersive environments increase student engagement by making abstract or microscopic chemical phenomena tangible. For instance, Nechypurenko et al., (2023) found that the AR chemical lab promoted deeper involvement in PJBL tasks, with students actively experimenting by scanning AR markers to simulate reactions. The interactivity enabled learners to manipulate virtual reagents and observe outcomes in real time, increasing their participation and interest in otherwise inaccessible experiments.

Similarly, Kubiliene et al., (2024) reported that digital tools, including VR-based simulations and virtual chemistry labs, significantly enhanced comprehension of complex concepts, such as molecular structures and reaction mechanisms. Their review found that students using immersive media in project tasks not only retained knowledge longer but also developed better spatial reasoning skills an essential competency in chemistry. This aligns with results from Rebello et al., (2024) ,who showed that AR in chemical engineering enhanced student engagement and autonomy through safe, visualized experimentation with complex systems.

Evidence from the pandemic era also highlights VR's motivational value. During the forced shift to online learning, Babinčáková & Bernard, (2020) observed that students found digital chemistry tasks more engaging than traditional textbook exercises. The ability to perform "virtual experiments" at home through guided project tasks maintained student interest during school closures, underscoring VR's role in sustaining motivation under challenging conditions.

In higher education, Han & Fung, (2024) showed that students not only understood chemistry content more effectively in spatial VR environments but were also more enthusiastic about participating in research-style PJBL activities. These virtual tools mimicked laboratory and collaborative scenarios, making learners feel like contributors to real scientific inquiry (Lu et al., 2021).

Additionally, Soroko et al., (2021) and Yağcı & Şentürk, (2023) emphasized that VR-driven environments promoted collaborative learning and autonomy, both of which are central motivators in PjBL. Students were more likely to take initiative, explore alternatives, and reflect on outcomes when immersed in interactive simulations that allowed peer collaboration and individual exploration (Tene et al., 2024).

Challenges in Implementing VR-Based PjBL in Chemistry Classrooms

While Virtual and Augmented Reality technologies have demonstrated strong pedagogical potential in Project-based Learning (PjBL) for chemistry, educators face significant challenges that impact adoption and effective implementation. These challenges fall into three main categories: technological barriers, pedagogical integration difficulties, and educator-related psychological resistance.

Technological Limitations

One of the most cited obstacles is access to suitable hardware and stable infrastructure. For example, Yağcı & Şentürk, (2023) reported that high costs of VR headsets and advanced computing equipment limit the widespread use of immersive tools in public school settings. This digital divide is particularly pronounced in under-resourced institutions, where even basic connectivity can be an issue (Mondal & Mondal, 2025).

Han & Fung, (2024) also highlighted that VR adoption requires not just hardware, but ongoing technical support, training, and reliable software ecosystems. Educators in their study expressed concerns over device compatibility, classroom setup time, and maintenance factors that often discourage routine use in chemistry labs (Castro et al., 2024).

Pedagogical Integration Challenges

Even when technology is available, many educators struggle to align VR tools with curriculum standards and to design coherent Project-based learning tasks. Kubiliene et al., (2024) noted that while VR tools can enhance student learning, teachers often lack guidance on how to transform immersive interactions into meaningful inquiry or assessment. The risk is that VR becomes a novelty rather than a deeply integrated part of a PjBL cycle (Rodriguez et al., 2023).

Li et al., (2023) emphasized the need for pedagogical frameworks that embed VR within structured project tasks, suggesting that success is highest when VR is paired with inquiry-based questioning, collaboration, and reflection—not used in isolation.

Psychological Resistance and Skill Gaps

Perhaps most significantly, Han & Fung, (2024) introduced the concept of "VR teaching anxiety" a form of psychological resistance that stems from unfamiliarity with immersive technology, fear of classroom failure, or lack of digital confidence. Many chemistry teachers, especially those trained in traditional methods, feel overwhelmed by the steep learning curve required to effectively implement VR-based lessons.

To counter this, the authors recommend gradual exposure to VR tools, peer mentoring, and embedding training into teacher professional development programs. They also stress the importance of institutional support to encourage experimentation and reduce fear of failure (Howorth et al., 2024).

FUTURE PERSPECTIVES

While the current body of research demonstrates the potential of integrating VR/AR within Project-based Learning in chemistry education, several avenues remain underexplored and present valuable directions for future work. First, there is a need for longitudinal studies that examine the sustained impact of immersive PJBL approaches on student learning outcomes over time. Second, teacher training and digital pedagogy must become central areas of research, particularly regarding how educators can be supported in designing and facilitating VR-based project tasks aligned with curricular goals. Additionally, there is room to develop standardized evaluation frameworks to measure the effectiveness of immersive PJBL across diverse educational settings. Finally, future studies should investigate scalability and accessibility, ensuring that immersive technologies do not widen the digital divide but are implemented in ways that are inclusive, equitable, and context-sensitive especially in under-resourced schools.

CONCLUSION

This review has synthesized recent research on the integration of Project-based Learning with Virtual and Augmented Reality in chemistry education, highlighting how immersive technologies are reshaping student engagement, conceptual understanding, and instructional design. The analysis of 8 selected studies revealed that VR/AR tools effectively support Project-based inquiry by enabling students to simulate experiments, visualize complex molecular interactions, and collaborate in authentic learning scenarios. These technologies enhance both motivation and comprehension, particularly in contexts where traditional laboratory access is limited.

At the same time, the review identified key challenges in implementation, including limited access to technology, curriculum alignment issues, and educator hesitation linked to digital competence and pedagogical confidence. Despite these barriers, the findings suggest that when VR/AR is purposefully embedded into PJBL frameworks, it can transform chemistry learning into a more student-centered, interactive, and inquiry-driven experience.

Given the limited number of deeply integrated studies, especially at the intersection of all three elements PjBL, VR/AR, and chemistry future research should focus on long-term classroom implementations, teacher professional development, and scalable models of immersive PJBL. This will be essential for realizing the full pedagogical potential of immersive learning in science education.

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