Development and Validation of a Mixed-Reality System to Enhance Student Engagement and Learning in Secondary Chemistry

Albertson D. Amante[1,2,*], Bryan John A. Magoling[3,4], John Paul B. Heje[2], Louie L. Villaverde[1,5], Matthew L. Mendoza[2], Lee Robert P. Velasquez[2], and Joash Samuel D. David[2]

[1]Department of Electronics and Communication Engineering, College of Engineering, Batangas State University, The National Engineering University-Alangilan, Alangilan, Batangas, Philippines
[2]STEER Hub, Batangas State University, The National Engineering University-Alangilan, Alangilan, Batangas, Philippines
[3]College of Arts and Sciences, Batangas State University, The National Engineering University-Pablo Borbon, Rizal Avenue Extension, Batangas, Philippines
[4]Material Testing and Calibration Center, STEER Hub, Batangas State University, The National Engineering University-Alangilan, Alangilan, Batangas, Philippines
[5]Manufacturing Research Center, STEER Hub, Batangas State University, The National Engineering University-Alangilan, Alangilan, Batangas, Philippines
Email: albertsonamante@g.batstate-u.edu.ph (A.D.A); bryanjohn.magoling@g.batstate-u.edu.ph (B.J.A.M.); johnpaul.heje@g.batstate-u.edu.ph (J.P.B.H); louie.villaverde@g.batstate-u.edu.ph (L.L.V.); matthew.mendoza@g.batstate-u.edu.ph (M.L.M.); leerobert.velazquez@g.batstate-u.edu.ph (L.R.P.V.); joashsamuel.david@g.batstate-u.edu.ph (J.S.D.D.)
*Corresponding author
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***Abstract*—This study developed and validated a web-based Mixed Reality (MR) system to enhance chemistry learning in schools with limited laboratory resources. Developed using WebXR and the Three.js JavaScript Library, the system delivers immersive, browser-based simulations of distillation and filtration laboratory experiments compatible with the Meta Quest 3 headset. Grade 10 students and six chemistry teachers from an integrated high school in the Philippines evaluated the system's usability, engagement, and instructional effectiveness through surveys and pre- and post-test comparisons. Results indicated a significant increase in students' conceptual understanding, with post-test scores rising from 89.33 to 94.67 ($t(44) = 2.737$, $p = 0.008919$). Students reported high engagement (mean = 3.71 for interaction enjoyment; 3.56 for learning excitement), while teachers rated usability and engagement at 3.83 and 4.00, respectively. These outcomes confirm that the Mixed Reality (MR) system fosters active and experiential learning while reducing reliance on physical laboratories, underscoring MR's potential to make chemistry education more accessible and pedagogically effective in resource-constrained settings.**

***Keywords*—Mixed Reality (MR), chemistry education, virtual laboratory, student engagement, learning outcomes**

I. Introduction

Many developing nations, including the Philippines, continue to face persistent challenges in science education, particularly in chemistry, as evidenced by their underperformance in the Program for International Student Assessment (PISA). Since joining PISA in 2018, the Philippines has consistently lagged behind, with only 22% of Filipino students reaching the minimum proficiency level in science, compared to 78% in OECD countries [1]. More specifically, only 23% of Filipino students attained Level 2 or higher in science, which is far below the OECD average of 76% [2]. Furthermore, the absence of top-performing students proficient at Level 5 or 6 further underscores the gap in students' ability to engage with complex scientific concepts [2]. This underachievement is attributed not only to a lack of resources but also to limited access to modern educational technologies and effective teaching methodologies.

A significant factor contributing to these challenges is the limited availability of resources for teaching and learning chemistry. Many schools, especially in rural areas, lack the necessary science laboratory facilities, updated instructional materials, and access to modern technology, which hinders their ability to effectively engage students in practical, hands-on learning experiences [3–6].

This gap in educational resources and pedagogical approaches results in limited opportunities for students to actively engage with core concepts and experiment in a laboratory setting. The absence of such resources limits the ability to implement inquiry-based and interactive learning approaches, which are essential for fostering deeper understanding and engagement in chemistry education. Even in better-resourced settings, concerns about the risk of accidents and breakage of fragile glassware often result in restricted or highly supervised access to laboratory facilities. These limitations contribute to low student engagement and a decline in interest in laboratory-based learning, particularly among younger students who may find it difficult to grasp abstract chemical concepts without experiential support.

Such challenges call for innovative educational solutions that uses technology to bridge the gap between theoretical knowledge and practical application in a safe, accessible, and engaging manner. Consequently, there is a growing need for alternative instructional approaches that are safe, cost-effective, and capable of fostering meaningful engagement with core Chemistry laboratory concepts in secondary education.

As educational practices evolved, technology-enhanced learning gained prominence, particularly through the adoption of blended learning models, personalized learning environments, and learner-centered instructional approaches [7, 8].

Among the most promising technological solutions was the integration of Virtual Reality (VR) and Augmented Reality (AR), often combined as Mixed Reality (MR), which provided immersive educational experiences that extended beyond traditional learning methods and helped bring complex, abstract concepts to life, making them easier for students to understand [9–11]. MR technology has the potential to offer immersive, interactive experiences that allow students to visualize complex chemical processes and conduct virtual experiments, addressing the limitations of traditional laboratory setups. However, while there is substantial research on the impact of AR and VR in education, a notable gap exists in studies focusing on the integration of MR in secondary education, particularly for chemistry instruction. This study aims to fill this gap by exploring the effectiveness of a Mixed Reality system specifically designed to enhance Chemistry teaching in the Philippine secondary education context.

Mixed Reality combines virtual and physical elements in a cohesive environment, allowing learners to interact with real-world and digital content in an immersive way. It is especially effective in teaching complex or abstract concepts, offering learners an experiential way to engage with content that would be challenging to visualize in traditional settings [12]. Augmented Reality (AR) enables the superimposition of computer-generated virtual 3D objects onto a real environment in real-time, facilitating ubiquitous, collaborative, and localized learning, which makes it the foundation of mixed reality [7, 13–16]. Mixed reality relies on three key elements: (a) blending physical objects with virtual ones, (b) allowing them to interact in real time, and (c) mapping the virtual and real objects so they can respond to each other instantly [17]. Even beyond the pandemic, mixed, virtual, and augmented reality remains a powerful tool, making hands-on learning more accessible and turning abstract scientific concepts into engaging, tangible experiences. This technology supports presentations and material explanations in improving student learning outcomes and understanding [18, 19]. More recent and pertinent studies on learners' self-efficacy and conceptions of learning have shown that applying MR, AR, and VR technology in education can significantly enhance educational effectiveness [20–23].

Geller *et al.* [24] have demonstrated that MR can enhance learning outcomes by improving students' understanding, retention, and application of scientific concepts. However, despite these benefits, there remains limited research on the effectiveness and acceptability of MR-based learning in secondary education, particularly for Grade 10 students. One challenge that MR, VR, and AR users face is the intuitive interface and hardware [13]. The MR interface must consider how to display the data to a user and how the user should interact with the data.

To address key gaps in the effective delivery of Chemistry laboratory concepts to Science, Technology, Engineering, and Mathematics (STEM) learners, this study aimed to develop Mixed Reality (MR) modules specifically designed for STEM education. These modules were intended to enhance students' conceptual understanding through interactive and immersive engagement, providing a safer, more cost-effective, and accessible alternative to traditional laboratory instruction. To facilitate broader access and ease of integration into educational settings, the researchers also developed a web-based platform that allows for the deployment of virtual laboratory modules. This platform enables learners to access simulations at any time and from anywhere using a standard web browser, eliminating the need for specialized hardware and ensuring greater flexibility in implementation across diverse learning environments.

This study evaluated the acceptability, usability, and effectiveness of the MR system, an MR-based chemistry laboratory learning tool, among Grade 10 students. It aimed to assess students' initial perceptions and overall satisfaction with the MR interface, specifically in relation to common laboratory glassware. The researchers further aimed to assess learning engagement, immersion, and conceptual understanding facilitated by the system compared to traditional instructional methods. Through a combination of user perception analysis, usability evaluation, and a pretest-posttest design, the study generated data-driven insights into the pedagogical impact of MR in enhancing laboratory experiences. Additionally, the research incorporated the perspectives of Chemistry teachers regarding integrating the MR system into the curriculum, providing a comprehensive evaluation of its educational value and implementation potential.

II. Literature Review

The integration of immersive technologies such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) into STEM education has been shown to significantly enhance teaching and learning by providing immersive, interactive experiences that bridge the gap between theoretical knowledge and practical application [25, 26]. While a growing body of research exists on the use of AR and VR in education, the application of MR—where physical and virtual elements are seamlessly blended—remains relatively underexplored, particularly in secondary education and specifically for Chemistry learning. Previous studies on AR demonstrate its ability to foster student-centered, discovery-based learning by enabling students to interact with virtual objects embedded within real-world environments [27].

This aligns with the educational philosophy of Maria Montessori, which emphasizes that intellectual growth is deeply connected to physical activity and sensory experiences [28, 29]. The researchers' system design reflects this philosophy by incorporating AR elements that allow students to manipulate 3D chemical structures and conduct virtual experiments, promoting active learning and deep engagement with chemistry content.

Studies have also shown that AR-based simulations can address common challenges in chemistry education, such as limited laboratory resources and safety concerns [30, 31]. These findings have directly influenced the researchers' decision to offer risk-free, virtual lab experiences that allow students to engage in complex chemical processes without the safety risks associated with traditional labs. Additionally, research on cognitive load suggests that MR environments can reduce extraneous cognitive load by simplifying complex tasks through real-time guidance, thereby helping students focus on core learning objectives [32]. This is crucial in

chemistry, where abstract concepts such as molecular geometry and chemical reactions are challenging for students to grasp.

MR technologies can provide interactive visualizations that simplify these complex topics. This principle has been incorporated into the system design by ensuring that the user interface is intuitive, with clear instructions and interactive elements to guide students through chemical simulations. According to Sanchez [33], the incorporation of innovative technologies, such as simulations and virtual laboratories, has been a critical aspect of enhancing student engagement and learning in chemistry education.

This aligns with the research highlighting the benefits of MR environments, where interactive and immersive simulations can overcome challenges in traditional lab setups, offering risk-free and engaging learning experiences. MR-based learning has been shown to enhance engagement by providing students with an active role in learning, enabling them to manipulate objects, explore virtual environments, and visualize abstract chemical concepts in a manner that traditional methods cannot achieve.

Furthermore, MR-based learning is shown to enhance not only the cognitive domain but also the affective and psychomotor domains [15, 34, 35], particularly in disciplines like chemistry, where abstract concepts like molecular geometry can be difficult for students to visualize and understand. These elements of engagement—cognitive, emotional, and practical—are essential for fostering deeper learning experiences, and MR supports this by providing hands-on, immersive simulations. The effectiveness of MR in this regard has led us to design our system to allow students to interact with 3D molecular models and visualize reactions in real-time, which research has identified as critical for improving student engagement and understanding [35, 36].

This approach is particularly important in chemistry, where traditional instructional methods often fail to provide students with the tools needed to grasp such abstract concepts. Sanchez emphasizes the importance of incorporating multiple representations—macroscopic, microscopic, and symbolic—in teaching chemistry [37]. This approach reduces cognitive load and enhances students' understanding of abstract concepts, such as molecular structures, thereby supporting the effectiveness of MR in reducing extraneous cognitive load.

Tools like Labster, HoloLab, and ARchemist have demonstrated the potential of immersive technologies to provide interactive, risk-free environments for simulating laboratory experiments [38–41]. The researchers develop the MR system influenced by these platforms, particularly in terms of their ability to offer real-time feedback and support repeated practice of lab protocols. While these platforms focus on simulations, our study further incorporates interactive 3D manipulation of lab equipment, offering a more hands-on approach that mirrors real-world experimental tasks.

Building on these models, tactile simulations and haptic feedback were integrated into the MR system to enhance the experiential learning process, as these elements have been shown to improve engagement and understanding in STEM disciplines [42]. This move toward including sensory feedback adds a layer of immersion that is critical for enhancing learner interaction and engagement in chemistry education. As identified by Sanchez [33], validating teaching innovations through comprehensive tools, such as the Chemistry Teaching Innovations Validation (CTIV) tool, is essential to ensure that new pedagogies align with curricular goals and enhance student learning outcomes. This validation process is crucial for MR systems to ensure they meet the learning objectives and support effective technology integration in classrooms.

While MR technologies show great promise, several studies highlight barriers, including technical constraints, high costs, and cognitive overload resulting from poorly designed interfaces [43, 44]. These challenges were carefully considered in the system's design, ensuring that the MR platform is accessible even in resource-constrained environments, with a web-based platform that minimizes hardware requirements. Papagiannidis and Marikyan [45], Ibáñez *et al*. [46] were focused on making the interface as user-friendly as possible, aligning with research on the importance of intuitive design for fostering technology adoption among students.

The Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) underscore the importance of perceived ease of use and usefulness in the adoption of new technologies [44, 45]. This research also draws from these models, aiming to assess how students perceive the usability and instructional efficacy of the MR system to gauge its potential for widespread adoption. Informed by these models, the study seeks to assess how Grade 10 students perceive the usability and instructional efficacy of the MR system, with a focus on navigability, engagement, and overall satisfaction [36]. Supporting findings from Ibáñez *et al*. [46] emphasize the importance of aligning technology interfaces with learning objectives to enhance student adoption and engagement, which directly influenced the user-centered design of our MR system.

In summary, the literature suggests that MR technologies hold significant potential for transforming chemistry education by providing interactive, risk-free environments where abstract concepts can be visualized and manipulated. Despite this promise, there remains limited research on how these technologies can be effectively integrated into the secondary-level curriculum. The developed MR system in this study addresses this gap by building on prior research findings and design principles, aiming to overcome key challenges in chemistry instruction while offering a more engaging, accessible, and pedagogically sound alternative to traditional laboratory methods.

Building on these insights, the reviewed studies collectively demonstrate that immersive technologies such as AR, VR, and MR transform science education by connecting abstract theory with tangible experience through interactivity and visualization. Previous AR and VR studies emphasized their role in enhancing engagement, reducing cognitive load, and supporting conceptual understanding through realistic simulations and intuitive interfaces.

These evidence-based insights guided the design of the developed MR system, which incorporates three core pedagogical features: (1) interactive 3D manipulation of laboratory apparatus to strengthen experiential and

constructivist learning; (2) real-time feedback and guided instruction to reduce extraneous cognitive load and improve procedural accuracy; and (3) web-based accessibility to promote inclusivity and usability in resource-constrained educational environments. By integrating these features, the present study extends prior AR/VR research into a Mixed Reality framework specifically tailored to secondary chemistry education, addressing both pedagogical and infrastructural limitations identified in earlier works.

III. Methodology

A. Research Design

The methodological framework for the MR system is guided by the theoretical model illustrated in Fig. 1, which outlines the essential phases for developing, implementing, and validating the proposed virtual engineering laboratory. These phases include stakeholder consultation, prototype development using Mixed Reality (MR), deployment *via* a web-based platform, and testing with academic and/or industry partners. This framework facilitated a structured approach to designing an interactive learning experience tailored to the needs of the students. The modules were refined through iterative evaluations and user consultations to enhance usability, engagement, and effectiveness in chemistry education.

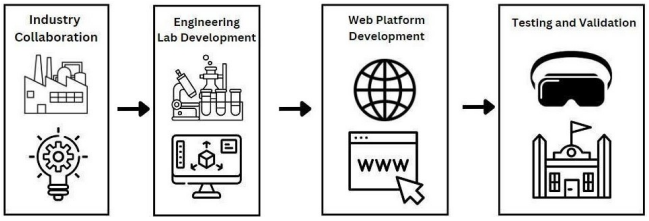

Fig. 1. Flowchart illustrating the development framework of the MR system. The diagram outlines the sequential stages involved in designing, implementing, and deploying mixed reality Chemistry laboratory modules within the platform.

For the hardware component, the learning modules were developed using the Meta Quest 3 Mixed Reality (MR)/Virtual Reality (VR) headset, which enabled immersive and interactive simulation experiences within the MR system. The Meta Quest 3 was selected for its economical, reliable, and flexible performance compared to other headsets in the market. As a standalone device, it eliminates the need for high-end external computing hardware, making it a cost-effective option for educational deployment. Its advanced mixed reality capabilities, robust developer support, and portability make it an ideal platform for delivering high-fidelity, physics-based Chemistry laboratory simulations in both classroom and remote settings.

The two Chemistry laboratory modules—Distillation and Filtration—were developed in alignment with the Grade 10 Science curriculum, ensuring that the content is pedagogically appropriate and relevant to learners at this educational level. These modules were specifically designed to enhance student engagement by providing an interactive and immersive learning experience through mixed reality. To ensure broader accessibility and ease of use, the developed Chemistry laboratory modules were designed to be deployed through a web-based platform.

Fig. 2 depicts the workflow of the MR system's architecture and deployment process. To support immersive deployment while minimizing installation complexity, the system was developed using WebXR in combination with the Three.js JavaScript library. WebXR enabled native virtual reality interactions directly within the Meta Quest 3 browser, while Three.js handled efficient rendering and real-time manipulation of 3D scenes. Compared with standalone Unity or Unreal applications, this web-based approach reduced CPU and memory demands, improved load times, and simplified scalability for classroom use without requiring large local installations.

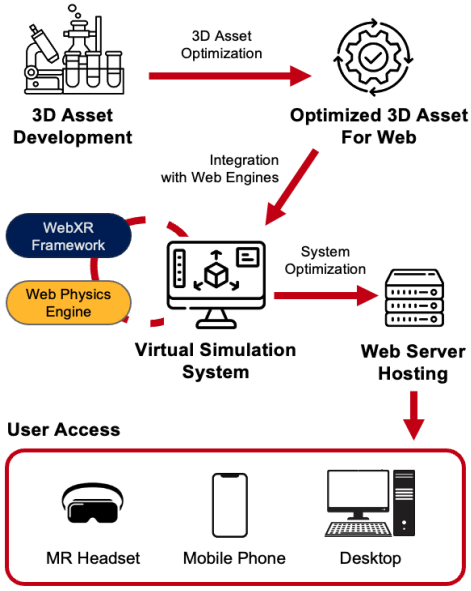

Fig. 2. Flowchart illustrating the MR system's architecture and deployment process.

The 3D assets and laboratory apparatus (e.g., flasks, condensers, funnels, filters) were created in Blender. Optimization techniques such as polygon reduction, texture compression, and efficient material mapping minimized GPU overhead. On the Meta Quest 3, scene memory consumption was maintained below 500 MB, with runtime memory usage averaging 1.2–1.5 GB. This configuration ensured smooth performance at 72–90 FPS. Compressed assets were streamed and cached directly on the headset, reducing storage requirements and avoiding long load sequences.

From a usability perspective, the system was designed to be lightweight and portable within the VR headset ecosystem. CPU utilization on Meta Quest 3 hardware typically ranged from 20–35% during interactive laboratory sessions, sustaining stable performance even during extended use. Accessibility was enhanced through intuitive controller mappings and interaction metaphors that mirrored real-world laboratory procedures, reducing learners' cognitive load.

Deployment and maintenance were streamlined through the web-based delivery model. Updates and feature upgrades required no user-side installation, as revisions were hosted centrally and automatically accessed through the headset browser. Backup and recovery mechanisms employed periodic asset and database snapshots, enabling quick restoration in case of server-side issues. A modular architecture supported incremental updates without disrupting ongoing classroom activities, while cloud hosting ensured scalability across multiple concurrent VR users.

Finally, the iterative development process combined technical assessment with pedagogical validation. Hardware performance monitoring (CPU load, memory usage, frame stability, latency) guided optimizations, while usability testing with students and consultations with educators informed refinements in interaction flow, instructional clarity, and curriculum alignment. These measures ensured that the MR system delivered a robust, efficient, and pedagogically effective VR learning platform, fully optimized for exclusive headset deployment.

B. Assessment of the MR System

The developed MR system for Chemistry laboratory instruction was assessed based on key evaluation parameters, including usability, student engagement and immersion, learning effectiveness, and overall acceptability and satisfaction. To measure the system's effectiveness and user experience, the researchers employed two primary instruments: a structured survey questionnaire and pre-test and post-test assessments. The survey captured student perceptions on the module's interface, interactivity, and overall satisfaction, while the test scores were used to evaluate learning gains and conceptual understanding before and after exposure to the mixed reality Chemistry modules.

1) Research participants

This study involved 48 Grade 10 students and six Science teachers from the Integrated School of Batangas State University—The National Engineering University, Batangas City, Philippines. The Grade 10 population consisted of two heterogeneous classes with 45 students each, totaling 90 students.

A random sampling procedure was conducted using an online random number generator. Initially, 10 students from each section were randomly selected for pilot testing, resulting in a total of 20 students. These participants were excluded from the actual testing to avoid bias. For the actual testing, the same randomization method was employed to select 24 students from each section.

Following data gathering, three students were unable to complete both the pretest and posttest, resulting in 45 valid paired responses for analysis. This sample size satisfied a 95% confidence level and a 5% margin of error, ensuring representativeness of the Grade 10 population.

All six Science teachers from the Integrated School participated in the study. They provided expert evaluations on the feasibility, pedagogical effectiveness, and curricular alignment of the Mixed Reality (MR) system, as well as its potential to enhance student engagement. Their feedback offered valuable insights into the system's applicability and integration within classroom instruction.

2) Survey instrument

A structured survey was administered to both students and teachers to evaluate the MR system across four key dimensions: usability, student engagement and immersion, learning effectiveness, and overall acceptability and satisfaction. The survey employed Likert scale-based items to systematically capture user experiences and perceptions regarding the functionality, interactivity, and instructional value of the mixed reality modules. The survey instrument used in the research underwent a validation process to ensure its reliability and competence. The face and content validation were conducted through a focus group discussion with three college chemistry professors and two program specialists, who served as experts to assess whether the survey adequately measured the intended constructs.

Following validation, pilot testing was conducted with 20 students to further validate the survey instrument. Table 1 shows the Cronbach's alpha values for usability, student engagement and immersion, learning effectiveness, and overall acceptability and satisfaction.

Table 1. Reliability coefficients obtained from the pilot testing of the MR system

Key Dimensions	Cronbach's alpha coefficient	Verbal Interpretation
Usability	0.858	Good
Student engagement and immersion	0.965	Excellent
Learning effectiveness	0.933	Excellent
Acceptability and satisfaction	0.984	Excellent

The key dimensions yielded Cronbach's alpha coefficients exceeding 0.90 for student engagement and immersion, learning effectiveness, and overall acceptability and satisfaction, indicating excellent internal consistency across these constructs. In contrast, the usability dimension demonstrated alpha values ranging from 0.80 to 0.90, which are considered indicative of good reliability. These robust reliability coefficients affirm that the items comprising the instrument for evaluating the MR system consistently measure the same underlying constructs. Accordingly, no items within the instrument appear to exhibit reliability concerns.

In addition to subjective feedback, pre-test and post-test assessments were conducted to objectively measure changes in student performance. The pre-test was administered prior to exposure to the MR system, while the post-test followed the completion of the simulation-based activities. These assessments focused on evaluating students' understanding of laboratory glassware, key chemical concepts, and their ability to retain information.

A comparative analysis of the pre-test and post-test scores was used to assess learning outcomes and determine the system's effectiveness in enhancing students' conceptual understanding through immersive and interactive instruction.

3) Data analysis

Quantitative data from the structured survey and pre-test/post-test assessments were analyzed using both descriptive and inferential statistical methods. Descriptive statistics, including mean scores and standard deviations, were computed using Excel to evaluate the effectiveness of the MR system across key criteria, such as system usability, student engagement, and knowledge retention. To assess whether the use of the Mixed Reality (MR) modules led to statistically significant improvements in learning outcomes, the pre-test and post-test results were compared using a paired-samples t-test conducted in SPSS. The significance level is set at $\alpha = 0.05$. A p-value of less than 0.05 was

considered statistically significant, indicating that any observed improvements in student performance could be reliably attributed to the use of the MR system.

IV. Results and Discussions

Of the total number of modules developed, two were specifically designed to simulate Chemistry laboratory environments, focusing on the core experimental topics of distillation and filtration (Fig. 3). To ensure broader accessibility and user convenience, these modules were deployed through a web-based platform. This approach enables students to access the simulations using various devices—including mixed reality headsets and standard web browsers—without the need for complex installations or specialized hardware.

The platform also supports both online and offline access, making it especially advantageous for remote learning contexts and educational institutions with limited laboratory resources. By utilizing a browser-based interface, the MR system allows seamless integration into existing Learning Management Systems (LMS), offering educators a scalable, user-friendly solution for delivering immersive and interactive laboratory instruction. This approach significantly enhances the reach and usability of the modules, promoting equitable learning opportunities for students regardless of their physical location or technological capacity.

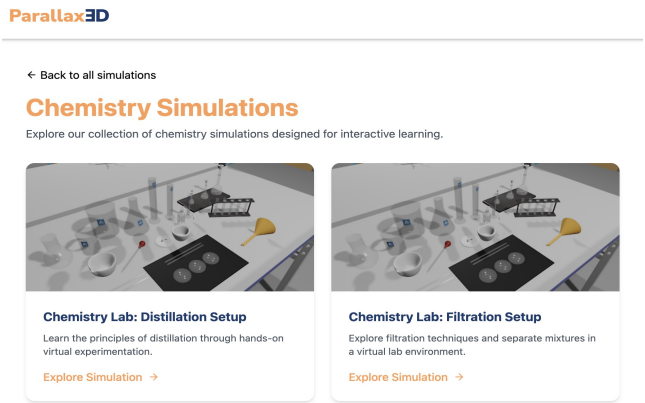

Fig. 3. Two chemistry laboratory modules, distillation and filtration, developed for the MR system and are accessible through a web platform.

Each module incorporates advanced mixed reality features to deliver immersive, interactive, and hands-on simulations, enhancing both learning and training in a virtual environment. These modules are accessible offline or via a web platform and are compatible with the MR headset (Fig. 4). By simulating laboratory procedures in a virtual environment, the system offers a safer alternative to traditional hands-on experimentation, significantly reducing the risk of accidents and minimizing glassware breakage—a common concern in introductory laboratory activities. Furthermore, the modules serve as an effective tool for introducing fundamental Chemistry laboratory concepts, allowing students to build confidence and familiarity with equipment and techniques before engaging in actual wet-lab sessions. This approach supports both conceptual understanding and procedural fluency in a controlled, accessible setting.

The Chemistry simulation modules feature key interactive elements designed to closely mimic real-world laboratory experiences. Central to the system is a realistic grabbing and manipulation protocol, which employs an advanced physics-based interaction model. This allows users to naturally grab, move, and position virtual apparatus using a Mixed Reality (MR) headset, resulting in an intuitive and lifelike experience comparable to handling physical laboratory equipment (Fig. 5).

Fig. 4. The mixed reality headset used to access the MR modules, enabling immersive simulation of laboratory environments.

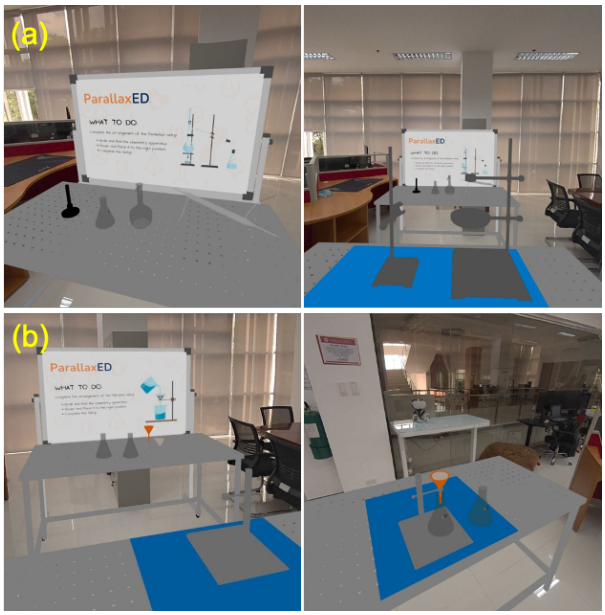

Fig. 5. Screenshots of the mixed reality chemistry laboratory environments showing the (a) distillation and (b) the filtration laboratory modules, as viewed through the MR headset.

The physics-based interaction with the chemistry apparatus further enhances realism by accurately simulating the behavior and physical properties of standard laboratory glassware, such as in a virtual distillation setup. This reinforces core concepts related to phase transitions, separation techniques, and laboratory safety. Within the interactive laboratory environment, users can select tools from a designated virtual workspace and assemble them on a laboratory bench following correct procedural steps. This guided assembly process promotes the development of proper laboratory techniques and adherence to best practices.

Delivering Chemistry laboratory concepts through Mixed Reality (MR) offers distinct pedagogical advantages, particularly in enhancing student engagement, interactivity, and confidence in exploration. Unlike traditional settings where learners may feel hesitant to actively participate due to the risk of breaking fragile glassware, MR environments provide a risk-free space that encourages experimentation without fear of damaging equipment or making mistakes.

This reduction in anxiety fosters a more inclusive and participatory learning experience, especially for students who may be shy or reluctant in hands-on settings. The interactive nature of MR simulations allows learners to manipulate virtual apparatus, follow procedural steps, and observe real-time outcomes of their actions, which promotes active learning and deeper cognitive engagement. By enabling repeated practice and exploration in a safe, immersive environment, MR helps students develop both confidence and competence, making them more prepared and enthusiastic for future real-world laboratory work.

To evaluate the effectiveness of the developed modules, a validation experiment was conducted with a group of Grade 10 students who had prior exposure to basic Chemistry concepts. The students were introduced to the Distillation and Filtration modules through the MR system using Meta Quest 3 headsets in a controlled classroom setting. Prior to the simulation, a brief orientation was provided to familiarize students with the mixed reality interface and navigation controls. During the activity, learners independently explored the virtual laboratory environments, performed tasks such as selecting and assembling apparatus, and followed procedural steps to complete the simulated experiments. Observations were recorded to assess ease of use, engagement levels, and procedural accuracy. After the simulation, students completed a structured survey and participated in a short focus group discussion to gather qualitative feedback on usability, content clarity, and perceived learning outcomes. This validation process provided essential insights into the modules' pedagogical value and user experience, guiding further refinements for broader implementation.

A. Assessment of the Usability of the MR System in Exploring the Chemistry Laboratory Apparatus for Experimental Procedures

To assess how effectively students could explore the Chemistry laboratory apparatus using the MR system, usability was examined across four dimensions: the responsiveness and reliability of the hardware, the intuitiveness of the user interface, the clarity of the instructional prompts, and the overall smoothness of the user experience. These aspects provided insight into the system's practicality and ease of integration into classroom settings.

Table 2 presents a summary of students' responses on the usability of the MR system. The mean score for hardware usability was 3.71, suggesting that students strongly agreed on the system's comfort and ease of use in terms of its hardware components.

These findings suggest that the MR system's physical design is well-suited for educational environments, effectively minimizing technical barriers and allowing students to focus on learning tasks. This is likely due to the system's ergonomic design and intuitive interface, which reduce cognitive distractions, enabling students to engage more deeply with the learning content. This aligns with Cognitive Load Theory, which emphasizes that intuitive tools reduce extraneous cognitive load, thereby enhancing learners' ability to process and retain instructional content [32]. By simplifying the user experience, the system enables students to direct their mental resources towards learning instead of struggling with technical complexities. This is reflected in the design choices made for the system, which incorporated real-time guidance and a user-friendly interface to simplify complex tasks and support focused learning.

Similarly, the user interface usability also received a mean score of 3.71, indicating that students found the platform intuitive and easy to navigate. This suggests that the system's design effectively facilitated interaction, possibly due to its consistency and clarity, which align with principles of Constructivist Learning Theory. According to this theory, user-friendly digital environments promote active engagement and knowledge construction, which encourages students to engage at a deeper level of learning [29]. The high usability score supports the idea that a well-designed interface can create an environment that fosters deeper learning experiences.

Table 2. Assessment of the usability of the MR system

Criterion	Statement	Student Response (Mean Score ± Standard Deviation)	Verbal Interpretation
Hardware Usability	The hardware of the MR system was simple and comfortable to use.	3.71 ± 0.54	Strongly Agree
User Interface Usability	The MR user interface was easy to operate and navigate through.	3.71 ± 0.60	Strongly Agree
Clarity of Instructions	The voice prompts and texts within each MR module were easy to understand and helped me to complete the tasks.	3.15 ± 0.76	Agree
Trouble-Free Usage	I did not encounter trouble while using the MR system.	3.25 ± 0.66	Agree
Composite Mean		3.46 ± 0.64	Strongly Agree

The clarity of instructions, while helpful, was still seen as an area for improvement, highlighting the need to refine these elements for enhanced learner support. The score of 3.15 suggests that while students could understand the instructions, they may have benefited from more detailed or clearer guidance during complex tasks. This aligns with findings from Cognitive Load Theory, which suggests that clear instructions are crucial in mitigating cognitive overload, especially in complex tasks [32]. The system's clear interface and guided interactions appeared to enhance students' autonomy while reducing potential frustration, as evidenced by the overall positive feedback regarding the system's ease of use [47].

However, the clarity of instructions was rated slightly lower, with a mean score of 3.15, indicating general agreement but also revealing room for improvement. This could be due to the nature of complex scientific procedures, which require step-by-step guidance for effective comprehension. The students' feedback suggests that while the voice prompts and on-screen texts were largely helpful, more detailed instructions would have improved their experience, particularly during advanced procedures.

Additionally, the trouble-free usage criterion scored 3.25, indicating that occasional technical issues may have disrupted the learning experience. This suggests that, while the system was generally effective, occasional glitches or

interface inconsistencies might have distracted students and hindered their focus. The results highlight opportunities for iterative design enhancements, such as improving the clarity of instructional cues and ensuring greater technical stability to prevent interruptions during the learning process.

Overall, the composite usability score of 3.46 reflects a generally positive student perception of the MR system, with particular strengths in hardware ergonomics and interface design, reinforcing its potential as an effective tool in MR-assisted Chemistry education. The favorable reception of the hardware and user interface supports the idea that well-designed technology can play a key role in enhancing engagement and learning outcomes in educational settings. As such, further improvements in instructional clarity and system stability could optimize the overall experience and enhance learning effectiveness.

B. Evaluation on Student Engagement and Immersion Level When Using the MR System

The level of student engagement and immersion with the MR system was evaluated using four key criteria: immersiveness, learning excitement, interaction engagement, interaction enjoyment, and interest in future use. These dimensions were chosen to capture both the emotional and cognitive aspects of learner involvement during the mixed reality experience (Fig. 6). Table 3 presents the summarized results of the students' responses, reflecting their perceptions of the system's ability to create an engaging and stimulating virtual laboratory environment.

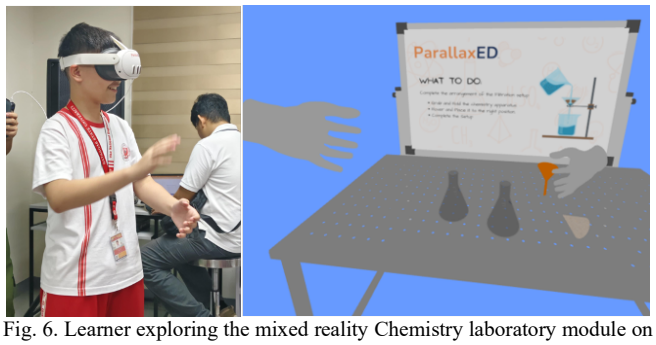

Fig. 6. Learner exploring the mixed reality Chemistry laboratory module on filtration through the MR system. The immersive simulation enables users to interact with virtual apparatus in a guided, physics-based environment, thereby reinforcing procedural accuracy and conceptual understanding.

Table 3. Evaluation of student engagement and immersion of the MR system

Criterion	Statement	Student Response (Mean Score ± Standard Deviation)	Verbal Interpretation
Immersiveness	I felt like I was inside the virtual environment while using the MR system.	3.25 ± 0.66	Agree
Learning Excitement	The MR system made learning the topic more interesting and exciting.	3.56 ± 0.64	Strongly Agree
Interaction Enjoyment	I enjoyed interacting with the objects within the environment of MR.	3.71 ± 0.54	Strongly Agree
Future Use Interest	I would like to use the MR system for learning future science lessons.	3.25 ± 0.66	Agree
Composite Mean		3.44 ± 0.63	Strongly Agree

Immersiveness and interest in future use both received a mean score of 3.25, indicating a positive yet improvable level of immersive engagement with the MR system. According to Kolb's [48] Experiential Learning Theory, immersive learning environments enhance conceptual understanding by encouraging active participation and enabling learners to engage directly with content through experience. The observed score suggests that while students found the experience engaging, further refinements could deepen immersion, supporting Kolb's model that emphasizes active and meaningful experiences. Enhancing the visual fidelity, improving environmental realism, or adding more interactive features could increase immersion and learner engagement. As previous studies on AR demonstrate its ability to foster student-centered, discovery-based learning, refining the system's visual elements would better bridge the gap between theoretical knowledge and practical application, promoting active learning and deeper engagement with chemistry content.

The next phase of the evaluation focused on the MR system's effectiveness in making learning more interesting and exciting. With a mean score of 3.56, students strongly agreed that the system enhanced the engagement level of their Chemistry lessons. This aligns with Self-Determination Theory, which posits that intrinsic motivation—driven by the psychological needs for autonomy, competence, and relatedness—plays a key role in fostering learner engagement [49]. The system's ability to offer risk-free, virtual lab experiences can fuel intrinsic motivation by providing a dynamic learning environment that encourages exploration without the safety concerns of traditional labs. By creating an exciting and dynamic environment, the system supports these motivational drivers, encouraging greater participation and involvement in the educational experience.

Among the evaluated dimensions, interactive enjoyment received the highest mean score of 3.71, indicating that students particularly enjoyed manipulating virtual objects and participating in simulated laboratory tasks. This finding aligns with Active Learning principles, which emphasize learner-centered, hands-on activities as pathways to deeper understanding and better knowledge retention [50]. This also supports the idea that MR-based learning, particularly in chemistry, can help students visualize and understand abstract concepts, such as molecular geometry. Enhancing the variety and complexity of interactive elements could further enrich the learning process, providing students with expanded opportunities to explore, experiment, and apply concepts in a virtual space.

Students also expressed a high level of enthusiasm regarding the system's continued use, with future use interest scoring a mean of 3.25. This positive response suggests a favorable overall impression of the platform. To maintain and build upon this interest, future developments should aim to expand content coverage and enhance interactivity, ensuring sustained engagement and long-term instructional value. The Technology Acceptance Model (TAM) suggests that

perceived ease of use and usefulness are crucial for sustained technology adoption, indicating that future iterations should prioritize intuitive design and usability to enhance ongoing engagement with the system [44].

The composite mean score of 3.44 across these dimensions indicates that the MR system is effective in engaging and immersing students in Chemistry learning. Continued refinements, focusing on immersive design, learning excitement, and interactive depth, will further enhance the system's educational impact and classroom relevance.

C. Learning Effectiveness of the MR System in Enhancing Student Understanding of Chemistry Laboratory Setups, Compared to Traditional Teaching Methods

Table 4 presents the assessment results of the learning effectiveness evaluation of the MR system. Students reported that the MR system significantly enhanced their conceptual understanding of laboratory glassware, reflected by a mean score of 3.71 for the criterion on visualization and understanding. This result can be attributed to the immersive nature of MR environments, which facilitates deeper engagement by allowing students to visualize complex chemical apparatus in 3D. According to Cognitive Load Theory, such interactive tools reduce extraneous cognitive load, enabling learners to focus on core content by eliminating distractions and simplifying task complexity [32]. The ability to visualize apparatus in realistic contexts allows students to form stronger mental models of chemical processes, thereby improving their understanding of structural and functional relationships. This finding aligns with research that shows how MR systems, by simplifying complex tasks through real-time guidance and immersive visualization, reduce cognitive load and enhance learning focus. To further support comprehension, the addition of detailed models and interactive annotations could deepen engagement and understanding of more complex laboratory setups.

Table 4. Assessment of the learning effectiveness evaluation of the MR system

Criterion	Statement	Student Response (Mean Score ± Standard Deviation)	Verbal Interpretation
Visualization and Understanding	The MR system helped me better visualize and understand different Chemistry laboratory setups.	3.71 ± 0.54	Strongly Agree
Overcoming Difficult Topics	Using the MR system helped me learn science topics I found difficult to understand.	3.15 ± 0.76	Agree
Memory Retention	The MR environment helped me remember science concepts more easily.	3.56 ± 0.64	Strongly Agree
Achievement of Learning Objectives	The MR system helped me achieve the learning objectives for the lesson.	3.25 ± 0.66	Agree
Composite Mean		3.42± 0.63	Strongly Agree

However, lower scores were observed for overcoming difficult topics (3.15) and achievement of learning objectives (3.25). This suggests that while students were able to engage with the MR system, additional support is needed to tackle challenging content. These results may reflect the cognitive load that students face when encountering unfamiliar or abstract concepts. To address this, additional scaffolding is necessary to guide students through these difficult topics. This finding aligns with Vygotsky's Zone of Proximal Development, as interpreted by Daniels [51], which emphasizes the importance of guided instruction in helping learners achieve tasks that are beyond their current independent capabilities. Research on MR-based learning environments emphasizes the importance of personalized guidance and scaffolding in helping students navigate complex concepts, particularly in abstract fields such as chemistry. Enhancements such as step-by-step tutorials, interactive problem-solving tasks, or in-system prompts may offer the necessary support to close these learning gaps.

The system also received a mean score of 3.56 for memory retention, indicating that the interactive nature of the MR system significantly aided in retaining key science concepts. The hands-on, immersive learning experience in the MR environment likely contributed to the formation of stronger long-term memory associations by promoting active engagement. This result is consistent with studies that demonstrate how active, hands-on learning environments promote long-term memory retention by forming deeper cognitive connections [52]. While the current results are promising, implementing spaced repetition features or review checkpoints could further reinforce learning by encouraging students to revisit and apply concepts over time [53]. Such strategies are supported by the literature on cognitive psychology, where frequent retrieval practice and spaced learning have been shown to significantly enhance long-term retention and understanding.

In terms of helping students meet learning objectives, the system scored 3.25 again, indicating that students generally found it useful in supporting their lesson goals. However, the slightly lower score suggests that the system's effectiveness may depend on how well the learning content is aligned with individual needs.

This supports the view in Constructivist Learning Theory that student-centered, interactive learning environments can foster meaningful engagement and deeper understanding [47]. The integration of personalized learning paths could further enhance alignment between the system's content and the diverse needs of learners.

To better accommodate learners of varying abilities, integrating personalized learning paths could help ensure differentiated support and more consistent attainment of outcomes. This approach aligns with findings from the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), which suggest that perceived usefulness and ease of use are key factors in students' acceptance and success with educational technologies [44, 45].

Overall, the composite mean score of 3.42 suggests that the MR system effectively enhances student understanding and conceptual retention. This result highlights the system's

potential to serve as a valuable tool in STEM education. To maximize its effectiveness, further refinement, particularly in the areas of scaffolding, personalization, and incorporating review mechanics, could address the observed gaps in student performance. Implementing personalized learning pathways could help accommodate diverse learning needs, ensuring that all students benefit from the system's full potential.

D. Measuring the Effectiveness of the MR Using Pre-Test and Post-Test

Table 5 presents a summary of students' pre-test and post-test scores, which were used to evaluate the overall effectiveness of the MR system in enhancing conceptual understanding and knowledge retention in Chemistry.

Table 5. Group-level analysis of pre-test and post-test scores

Criteria	Pre-test Mean Score ± Standard Deviation	Post-test Mean Score ± Standard Deviation	Mean Diff.	*t*-value	*p*-value
Overall Results	89.33 ± 13.21	94.67 ± 9.91	5.33	2.737	0.008919*

Degrees of Freedom (df) = 44; *p-value < 0.05 = significant

The effectiveness of the MR system was quantitatively validated through significant learning gains. Students' average scores improved from 89.33 in the pre-test, rated as very satisfactory, to 94.67 in the post-test, rated as outstanding.

The results of the *t*-test indicate a statistically significant difference between the mean pre- and post-test scores, $t(44) = 2.737$, $p = 0.008919$. This level of significance demonstrates that the observed effect is unlikely to be attributed to random variation alone. Rather, the findings suggest that the use of mixed reality has a positive effect on students' conceptual understanding. This change can be attributed to the engaging and interactive nature of the MR system, which likely enhanced cognitive engagement and retention.

As students manipulated virtual laboratory apparatus and observed real-time chemical reactions, the learning environment facilitated a deeper understanding of abstract chemical concepts that are otherwise challenging to visualize or experiment with in traditional settings [25, 30, 36]. This finding aligns with research highlighting the effectiveness of immersive technologies in enhancing learning outcomes. Studies have demonstrated that immersive environments provide richer experiences that stimulate active learning and increase engagement with the subject matter.

These results support the pedagogical value of experiential and retrieval-based learning environments, demonstrating how interactive, immersive tools like MR can reinforce knowledge acquisition and promote deeper cognitive processing in Chemistry education [53]. The positive impact on conceptual understanding may also stem from the MR system's ability to present complex chemical processes in a simplified and manipulable format, allowing students to focus on key concepts rather than extraneous information.

Furthermore, the positive change in students' scores reflects the benefits of reducing cognitive load, as MR environments simplify complex tasks, helping students focus on key learning objectives [32]. This reduction in cognitive overload is especially beneficial in chemistry education, where abstract concepts, such as molecular geometry and reaction mechanisms, are traditionally difficult for students to grasp using conventional teaching methods.

E. Students' Overall Acceptability and Satisfaction with the MR System in Chemistry Education

The overall student acceptability and satisfaction with the MR system in Chemistry education was assessed across four key criteria: overall enjoyment, satisfaction with the learning experience, willingness to recommend the system to peers, and interest in using the system in future lessons. These dimensions were selected to capture both the affective and motivational responses of learners, providing insight into how well the system was received and its potential for sustained use in the classroom. Evaluating these aspects helps determine not only the system's effectiveness in delivering content but also its appeal, perceived value, and likelihood of adoption by students in future instructional settings.

Table 6. Evaluation of the acceptability and satisfaction evaluation of the MR system

Criterion	Statement	Student Response (Mean Score ± Standard Deviation)	Verbal Interpretation
Overall Enjoyment	I enjoyed using the MR system.	3.71 ± 0.54	Strongly Agree
Satisfaction with Learning	I am satisfied with the level of knowledge I learned using the MR modules.	3.71 ± 0.54	Strongly Agree
Recommendation to Others	I would recommend the MR system to other students.	3.25 ± 0.64	Agree
Future Use Interest	I want my teachers to use the MR system in the delivery of our future science lessons.	3.15 ± 0.74	Agree
	Composite Mean	3.45 ± 0.63	Strongly Agree

As shown in Table 6, students demonstrated a high level of satisfaction with the MR system, as reflected in the mean scores of 3.71 for both overall enjoyment and learning satisfaction. This strong positive response suggests that the system was not only engaging but also effective in supporting student understanding of Chemistry concepts. The high enjoyment and satisfaction scores may be attributed to the immersive nature of the MR technology, which aligns with the tenets of Self-Determination Theory (SDT) [49].

According to SDT, intrinsic motivation—fueled by enjoyment and personal satisfaction—is a core factor in fostering student engagement and sustained interest. The interactive and engaging nature of MR environments can stimulate students' intrinsic motivation, contributing to a more profound learning experience. This finding is consistent with previous studies that indicate how immersive technologies, such as MR, promote deeper involvement and greater retention, particularly in STEM subjects.

Although the system was perceived as enjoyable, future iterations could benefit from expanded features and enriched content to sustain high levels of engagement across a broader range of learners. This recommendation is based on research into the effectiveness of technological interventions, which emphasizes that for sustained engagement, systems must continually evolve to meet the diverse needs of learners. Enriching the content can provide a wider variety of challenges and stimuli that maintain student interest over time, thereby addressing the potential for learner fatigue.

The students' willingness to recommend the system to others, with a mean score of 3.25, further underscores its positive reception and perceived usefulness. These results align with the principles of Universal Design for Learning (UDL), which advocates for flexible, engaging, and accessible learning environments that cater to the diverse needs of learners [54].

The recommendation score indicates that the system was well-received not only in terms of enjoyment but also in its perceived educational value. The feedback supports the idea that further incorporating customizable content and adaptive learning pathways could better accommodate different learning styles, thereby enhancing both engagement and educational outcomes.

Students' interest in future use of the system scored 3.15, reflecting a generally favorable response but indicating that improvements are necessary for long-term adoption. This score suggests the importance of seamlessly integrating the system into the classroom.

According to the Technological Pedagogical Content Knowledge (TPACK) framework, effective technology integration depends not only on the tool itself but also on teachers' ability to incorporate it into the curriculum and pedagogy [55]. Thus, the integration of MR systems into regular classroom practices is crucial, and ensuring that teachers are equipped to effectively utilize the system can enhance its potential.

Teacher buy-in and adequate training are essential to maximizing the system's impact, aligning with research that emphasizes the role of educators in the successful adoption of educational technologies.

The composite mean score of 3.48 across these satisfaction criteria confirms that the MR system was well received by students. While the current findings validate its potential as a valuable instructional tool, enhancing content depth, supporting personalized learning experiences, and ensuring teacher readiness will be key to amplifying its educational benefits in future classroom applications. These improvements are important as research on educational technology adoption highlights the need for systems that evolve and adapt to the diverse needs of both students and educators.

F. Teachers' Perspective on the Usability and Effectiveness of the MR System

In addition to student feedback, the perspectives of science teachers were also gathered to assess the usability and effectiveness of the MR system (Table 7). Teacher evaluations focused on three main criteria: the usability of the tool, its impact on student engagement and immersion, and its overall acceptability and potential for future classroom use. These insights provided a broader understanding of the system's instructional value and practical applicability from the viewpoint of educators responsible for implementing technology-enhanced learning in secondary science education.

The evaluation of the MR system from the teachers' perspective revealed a highly positive reception across key areas: usability, student engagement, and potential for future classroom use. Teachers strongly agreed that the system's hardware was comfortable and easy to operate, as reflected by a mean score of 3.83, indicating minimal barriers to physical interaction. This high rating can be attributed to the system's ergonomic design, which minimizes discomfort during extended use. Research on technology integration emphasizes that user comfort directly impacts engagement and usability, supporting the ease of use observed in this study.

Table 7. Teacher evaluation of the MR System's usability, student engagement, and acceptability for future use

Criterion	Statement	Teacher Response (Mean Score ± Standard Deviation)	Verbal Interpretation
Usability of the Tool	1. The hardware of the MR system was simple and comfortable to use.	3.83 ± 0.37	Strongly Agree
	2. The MR modules integrate well with my lesson.	3.17 ± 0.90	Agree
	3. The time needed to teach students how to use the MR was reasonably fast.	3.67 ± 0.47	Strongly Agree
	4. The MR system can be used for small and large classes because of its versatile and robust design.	3.83 ± 0.37	Strongly Agree
Student Engagement and Immersion	5. The MR system increased the students' interest in the lesson.	4.00 ± 0.00	Strongly Agree
	6. Students became more focused and involved in learning the topics while using the MR system.	4.00 ± 0.00	Strongly Agree
	7. The MR system helped students become more active and collaborative with their classmates.	3.83 ± 0.37	Strongly Agree
	8. Using the MR system increased the students' recall of the objects within the MR environment.	3.67 ± 0.47	Strongly Agree
Acceptability and Future Use	9. I am satisfied with the overall performance of the MR system.	4.00 ± 0.00	Strongly Agree
	10. I would use the MR system again in future lessons	3.83 ± 0.37	Strongly Agree
	11. I would recommend the MR system to other teachers.	3.83 ± 0.37	Strongly Agree
	12. Using the tool helped me explain things I found hard to deliver to my students before.	3.67 ± 0.47	Strongly Agree
Composite Mean		3.78 ± 0.35	Strongly Agree

Additionally, the time required to train students was deemed manageable (Mean = 3.67), and the tool's versatility for both small and large class sizes received high ratings (Mean = 3.83). These findings suggest that the system's intuitive design and scalability make it adaptable to various teaching environments. In line with the Technology

Acceptance Model, ease of training and flexibility are crucial factors for successful technology adoption in classrooms [44].

Although the system's integration into existing lessons was rated moderately (Mean = 3.17), feedback suggests that stronger alignment with specific lesson goals is necessary to fully support classroom instruction. This observation points to the challenge of aligning new technologies with established curricula. According to the TPACK framework, effective technology integration requires a careful balance between content, pedagogy, and technology [55]. The moderately low score here highlights the importance of refining content to align with curriculum standards, ensuring that the MR system effectively complements teaching objectives. This aligns with Sanchez's findings, which emphasize the need for technology integration that aligns directly with curricular goals to enhance student outcomes [33].

In terms of student engagement and immersion, the system received consistently high ratings. Teachers unanimously agreed that it significantly enhanced student interest in lessons (Mean = 4.00) and helped students become more focused and involved in learning (Mean = 4.00). These results indicate that the MR system successfully captured students' attention, which is crucial for fostering a learning environment where students can actively engage with content. Constructivist Learning Theory supports this by emphasizing the importance of hands-on, interactive learning experiences that deepen understanding [47]. The interactive nature of MR environments allows students to experiment with and explore complex concepts, making abstract topics like molecular structures more tangible and relatable.

They also observed that the system fostered collaborative learning among students (Mean = 3.83) and improved their recall of objects and tasks within the MR environment (Mean = 3.67). The improvement in student recall could be attributed to the multimodal sensory engagement offered by MR, which reinforces memory through visual, auditory, and tactile inputs. Studies on the cognitive benefits of MR suggest that these immersive environments support long-term retention by creating meaningful learning experiences that students can revisit and explore at their own pace.

Regarding acceptability and future use, teachers expressed strong satisfaction with the system's overall performance (Mean = 4.00). This result reflects the perceived value of the MR system as an educational tool that enhances student engagement and understanding. The high satisfaction rating is consistent with findings from previous research on immersive technologies, which highlight their potential to transform teaching by providing dynamic and risk-free learning environments.

They indicated a willingness to integrate it into future lessons (Mean = 3.83) and to recommend it to other educators (Mean = 3.83), highlighting both their confidence in the tool and its perceived value in teaching complex scientific concepts. This strong future use interest is consistent with studies that show educators are increasingly open to adopting innovative technologies when they align with pedagogical goals and demonstrate measurable improvements in student outcomes.

The composite mean score of 3.78 reflects strong overall agreement among teachers on the system's effectiveness, usability, and educational value. While the results indicate that the MR system is a highly acceptable and engaging instructional tool, targeted refinements in lesson integration would further enhance its adaptability and pedagogical alignment, thereby improving its impact in real-world classroom settings. The moderate feedback on lesson integration provides an opportunity for future development focused on better tailoring content to specific lesson objectives, which would enhance the overall impact of the system. As evidenced by the TPACK framework, aligning technology with curricular goals is crucial for maximizing its pedagogical effectiveness [55].

V. Conclusions

This study highlights the potential of Mixed Reality (MR) technology to enhance Chemistry education by providing immersive, interactive simulations of laboratory environments. The MR system enables students to safely explore complex chemistry concepts, fostering improved conceptual understanding, procedural fluency, and memory retention, particularly in areas such as distillation and filtration. The positive impact of MR on student engagement, enjoyment, and focus aligns with key learning theories, such as Constructivism and Cognitive Load Theory, further validating its pedagogical value.

The practical implications of this research suggest that MR technology can be effectively integrated into Chemistry instruction. For teachers, MR provides an engaging tool to support the delivery of complex concepts, allowing them to guide students through virtual laboratory procedures while offering real-time feedback. This approach can deepen understanding and improve procedural skills, as the interactive nature of MR also encourages collaboration and enhances peer learning.

For students, especially in resource-constrained settings, MR offers access to virtual laboratories, providing opportunities for hands-on learning without the need for physical lab equipment. This not only enhances student engagement with the material but also improves retention and conceptual clarity. Additionally, the system's flexibility allows students to repeat experiments and practice procedures, reinforcing learning and mastery of challenging topics.

For schools, MR offers a cost-effective solution to the challenges posed by limited laboratory resources. Its web-based nature makes the system accessible across diverse educational settings, including both urban and rural areas. To fully leverage the benefits of MR, schools must invest in necessary infrastructure, including high-performance devices and stable internet connections. Teacher training programs are also essential to ensure effective integration of MR into existing curricula.

Despite promising outcomes, several limitations must be acknowledged. The study's sample size was limited, which may not fully represent the broader student population. Additionally, the study's short duration and focus on Chemistry may limit the generalizability of these findings to other disciplines or longer periods. Technological and infrastructural constraints, such as the high cost of devices

and internet connectivity issues, may hinder the widespread adoption of MR. These barriers must be addressed to ensure equitable access to MR technology in diverse educational contexts.

Overall, the MR system offers a promising, adaptable approach to STEM education, particularly in Chemistry. With further development and institutional support, it has the potential to improve the effectiveness and inclusivity of science education in both traditional and blended learning environments. Future research should explore the system's applicability across other subjects, assess its long-term impact, and refine its integration into broader curricula.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

A.D.A., J.P.H., and B.J.A.M. conceptualized and designed the study; J.P.H. and M.M. contributed in the frontend design and backend programming of the project; L.R.V. and J.S.D. developed 3D objects for the project; A.D.A., B.J.A.M, J.P.H., L.R.P.V., J.S.D.D., M.M., and L.L.V. implemented the product validation and evaluation activities; A.D.A. and B.J.A.M. performed the data analyses and interpretation. The manuscript was written by A.D.A., B.J.A.M., and J.P.H. with input from all authors. All authors had approved the final version.

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