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Design an Immersive Learning Media Based on Spatial Augmented Reality Using Hand Tracking in the ChemMaster Application

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Abstract

Today's technological progress gives educators new ways to create engaging and effective learning experiences. This research introduces ChemMaster, a learning media application that combines Spatial Augmented Reality (AR) and hand-tracking technology to help high school students understand complex chemistry concepts. The development of ChemMaster followed a Design Thinking process, beginning with exploring students' learning challenges through interviews and observations. As a core contribution, ChemMaster integrates an AI-powered automatic question scanning feature that provides step-by-step solutions, interactive 3D AR models of molecules and reactions, and gamified elements like quizzes and leaderboards to maintain motivation. To evaluate its usability and learning impact, a pilot study was conducted involving 15 participants, specifically 12 high school students and 3 chemistry teachers. Preliminary results show a high rate of task completion and user satisfaction; specifically, gesture-based hand-tracking interactions (e.g., zooming and rotating models) effectively bridged the gap between theoretical explanations and tangible visual comprehension. Although the study identified minor constraints, such as reduced tracking accuracy in low-light conditions, the findings demonstrate that ChemMaster significantly increases student engagement compared to traditional methods and offers a promising interactive tool to deepen chemistry understanding.

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Keywords

Augmented Reality; Design Thinking; Gamification; Hand Tracking; Immersive Learning Media; Interactive Learning; Spatial Computing

1. Introduction

Education has been profoundly affected by recent digital technology advancements, offering new methods to enhance learning engagement and effectiveness (Yasin et al., 2024). Augmented Reality (AR), a rapidly evolving technology, merges virtual content with the real world in real time, facilitating immersive and interactive learning environments (Kumar et al., 2025). AR's capability to deliver realistic 3D visualizations may assist students in developing a better conceptual understanding of abstract scientific concepts (Mansour et al., 2024), especially in chemistry, where visualizing molecular structures and chemical reactions is often challenging.

Despite these technological opportunities, many students in Indonesia still face challenges in learning chemistry, reflected in their low performance in international assessments such as PISA (Alfaruqi & Nurwahidah, 2025). Traditional teaching methods often rely on passive learning through textbooks and lectures, which may decrease

student motivation and engagement (Silva, 2023). This presents a critical need for interactive and motivating educational tools. Emerging AR devices such as AR glasses offer a hands-free, immersive platform for students to engage with virtual 3D models using natural hand gestures through hand tracking technology (Joshi, 2025). This interaction may facilitate more active learning experiences, allowing students to manipulate and explore chemical phenomena dynamically.

The transition to distance learning during the COVID-19 pandemic served as a "major blow" to the teaching of experimental sciences, as many educational institutions were unprepared to facilitate practical laboratory work remotely (Karnishyna et al., 2022). This challenge is often exacerbated by a critical lack of laboratory equipment, reagents, and physical space, which prevents students from engaging in quality hands-on activities (Rusdi et al., 2023). Consequently, students frequently demonstrate a limited ability to bridge the gap between macroscopic observations and the non-visible submicroscopic entities, such as molecules, atoms, and ions—required to explain chemical phenomena (Peeters et al., 2023). This pedagogical disconnect is further complicated by the difficulty of mastering Johnstone's Triangle (macroscopic, submicroscopic, and symbolic levels), often resulting in rote learning and a persistent "phobia" toward chemistry (Neji et al., 2025; Ripsam & Nerdel, 2022). Systematic reviews indicate that traditional "chalk and talk" methods fail to address these abstract complexities, necessitating a shift toward more natural, interactive interfaces (Koumpouros, 2024).

To address these systemic issues, the integration of Augmented Reality (AR) has become a vital catalyst for promoting academic achievement and student participation. Empirical evidence shows that AR instructional strategies are associated with significantly higher performance, recording mean gain scores of 23.76 compared to 18.28 in conventional groups (Neji et al., 2025). In regional contexts, virtual laboratories like VILBAR have proven effective in overcoming resource shortages, with students achieving high practical portfolio scores of 90 (Rusdi et al., 2023). Beyond chemistry, AR is being used to "revive" traditional textbooks in fields such as computer science and STEM, enhancing spatial imagination and cognitive experience (Oleksiuk & Oleksiuk, 2022). The motivational impact is equally substantial; over 96% of students agree that AR activities effectively catch their attention and foster interest in scientific fundamentals (Guaya et al., 2023; Karnishyna et al., 2022). Furthermore, 90% of students believe AR directly helps develop subject competencies, while advanced platforms like smart glasses have been shown to improve self-efficacy and reduce technological anxiety compared to mobile devices (Guaya et al., 2023; Kapp et al., 2022). However, designers must carefully manage Cognitive Load Theory, as the simultaneous processing of virtual and macroscopic data can increase intrinsic mental demands (Peeters et al., 2023; Ripsam & Nerdel, 2022).

So, this study presents ChemMaster, an immersive learning media application employing Spatial Augmented Reality and hand tracking to help high school students understand complex chemistry concepts. ChemMaster integrates features such as automatic question scanning, interactive 3D models, quizzes, and leaderboards that are designed to support learning motivation, accessibility, and conceptual understanding. By combining spatial computing with interactive technologies, ChemMaster is intended to offer an interactive learning environment that may assist students in engaging with complex chemistry concepts beyond traditional learning approaches. Currently, as this research represents an exploratory pilot study, the ChemMaster application is still in its prototype phase and has not yet been patented or copyrighted.

2. Related Works

The integration of Augmented Reality (AR) in chemistry education has demonstrated a significant positive impact on academic achievement and conceptual understanding. Recent research by Neji et al. (2025) found that students who were taught chemistry practical activities using VR and AR instructional strategies recorded significantly higher achievement scores compared to those taught through conventional "chalk and talk" methods. This is attributed to the technology's ability to transform abstract scientific concepts, which are often difficult to perceive on a macroscopic level, into interactive 3D visualizations. Similarly, Karnishyna et al. (2022) developed an AR training kit using the Blippar platform specifically for organic chemistry, which successfully improved students' spatial imagination and facilitated a deeper understanding of molecular structures. These studies suggest that AR serves as a catalyst for active participation by providing a safe and engaging environment for experimentation.

Beyond academic performance, AR is a powerful tool for enhancing student motivation, particularly when combined with active learning methodologies. Guaya et al. (2023) implemented Project-Based Learning (PBL) assisted by AR for chemical engineering laboratories and evaluated student motivation using Keller's ARCS model (Attention, Relevance, Confidence, and Satisfaction). Their findings indicated high levels of student engagement, with over 96% of participants agreeing that AR materials successfully caught their attention and encouraged interest in fundamental engineering principles. This research highlights that AR-assisted PBL allows students to bridge the gap between theoretical knowledge and industrial application, fostering a sense of achievement and satisfaction.

However, the design of immersive media must account for the Cognitive Load Theory, which suggests that working memory has limited capacity. While AR can reduce extraneous load by increasing spatial and temporal contiguity, placing digital models directly alongside real-world experiments—it may simultaneously increase intrinsic cognitive load. Peeters et al. (2023) observed that students using AR during hands-on experiments may face higher cognitive demands because they must process simultaneous information from both the macroscopic and submicroscopic levels. Their study concluded that while AR has the potential to connect these levels, it requires careful interface design to prevent overstraining the learner.

While the aforementioned studies predominantly utilize marker-based AR on mobile devices, there is an emerging opportunity for more intuitive interaction. ChemMaster addresses this by employing Spatial Augmented Reality and hand tracking technology. Unlike traditional touch-based mobile AR, spatial computing on AR glasses allows for a hands-free experience where students can manipulate 3D molecular models using natural gestures. This study builds upon existing literature by exploring how these advanced immersive interactions can further reduce distractions and deepen conceptual comprehension beyond the constraints of traditional and mobile-based educational tools.

3. Methods

This study aims to develop and evaluate ChemMaster, an immersive chemistry learning media application based on AR and utilizing hand tracking technology. The development of this application effectively employs the Design Thinking approach to ensure a strictly user-centered solution. Rather than simply applying technology for its own sake, this approach allowed the research team to systematically translate actual user pain points, such as the inability to visualize abstract molecules, into specific functional features. The process effectively bridges the gap between user needs and technical implementation through an iterative cycle. The stages of this development process map directly to the core phases of Design Thinking: Empathize and Define, Ideate and Prototype, and Test. By continuously looping feedback from real users back into development, the Design Thinking process effectively guaranteed that the application closely aligned with students' cognitive needs and engagement preferences. The following is a detailed description of how these stages were implemented:

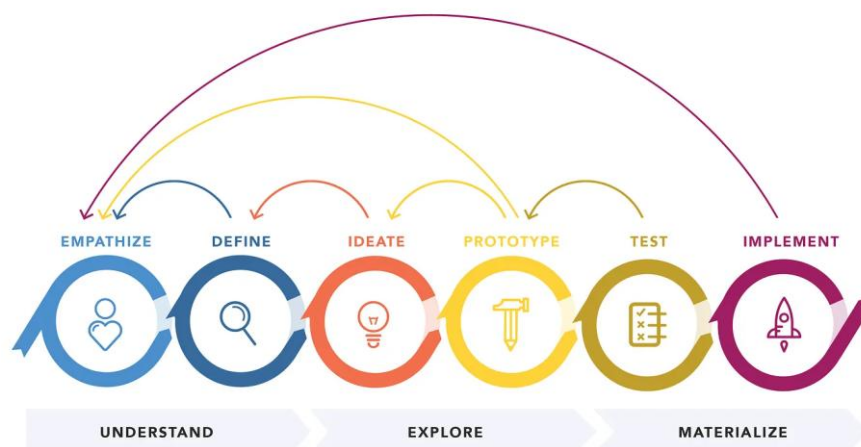


Figure 1. The flowchart of the ChemMaster methodology based on the Design Thinking approach.

3.1. Empathize and Define: Problem Exploration and User Needs Identification

In the initial phase of the research, the team focused on exploring the challenges that students face when learning complex chemistry concepts. This process involved two primary methods: in-depth interviews with teachers and students, and direct classroom observations. During the interviews, chemistry teachers and high school students (grades 10-12) from various schools were asked about their experiences. Teachers shared the challenges they face when trying to explain abstract chemistry concepts, such as molecular structures and chemical reactions, which are difficult to visualize and understand. On the other hand, students discussed their personal learning experiences, revealing that they struggled to grasp these concepts and felt that traditional teaching methods, like textbooks and lectures, were not engaging enough to help them understand complex material.

Additionally, classroom observations were conducted to further explore how chemistry lessons were being delivered and to assess the level of student engagement. These observations revealed that students often struggled with the visual and conceptual aspects of chemistry. Many relied heavily on textbooks and lectures, which did not provide the interactive or visual elements needed to truly engage with abstract concepts. Based on these findings, the research team identified three main needs: first, there was a clear need for better visualization of chemistry concepts like molecular structures and chemical reactions; second, students required more interactive and engaging learning media to increase their involvement and motivation; and third, there was a need for a feature that would allow students to learn independently and receive immediate feedback on their understanding.

3.2. Ideate and Prototype: Solution Development and Prototype Creation

With the challenges and user needs identified, the research team then began to design a solution. The solution developed was ChemMaster, an educational application that integrates AR and hand tracking technologies to create a more immersive and interactive learning experience for students. The design process focused on incorporating key features that aligned with the identified needs. For example, the application includes 3D visualizations of molecular structures and chemical reactions through AR, allowing students to interact with these models directly and gain a deeper understanding of complex concepts that are difficult to grasp using traditional methods. Additionally, hand tracking technology was incorporated to enable students to interact with AR objects using hand gestures, which enhances engagement and makes the learning process more dynamic.

Another key feature developed was the automatic question scanning functionality, which allows students to scan chemistry problems that they find challenging. The application then provides the correct answers along with detailed explanations, helping students understand the process of solving problems. To further motivate students and enhance their learning experience, ChemMaster also includes quizzes and a leaderboard. These features allow students to test their knowledge, track their progress, and compete with their peers, adding an element of gamification to the learning process. Once the key features were identified and designed, the first prototype of the ChemMaster application was developed for use on both AR glasses and mobile devices (Android and iOS). This high-fidelity prototype was tested to ensure that all features worked as expected and met the needs of the users.

The technical architecture of ChemMaster is anchored by the Unity game engine and the Vuforia SDK, which are utilized to provide stable marker-based tracking and high-fidelity 3D object registration within the user's environment. Central to the immersive experience is the implementation of a Natural User Interface (NUI) through hand tracking technology. This system allows students to manipulate virtual molecular models using natural gestures, such as zooming, rotating, and manipulating objects, hands-free, which reduces the "cyborg feel" of traditional button-based interfaces and fosters a deeper sense of spatial presence.

Furthermore, the Scanalyze feature incorporates an AI-powered OCR (Optical Character Recognition) model that allows the application to capture and process complex chemistry problems via the device's camera. Specifically, the OCR engine is built on a deep learning-based text recognition pipeline, an approach commonly used in mobile-optimized OCR frameworks, which was further configured to recognize chemistry-specific notations such as chemical formulas, subscripts, and reaction symbols. The hand tracking module relies on a skeletal hand pose estimation approach that maps joint coordinates in real time to enable gesture recognition. While this approach performed reliably under typical indoor lighting during testing, its accuracy was qualitatively observed by participants to

decrease under low-light conditions; this observation was based on user-reported experience rather than controlled measurement, indicating a need for systematic robustness testing under varied lighting conditions in future development. The system then generates step-by-step solutions that detail the necessary formulas and intermediate calculations, prioritizing the pedagogical reasoning process over simple answer retrieval. To ensure broad accessibility, the application is optimized for cross-platform compatibility, supporting Android and iOS mobile devices as well as AR smart glasses such as the NReal Air. The system's performance and technical credibility were evaluated through specific metrics, including task success rates for core functionalities (scanning, material access, and quizzes) and user satisfaction scores derived from Keller's ARCS model to measure the application's impact on learning motivation.

3.3. Test: Prototype Testing

This research was conducted as an exploratory pilot study to evaluate the initial effectiveness of ChemMaster in enhancing students' understanding and engagement with chemistry. To accomplish this, the team used User Testing, a method that allows researchers to gather direct feedback from users regarding their experience with the application. A total of 15 participants were involved in this study, comprising 12 high school students (6 males and 6 females, aged 15–18) and 3 chemistry teachers (all females, aged 30–35). The participants were selected using a purposive sampling approach, justified by the need to evaluate the application with target end-users who are directly involved in the current 10th–12th grade chemistry curriculum. Furthermore, participants were chosen based on their basic comfort with mobile digital technology, although none of the participants (0%) had any prior experience with AR technology or hand-tracking interfaces. Each participant was asked to install the app on their mobile devices or AR glasses and interact with various features, including selecting chemistry topics to study, using the question scanning feature to solve chemistry problems, interacting with 3D AR models via hand tracking, and completing quizzes to assess their understanding of the material. Prior to conducting the user testing, verbal consent and permission were obtained from the participating chemistry teachers and the students. As this was an initial pilot study, formal written informed consent was not collected; however, strict ethical guidelines regarding user privacy were maintained, and formal consent protocols will be implemented in future large-scale evaluations.

The testing was conducted individually to ensure that each participant's interaction with the app was observed closely and recorded for later analysis. This process was aimed at capturing data on the users' experiences, identifying any challenges they encountered, and collecting suggestions for improvement.

3.4. Data Collection and Analysis

During the prototype testing phase, the research team collected both qualitative and quantitative data. The qualitative data consisted of observations made during the testing sessions, including the difficulties participants encountered while interacting with the app's features (such as issues with AR objects or the question scanning function). Feedback was also gathered from participants in post-test interviews, where they shared their opinions and suggestions for improving the app's usability and functionality. Additionally, quantitative data were collected using a post-test questionnaire based on the System Usability Scale (SUS). This validated 10-item framework was utilized to provide a global view of subjective assessments, requiring participants to rate the ease of use, perceived usefulness, and overall satisfaction with the learning experience on a 5-point Likert scale.

Once the data were gathered, the team analyzed them to identify usability issues. For instance, they looked for difficulties in navigation, problems with the responsiveness of hand tracking, or inaccuracies in the question scanning feature. The quantitative data, including the calculated SUS scores, were also analyzed to detect patterns in task completion times, task success rates, and overall user satisfaction.

3.5. Iteration: Refinement and Improvement

Based on the analysis of the collected data, the research team compiled a set of recommendations to improve the app's user interface and functionality. These recommendations addressed issues such as improving the responsiveness of hand tracking, enhancing the visual quality of 3D models, and refining the question scanning feature to ensure more accurate results. After implementing these improvements, the updated prototype was tested again to ensure that

the identified issues had been resolved. This iterative process of testing and refining continued until the app reached a level of usability and effectiveness deemed optimal for student learning. By using this iterative approach, the research team was able to continuously enhance the app to better meet the needs of students and improve their chemistry learning experience.

4. Results

The outcomes of the design and development of the ChemMaster application highlight the user interface design, augmented reality (AR) features, hand tracking integration, device compatibility, preliminary user testing results, and educational impact.

4.1. User Interface (UI) Design

4.1.1. Home Page

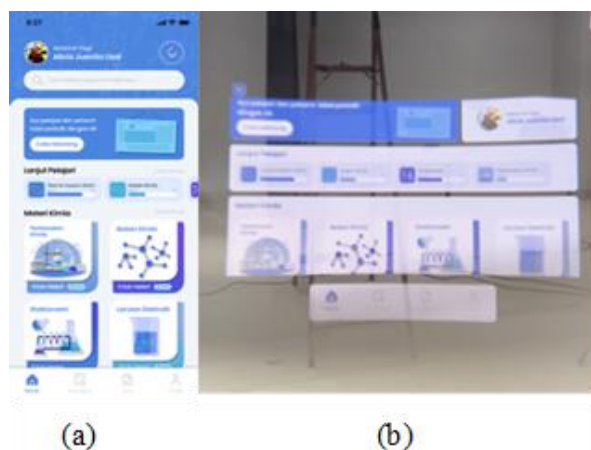


Figure 2. ChemMaster home screen on (a) mobile interface and (b) AR glasses.

The home screen functions as the main navigation hub, allowing users to either continue their previous lessons through the Continue Learning panel or explore new topics listed in the Chemistry Materials section. Progress bars help students track completion, while visual icons make each module easily identifiable. A highlighted card introduces AR-based features, such as the periodic table, encouraging immersive exploration. Consistent bottom navigation provides quick access to Home, Scanalyze, Quiz, and Profile, ensuring smooth transitions across modules.

4.1.2. Learning Modules and AR Integration

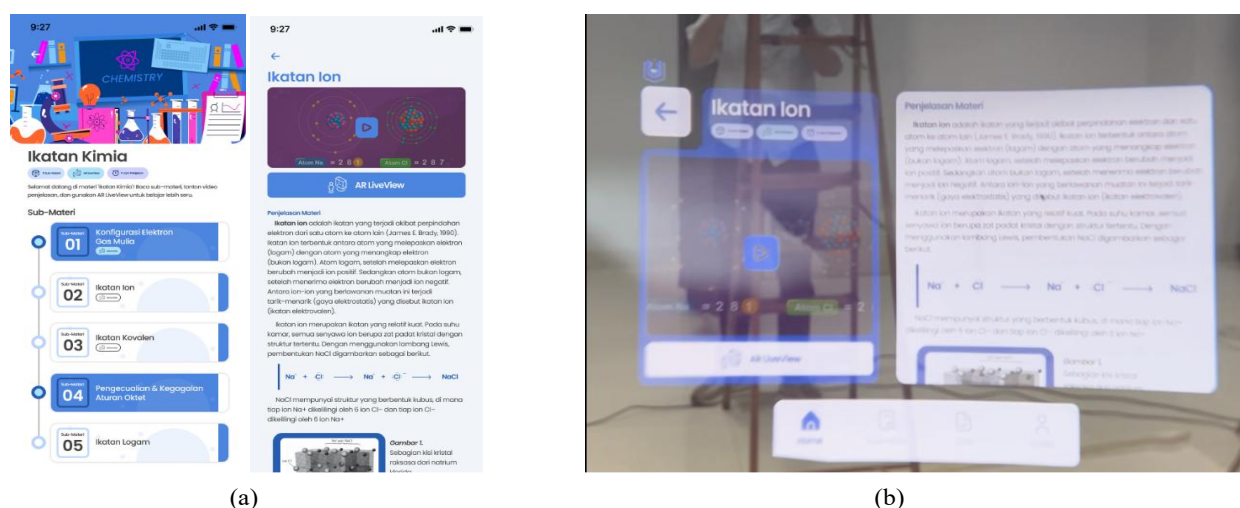


Figure 3. Learning modules and AR integration: (a) mobile sub-module navigation; (b) spatial interaction in AR glasses.

When a topic is selected from the home screen, the system displays a list of sub-modules that must be studied sequentially. Each sub-module includes text explanations and educational videos, providing both visual and textual support for understanding the material. To enhance immersion, certain sub-modules integrate the AR LiveView feature, allowing students to visualize chemical structures in three dimensions. Through this feature, learners can manipulate models using hand tracking gestures such as zooming and rotating, making abstract chemical concepts more concrete and interactive.

4.1.3. Scanalyze Feature

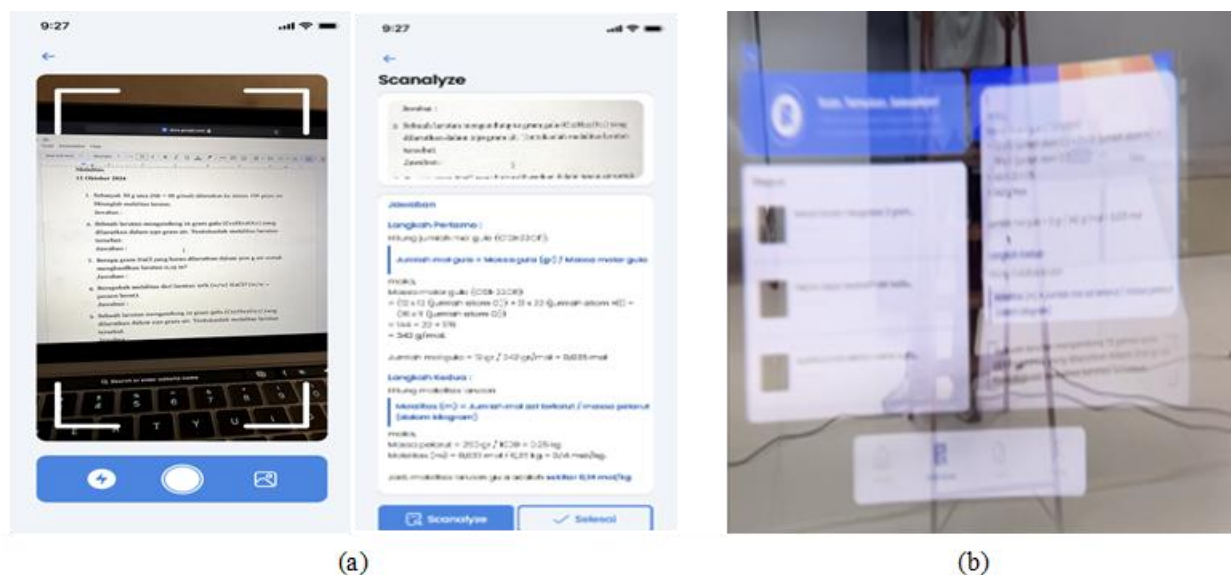


Figure 4. Scanalyze feature: (a) mobile step-by-step AI solution; (b) immersive solution display in AR glasses.

The Scanalyze feature enables students to solve chemistry problems by scanning them directly through the application. The main page displays a history of previously scanned questions and provides a shortcut button to initiate a new scan. Once the camera view is opened, users can capture a photo of the problem, which is then processed by the system. The output is presented in a step-by-step solution format, including formulas, intermediate calculations, and final results. The design not only provides the correct answer but also emphasizes the reasoning process, supporting students in developing a deeper understanding of problem-solving in chemistry.

4.1.4. Quiz Feature

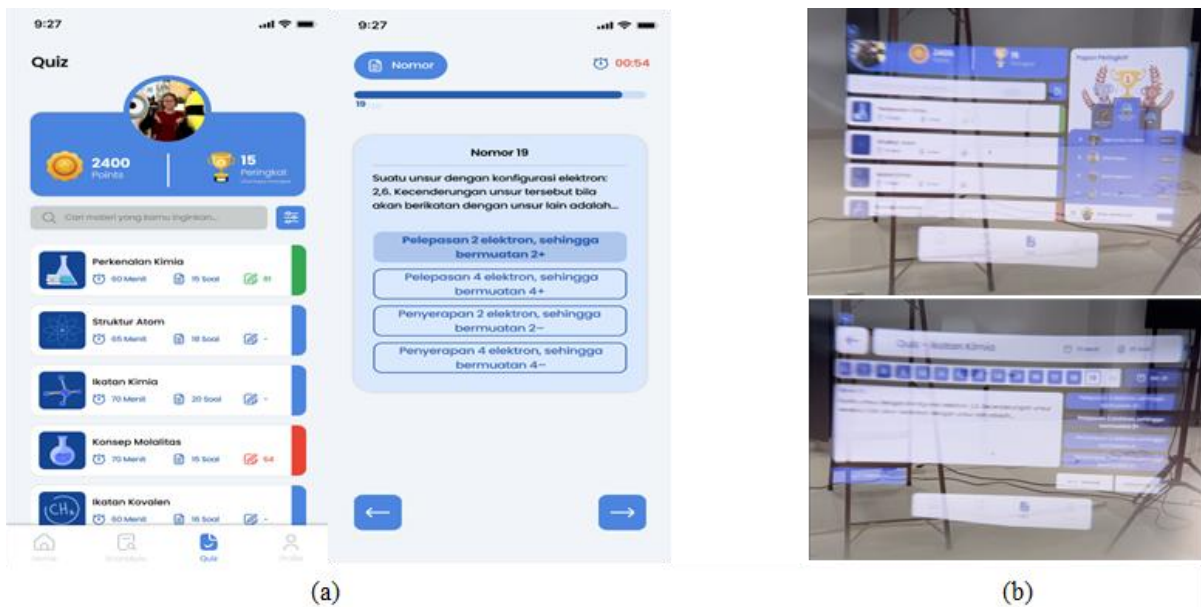


Figure 5. Quiz feature: (a) mobile interface with progress tracking; (b) immersive AR quiz and leaderboard.

The quiz features provide an evaluation tool that can combine practice with gamification. Upon entering the quiz menu, users are greeted with a profile summary, showing total points earned and their current ranking. Below, a list of quiz modules is presented, each with details on duration, number of questions, and completion status. Color indicators mark progress: green for completed and passed, red for completed but failed, and blue for not yet attempted. Before starting a quiz, users are shown an instruction screen outlining time limits and question counts. During the quiz, a progress bar and countdown timer appear at the top, ensuring students can monitor their performance and pacing. Once the quiz is completed, the system immediately provides results with scores, number of correct and incorrect answers, and points gained. Students may also review detailed explanations for each question, reinforcing learning beyond evaluation.

4.1.5. Profile Page

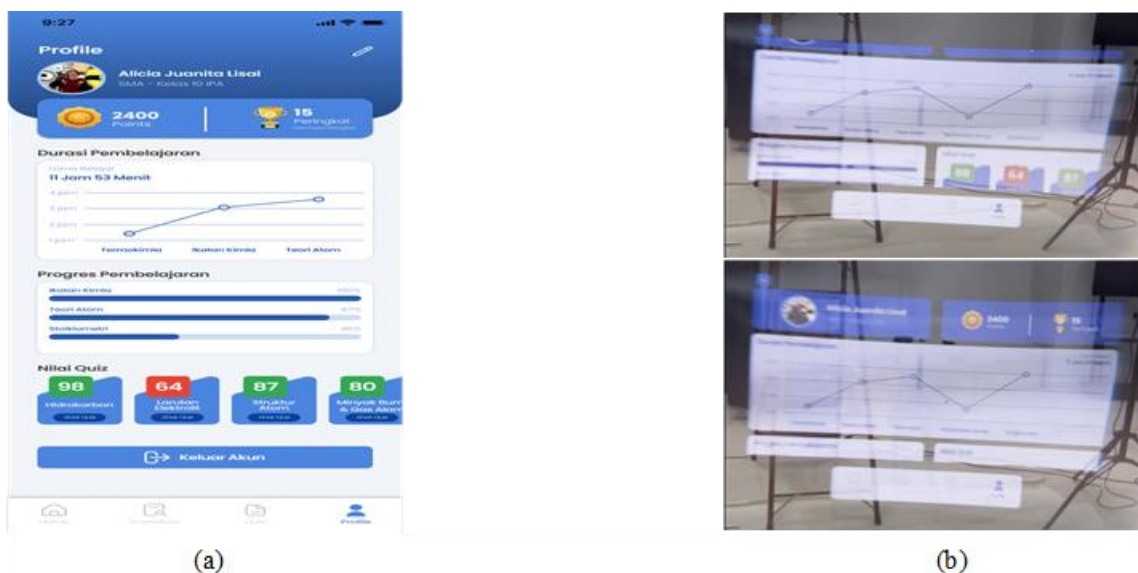


Figure 6. Profile page: (a) mobile progress dashboard; (b) immersive performance overview in AR.

The profile page provides a comprehensive overview of student progress by displaying identity information, total points, and leaderboard ranking at the top, followed by a visualization of learning duration across different topics. Progress bars indicate the completion level of each module, while quiz results are summarized with individual scores for every subject. This layout allows students to monitor their achievements easily and supports motivation by combining performance tracking with gamified elements.

4.2. Integration with AR Devices

The ChemMaster application supports deployment on both mobile devices and AR glasses, enabling flexible learning experiences across different contexts. While the mobile interface allows easy access through touch-based interaction, the AR glasses provide a significantly more immersive environment by projecting chemical content into the learner's physical surroundings. Through hand-tracking gestures, students can rotate, zoom, and manipulate molecular models naturally. This immersive integration makes the learning process more interactive and supports deeper conceptual comprehension.

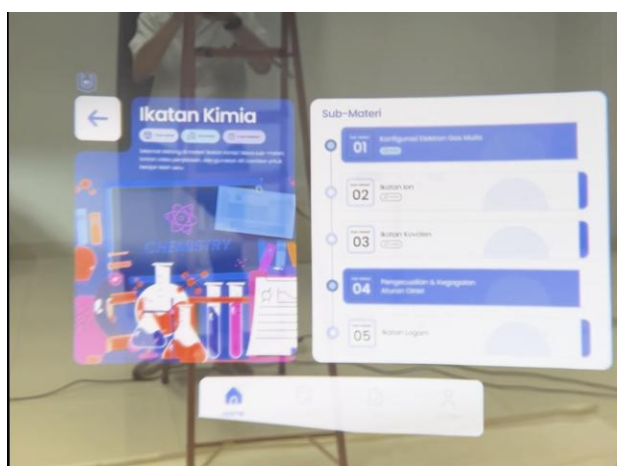


Figure 7. Immersive projection of learning modules in the AR glasses interface.

In contrast, the mobile version offers a more accessible but less immersive experience. On smartphones, AR modules are presented through the screen, and users interact via taps and swipes. Although functional, this approach restricts the sense of spatial presence compared to AR glasses. By comparison, AR glasses allow students to interact with life-sized 3D objects in real space, maintaining focus and reducing distractions. The integration of both platforms ensures that the application is inclusive for users without AR devices while still demonstrating the advantages of immersive learning for those with access to AR technology.

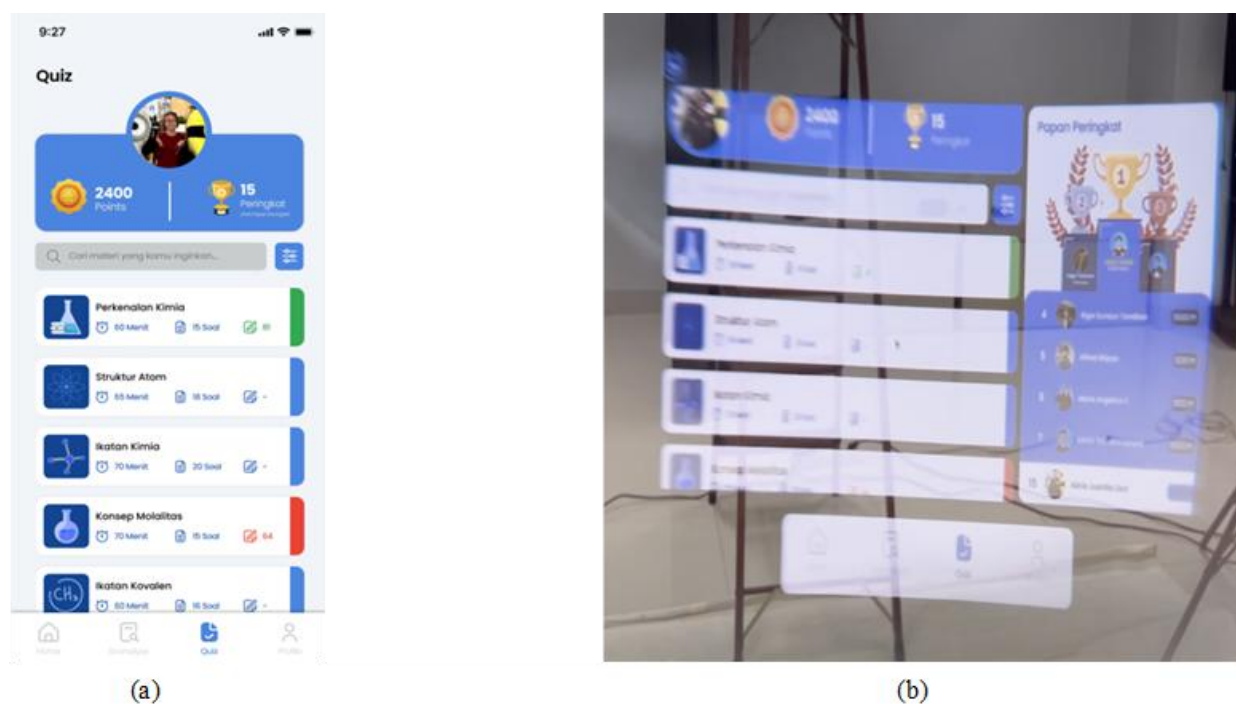


Figure 8. Comparison of the Quiz feature between the mobile interface and AR glasses.

4.3. User Testing and Feedback

User testing was conducted with a group of high school students and one chemistry teacher to evaluate the usability and learning effectiveness of the ChemMaster application. The usability of ChemMaster was quantitatively evaluated using the System Usability Scale (SUS). The analysis yielded an average score of 81.5 with a standard deviation of 5.2. According to the SUS grading scale, this result places the application in the 'Excellent' category, indicating that the interface is highly intuitive for both students and teachers, even those without prior AR experience. Overall, participants reported that the system was easy to navigate, with most tasks successfully completed without significant difficulties. Both students and the teacher agreed that the application supported their learning process and increased engagement, particularly compared to conventional methods.

Specific attention was given to the hand tracking and spatial AR features, which were perceived as the most engaging aspects of the system. Students highlighted that manipulating molecular models with gestures such as rotation and zoom made abstract concepts more understandable and interactive. The chemistry teacher emphasized that these immersive elements helped bridge the gap between theoretical explanations and tangible visualization, improving conceptual comprehension. Despite the positive responses, several challenges and areas for improvement were identified. Some participants reported reduced accuracy in hand tracking under low-light conditions, while others suggested that additional tutorials would help new users adapt more quickly to AR interactions. In terms of navigation, a few students noted delays in leaderboard updates and occasional difficulty switching between modules.

Table 1. Summary of usability testing results across different evaluation aspects.

Evaluation Aspect	Findings
System Usability (SUS)	The application achieved an average SUS score of 81.5, placing it in the "Excellent" category and indicating high intuitiveness for novice users.
Ease of use	Most participants found the application easy to navigate and intuitive.
Task completion	Core tasks (accessing materials, scanalyze, quizzes) were successfully completed by the majority of users.
Satisfaction	Students and the teacher expressed positive feedback; higher engagement compared to traditional learning.
Hand tracking and spatial AR	Gesture-based interaction (rotate, zoom, explore) improved understanding of molecular structures and reactions.
Strengths highlighted	Immersive visualization, clear module structure, motivating quiz and leaderboard system.
Challenges identified	Reduced tracking accuracy under low-light conditions, occasional delay in leaderboard updates, and navigation between modules could be smoother.

5. Discussion

The development of ChemMaster demonstrates that integrating Spatial AR with hand tracking provides an engaging learning experience, helping students visualize abstract molecular structures more effectively than conventional textbooks. User testing confirmed the system's usability, yielding an average SUS score of 81.5, which categorizes the interface as 'Excellent' and highly accessible for novice users. Participants successfully utilized features like Scanalyze and AR models to solve problems and interact with 3D content. However, as an exploratory pilot study, the small sample size of 15 participants and the absence of a controlled comparison group or pre-test/post-test measures limit the ability to definitively quantify academic improvement relative to traditional methods. To address this limitation, future research should adopt a quasi-experimental design involving a larger and more diverse sample drawn from multiple schools, randomly or purposively assigned to an experimental group using ChemMaster and a control group taught with conventional methods. Learning outcomes in both groups should be measured using validated chemistry concept tests administered before and after the intervention, allowing gain scores to be statistically compared between groups. Such a design would provide objective, quantifiable evidence of ChemMaster's educational effectiveness beyond the subjective usability indicators reported in this pilot study.

While hand-tracking gestures made abstract ideas more tangible, the system still faces technical constraints. Performance remains highly device-dependent and sensitive to lighting conditions, which can reduce tracking accuracy. Furthermore, this evaluation focused on short-term usability and perception-based feedback rather than long-term knowledge retention. These constraints also carry implications for Cognitive Load Theory. On one hand, by allowing students to manipulate 3D molecular models directly through natural hand gestures, ChemMaster increases spatial and temporal contiguity between abstract submicroscopic representations and the learner's physical environment, which may reduce extraneous cognitive load compared to interpreting static textbook diagrams (Peeters

et al., 2023). On the other hand, the simultaneous demands of processing real-time visual feedback, interpreting gesture-based interactions, and reasoning through the underlying chemistry concept may increase intrinsic cognitive load, particularly for novice users encountering AR and hand tracking for the first time (Ripsam & Nerdel, 2022). This trade-off suggests that interface simplicity and scaffolded onboarding are important design considerations, since an immersive experience that is technically impressive but cognitively demanding may inadvertently hinder rather than support conceptual understanding. Future improvements should focus on enhancing tracking responsiveness and incorporating objective performance metrics. By addressing these limitations, ChemMaster has the potential to serve as a foundational model for more rigorous and interactive STEM educational tools.

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Funding Declaration

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Ethics Approval

The study involved human participants (students and teachers) through questionnaires and interviews. Verbal informed consent was obtained from all participants and their respective institutions before the study. Data were anonymized to ensure participant privacy. Ethics approval was issued by the ethics review committee at Universitas Ciputra Makassar.

Conflict of Interest

The authors declare that there are no competing interests.

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