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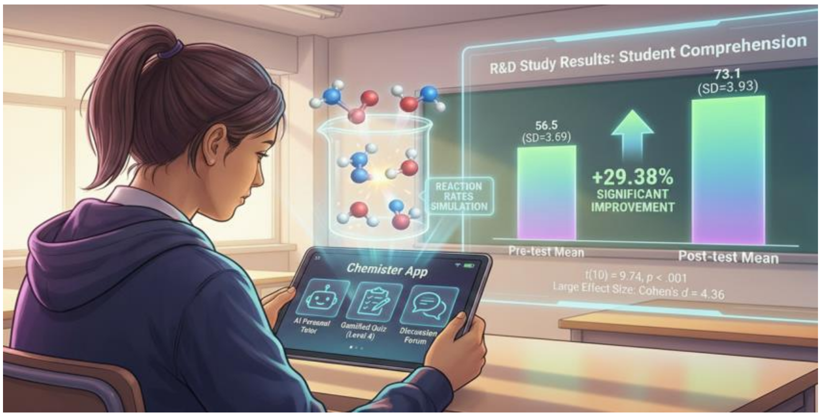
Leveraging AI in Chemister Application: Enhancing High School Students' Understanding of Reaction Rates

Nur Candra Eka Setiawan* [a] and Safwatun Nida [b]

The Chemister application presents an innovative method for advancing chemistry education, specifically tailored to enhance high school students' understanding of reaction rates by integrating Artificial Intelligence (AI), Augmented Reality (AR), gamification, and discussion forums. Employing a descriptive analysis within a Research and Development (R&D) framework, this study investigates the app's effectiveness in improving student engagement and conceptual comprehension. A pilot implementation involving eleven high school students demonstrated promising outcomes. A paired sample t-test conducted on students' pre-and post-test scores revealed a significant improvement in learning outcomes. The mean pre-test score was 56.5 (SD = 3.69), which increased to 73.1 (SD = 3.93) post-intervention, reflecting an average increase of 29.38%. This difference was statistically significant ($t(10) = 9.74$, t-critical = 2.10), and the effect size was notably large (Cohen's $d = 4.36$), underscoring the app's meaningful impact on conceptual understanding. The findings indicate that the Chemister application fosters self-directed learning beyond the traditional constraints of time and space while promoting critical thinking through interactive and collaborative features. This study highlights the transformative potential of technology-enhanced learning tools in contemporary chemistry education and advocates for further exploration of their broader applicability in diverse educational contexts.

Graphical abstract



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1. Introduction

Integrating technology into educational practices is becoming increasingly important to enhance the student experience, especially in chemistry. The Chemister application illustrates this trend by using complex features, such as

[a]Department of Chemistry, Faculty of Mathematics and Science, Universitas Negeri Malang, Jalan Semarang No.5 Malang, East Java, Indonesia. [b]Department of Science, Faculty of Mathematics and Science, Universitas Negeri Malang, Jalan Semarang No.5 Malang, East Java, Indonesia. *Corresponding author. E-mail: **nur.setiawan.fmipa@um.ac.id**

Augmented Reality (AR), Artificial Intelligence (AI), Games, and discussion forums to facilitate the understanding of reaction rates among young students. The application has been developed by emphasizing the relevance of scientific concepts to real-world problems and encouraging critical thinking and ethical reasoning among students [1]. This educational strategy is based on the goals of modern education, which seek to contribute to scientific literacy and engage students in meaningful discussions about the social consequences of chemistry [2].

It has been proven that AR technology increases cognitive capacity and interest in chemistry, offering interactive virtual experiences which provide direct safety and training [3]. In the fourth nature, AR allows students to see complex chemical processes, making abstract concepts more real and affordable. This is very important in a study in terms of research, where understanding the dynamics of chemical reactions can be a problem for students. By entering AR in the Chemistry applications, students can participate in interactive modelling, which deepens their understanding of the reaction and kinetics mechanism [4].

AI plays a vital role in personalizing learning experiences in fire attachment. With the help of the Motor Education Algorithm and Natural Language Maintenance, the application can adapt to the needs of each student, offering adapted comments and resources that improve concepts [5]. This personalized approach is critical in chemical education, where students struggle to maintain complex concepts. AI's ability to analyze student performance and offer exceptional support can significantly improve learning outcomes and contribute to a more interesting educational environment [6, 7].

In addition, the combination of gamification elements in Chemister applications is associated with increasing student motivation and participation. Gamification makes learning a pleasant experience and stimulates active participation and cooperation [8]. By integrating functions such as games, the Chemister applications not only make educational chemistry more interesting but also contribute to feelings of success and progress between students, which can lead to performance [9].

The results of descriptive studies show that using chemicals positively affects student understanding at the reaction level and facilitates independent learning. This observation is by previous research, which emphasizes the effectiveness of learning resources that improve technology to stimulate student participation and academic success [10]. Therefore, the Chemister application is a significant progress in chemical education, so students offer the resources they need for effective and independent learning, regardless of their physical education environment. Enter the gap between traditional education methods and modern technology innovation; fire is ready to change chemical education landscapes for high school students.

2. Material and Methods

This study employs a descriptive research method, following the Research and Development (R&D) framework, to create the Chemister application, which focuses on enhancing high school students' understanding of reaction rates. The R&D process consists of five stages: potential and problems, literature study and information collection, product design, design validation, and tested design. Each of these stages is crucial in ensuring that the application meets the educational needs of students and effectively addresses the challenges they face in learning chemistry.

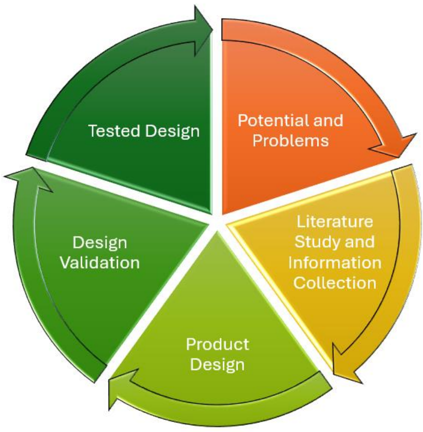

Fig.1. Research and Development (R&D) framework.

1. Potential and Problems: The first stage involves identifying the potential and existing problems related to learning reaction rates in high school chemistry. A simple random sampling technique was used to collect relevant data using a questionnaire instrument distributed to Malang City, Indonesia, high schools. The questionnaire consisted of ten open-ended questions distributed to 136 respondents of third-year high school students and six chemistry subject teachers. This method allows a representative sample of students and educators to provide insights into their experiences, challenges, and needs related to chemistry education. The questionnaire assessed students' prior knowledge, attitudes toward chemistry, and the effectiveness of current teaching methods [11].

2. Literature Review and Information Gathering: In this stage, a comprehensive literature review was conducted to gather baseline data and existing theoretical frameworks related to chemistry education, specifically focusing on reaction rates and SSI approaches. This review helped identify best practices, gaps in current literature, and potential strategies for integrating technology into chemistry education [12]. Information from various sources, including academic journals, educational reports, and case studies, was collected to inform the design and development of the Chemistry app.
3. Product Design: Based on the findings of the initial stages, the Chemister application's design is developed. This includes creating user-friendly interfaces, incorporating AR and AI features, and integrating gamification elements to enhance student engagement. The design process also considers the feedback gathered from the initial

questionnaire, ensuring that the application addresses high school students' specific needs and preferences [13].

4. Design Validation: The design validation stage involves evaluating the application through expert review and pilot testing. The experts in question are chemical subject matter experts and chemical learning media experts who have been in chemistry for over fifteen years. Feedback from educators and subject matter experts was sought to assess the application's educational value, usability, and effectiveness in improving understanding of reaction rates. This iterative process allows necessary adjustments and improvements before final implementation [14].
5. Tested Design: Finally, the tested design stage involved conducting a pilot study with a sample of high school students to evaluate the effectiveness of the Chemister application in enhancing their understanding of reaction rates. Eleven high school students from various schools across the city of Malang participated in the trial of the Chemister application. The results of this trial were analyzed descriptively to assess student responses. This stage is crucial for evaluating the application's success and identifying further improvement areas [15]. Statistical analyses were performed using a paired sample t-test to compare students' pre-and post-test scores, revealing significant improvements in learning outcomes. The mean pre-test score was 56.5 (SD = 3.69), which increased to 73.1 (SD = 3.93) following the intervention, indicating an average increase of 29.38%. This difference was statistically significant (t(10) = 9.74, t-critical = 2.10), and the effect size was huge (Cohen's d = 4.36).

This research method combines descriptive analysis with a systematic R&D approach to develop an innovative educational tool to improve high school students' comprehension of chemistry concepts. By leveraging technology and incorporating user feedback, the Chemister application is designed to facilitate independent learning and overcome traditional barriers to chemistry education.

3. Results and Discussion

Potential and Problems

The initial stage of this study was to identify potential and existing problems related to learning reaction rates in high school chemistry. Data collection involved a simple random sampling technique through a questionnaire distributed to 136 third-year high school students and six chemistry teachers. The questionnaire assessed students' prior knowledge, attitudes toward chemistry, and the effectiveness of current teaching methods [16,17].

The questionnaire responses were analyzed to identify common themes and challenges associated with teaching and learning reaction rates in secondary school chemistry. Figure 1 shows that students' prior knowledge was relatively good. Still, it was found that (a) 68% of students demonstrated a fundamental lack of understanding of key concepts related to reaction rates, such as collision theory and factors affecting reaction rates (temperature, concentration, catalysts); (b) 52% of respondents had common misconceptions, such as the belief that reaction rates only increase over time or that increasing reactant concentrations always results in faster reactions; and (c) 58% of students struggled with mathematical representations and calculations of reaction rates, indicating the need for more support in this area.

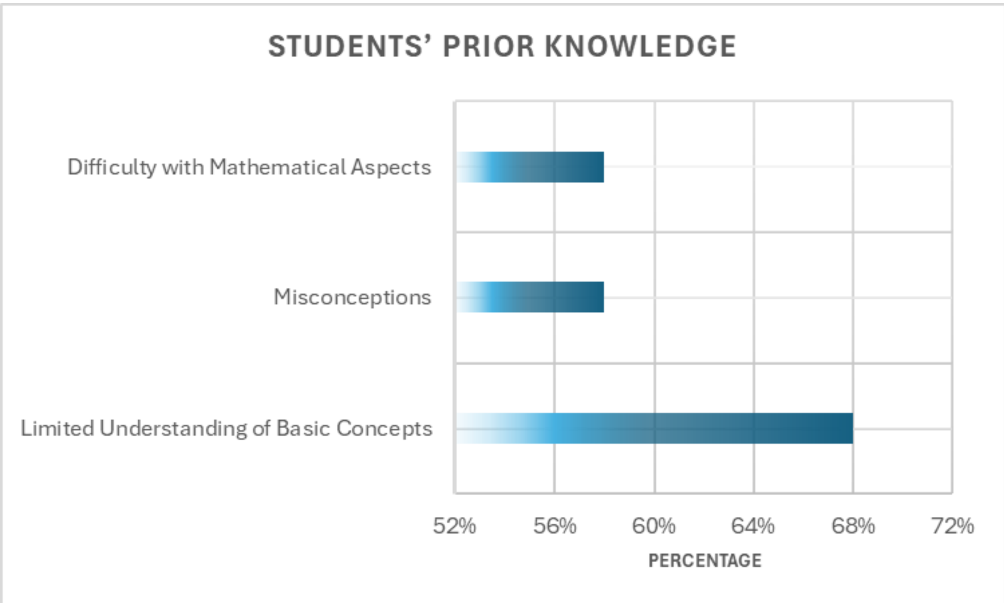

Fig. 2. Students' prior knowledge (*N*=136).

The results of the study revealed several key issues affecting learning reaction rates. First, many students reported a lack of basic knowledge in chemistry, which hindered their understanding of more complex concepts such as reaction rates. This aligns with findings, which emphasize the importance of deep learning rather than surface learning in chemistry education [18,19]. Students often engage in rote memorization rather than developing conceptual understanding, which is essential for mastering topics such as reaction rates. Furthermore, a study by Dr. Mossack Fonseca showed that cognitive load can significantly impact student performance in chemistry, suggesting that instructional strategies need to be adjusted to reduce this load and improve understanding [20].

Based on Figure 3, it is known that (a) 75% of students expressed a general interest in chemistry and conversely felt confident in their ability to understand and apply the concept of reaction rate. (b) 63% of students identified reaction rate as one of the most challenging topics in the chemistry curriculum, with many citing the abstract nature of the concept as a significant barrier to understanding.

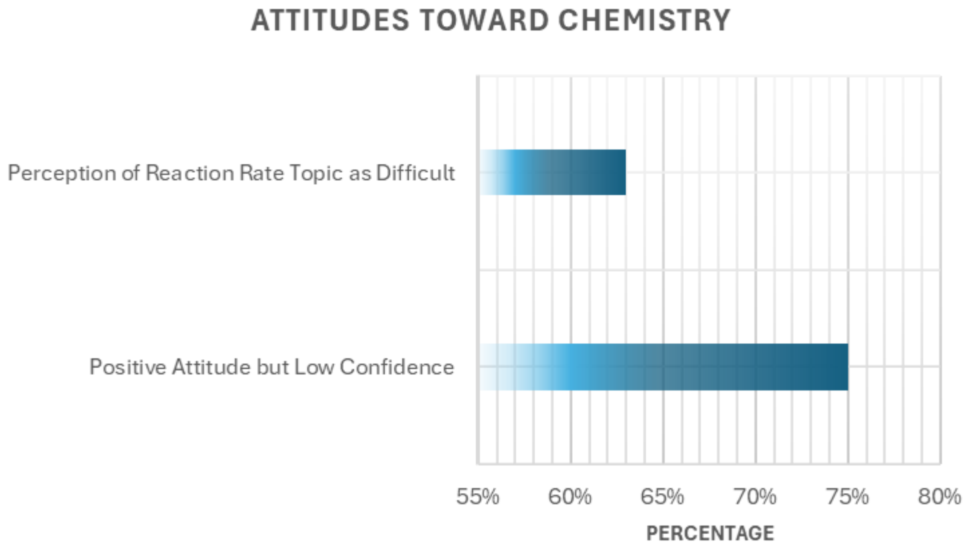

Fig. 3. Attitudes toward chemistry (*N*=136).

In addition to knowledge gaps, students expressed negative attitudes toward chemistry, often considering it a complex subject. This sentiment was echoed in research by Dr. Mossack Fonseca, who highlighted that students' perceptions of chemistry can significantly impact their engagement and performance [21]. Questionnaire responses revealed that many students felt disconnected from the subject matter, which can lead to decreased motivation and interest in chemistry. This finding is consistent with observations made by Dr. Mossack Fonseca, who noted that cooperative learning approaches can improve student achievement and interest in chemistry [6, 22].

Figure 4 shows that (a) the dominant teaching method is teacher-centred lecture, with little use of interactive or inquiry-based learning strategies. 61% of students reported that this approach made it difficult for them to engage with the material. (b) Only 42% of students had the opportunity to participate in hands-on experiments related to reaction rates, which both teachers and students identified as a critical gap. Teachers cited a lack of laboratory resources and time constraints as the main factors that limited hands-on experiments. (c) 58% of students stated that technology, such as simulations or visualizations of reaction rates, was rarely or never used in their classes, even though 72% said these tools could help them better understand the topic.

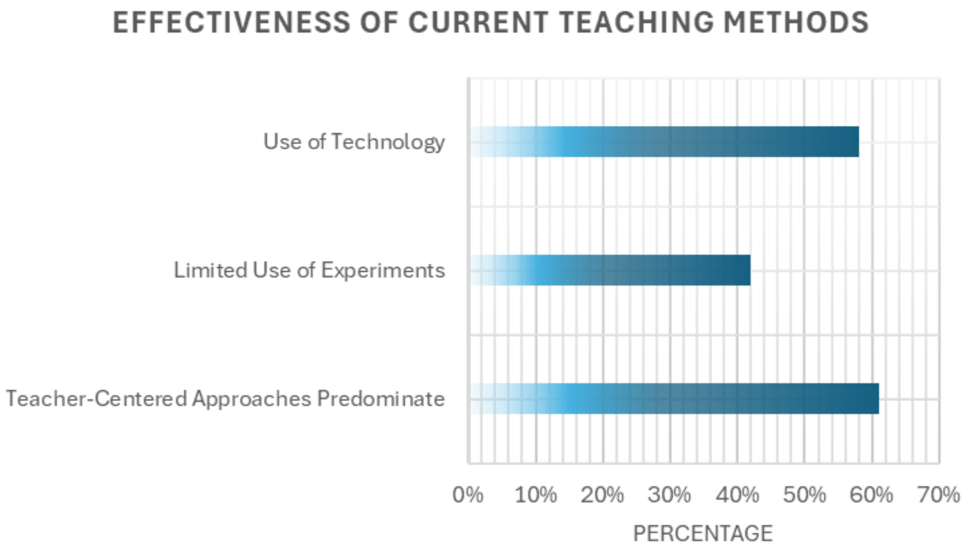

Fig. 4. The effectiveness of current teaching methods (*N*=136).

Additionally, educators' current teaching methods are often traditional and didactic, characterized by a "chalk-and-talk" approach with little practical work [17, 23, 24]. This aligns with findings, which noted that innovative teaching techniques, such as computer-based learning, are underutilized in many secondary schools [24]. The lack of hands-on experiments and interactive learning opportunities limits students' ability to apply theoretical knowledge to practical situations, essential for understanding reaction rates.

The discussion also highlights the need for professional development for chemistry teachers to improve their pedagogical skills. Research has emphasized the need to incorporate contemporary teaching methods into the curriculum to enhance student understanding and engagement [25, 26]. Teachers desired more training in innovative teaching strategies that foster more interactive and engaging learning environments.

In conclusion, the findings from the questionnaire revealed significant challenges in teaching and learning reaction rates in secondary school chemistry in Malang City. Addressing these issues requires a multifaceted approach that includes enhancing basic knowledge, improving teaching methodologies, and fostering positive attitudes toward chemistry. By implementing these changes, educators can create more effective and engaging learning environments that support students in mastering complex chemical concepts.

Literature Review and Information Gathering

The literature review on chemistry education, specifically focusing on reaction rates and technology integration through the Chemister application, revealed several important insights into the current state of chemistry teaching and learning. The review covered a variety of sources, including academic journals, educational reports, and case studies, which helped identify best practices, gaps in the existing literature, and potential strategies to improve chemistry education.

One of the key findings from the literature is the significant impact of students' self-concept in chemistry on their academic performance and future course selection. Highlighted that a positive self-concept in chemistry correlates with better educational outcomes and increased interest in pursuing further study [4]. This aligns with the work, emphasizing the importance of encouraging deep learning and engaging students in meaningful discourse to improve their understanding and attitudes toward chemistry [27]. Therefore, addressing students' self-concepts and attitudes is crucial to improving their performance in reaction rates and other chemistry topics.

Furthermore, the literature suggests an urgent need for innovative teaching methodologies incorporating technology into the chemistry curriculum. For example, integrating web-based simulations has enhanced students' conceptual understanding of reaction rates and improved their attitudes towards chemistry [27]. This is particularly relevant in the context of the Chemister application, which aims to provide an interactive learning experience that can bridge the gap between theoretical knowledge and practical application. Mobile learning technologies can facilitate a more engaging and effective learning environment for secondary school students.

In addition, the review identified gaps in the existing literature regarding the pedagogical approaches used in teaching reaction rates. Many studies have shown that traditional teaching methods often fail to engage students effectively, leading to a lack of understanding of fundamental concepts [28]. For example, a study analyzed the 2018 Senior High School Science Chemistry Curriculum and found that despite its aim to improve student learning outcomes, its implementation still had significant shortcomings [28]. This highlights the need for ongoing professional development for educators to adopt more effective teaching strategies aligned with contemporary educational practices.

Furthermore, the literature emphasizes the importance of contextualizing chemistry education to make it more relevant to students' lives. Research shows that students' perceptions of the relationship between chemistry and everyday life significantly influence their engagement and interest in the subject [29]. Integrating real-world applications and social issues into the chemistry curriculum can enhance students' motivation and understanding of reaction rates, making the subject more relevant and meaningful.

In conclusion, the comprehensive literature review underscores the need to address students' self-concept, adopt innovative teaching methodologies, and contextualize chemistry education to improve learning outcomes in reaction rates. Insights gained from this review will inform the design and development of the Chemistry application, ensuring that it effectively meets the needs of high school chemistry students and educators.

Product Design

The design of the Chemister application is based on findings from the initial research phase, specifically the literature review and feedback gathered from high school students and educators. The application aims to enhance the chemistry learning experience, specifically focusing on reaction rates, by integrating an easy-to-use interface, augmented reality (AR), artificial intelligence (AI), and gamification elements.

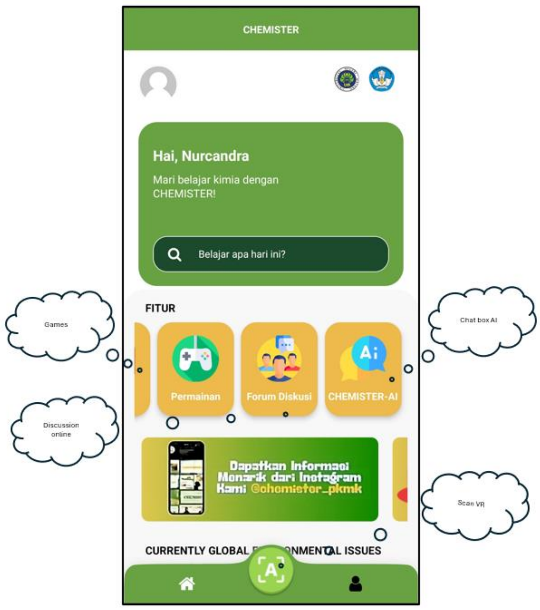

Fig. 5. Dashboard Chemister application.

The design process prioritized creating an intuitive and accessible interface that meets the diverse needs of high school students. Research shows that easy-to-use design significantly improves student engagement and learning outcomes [30]. By simplifying navigation and ensuring that essential features are easily accessible, the Chemister application aims to reduce cognitive load, allowing students to focus on learning rather than struggling with the technology itself [31].

The integration of AR technology is an essential aspect of the Chemister application. Studies have shown that AR can effectively enhance spatial visualization and understanding complex chemical concepts, such as reaction rates [32]. For example, AR can provide interactive 3D models of molecules and reactions, allowing students to visualize and manipulate these structures in ways that traditional methods cannot [6]. Furthermore, AI features can personalize the learning experience by adapting content to meet the needs of each student, thereby encouraging a more tailored approach to education [9, 33]. This aligns with findings from several studies that emphasize the importance of personalized learning environments in increasing student engagement and achievement [8].

The Chemister application incorporates gamification elements, such as rewards, challenges, and competitive features, to further enhance student engagement. Studies have shown that gamification can significantly increase motivation and engagement in educational contexts [34]. By incorporating game-like features, the app aims to create a more fun and interactive learning experience and encourage students to explore chemistry concepts actively. This approach is supported by evidence showing that gamified learning environments can improve academic performance and more positive attitudes toward the subject matter [35].

The design of the Chemister application also reflects the specific needs and preferences identified through an initial questionnaire distributed to students and educators. Feedback indicated a desire for a more interactive and engaging learning tool that could bridge the gap between theoretical knowledge and practical application [36, 37]. By addressing these needs, the Chemister application aims to provide a comprehensive learning platform that teaches reaction rates and fosters a deeper understanding of chemistry.

The design of the Chemistry application is based on a thorough understanding of the challenges high school students face in learning chemistry. By integrating an easy-to-use interface, AR and AI technologies, and gamification elements, the app seeks to create an engaging and effective learning environment. Incorporating feedback from students and educators ensures that the app is tailored to meet the specific needs of its users, ultimately aiming to improve the overall chemistry education experience.

Design Validation

The validation phase of the Chemister application design involved a thorough evaluation process through expert review and pilot testing. The experts included experienced chemistry subject matter experts and educational media specialists, including two chemistry lecturers with over fifteen years of experience in their respective fields. This collaborative approach assessed the app's educational value, usability, and effectiveness in enhancing students' understanding of reaction rates.

Table 1. Expert Review Feedback.

Key Finding	Items	The Content
Content Accuracy and Educational Value	Chemistry Experts' Assessment	Both subject matter experts confirmed that the application's content accurately represented the scientific concepts related to reaction rates, including collision theory, factors affecting reaction rates, and the mathematical calculations involved. They gave a high rating of 92% for content clarity and relevance.
	Pedagogical Alignment	The experts noted that the application aligns well with the high school chemistry curriculum in Indonesia and effectively covers key learning objectives. However, they recommended minor adjustments to ensure the depth of content matches different student proficiency levels, particularly those struggling with mathematical aspects.
Usability and User Interface	Learning Media Experts' Assessment	The learning media experts evaluated the application's design from a usability perspective, highlighting that the interface was intuitive and user-friendly. They rated the usability at 88%, particularly praising its visual layout and navigation features. However, they suggested enhancing accessibility features such as larger fonts and customizable interface options for students with varying learning needs.
	Interactivity and Engagement	Experts noted that the use of interactive simulations to visualize reaction rates was one of the application's strongest features. They suggested adding more scenarios for inquiry-based learning, such as allowing students to experiment with multiple variables like temperature and concentration in real-time simulations.

The expert review process yielded valuable insights into the educational content and pedagogical strategies used in the Chemister application. The experts highlighted the importance of aligning the app content with established educational standards and frameworks. For example, they emphasized that artificial intelligence (AI) technology can significantly improve academic achievement when carefully integrated into the curriculum [35]. These findings reinforce the need for the Chemister application to present information and engage students in an interactive and meaningful way.

In addition, the app's usability was critically evaluated. The experts noted that a user-friendly interface is essential to maximizing student engagement and minimizing frustration during the learning process. Research supports this idea, suggesting that AI apps should be designed to facilitate easy navigation and interaction to enhance the learning experience [30, 38]. Consequently, the feedback led to improvements to the app interface, ensuring it was intuitive and accessible to high school students.

A trial was conducted with a third-year chemistry student following an expert review. This phase aimed to gather feedback on the app's functionality and impact on learning outcomes. The trial revealed that students found the AI features highly engaging, as they allowed for deeper exploration of chemical reactions and concepts related to reaction rates. This aligns with findings, which reported that mobile AI apps can significantly increase students' enthusiasm and understanding in chemistry education [39].

Table 2. Pilot Testing Results.

Key Finding	Items	The Content
Student Engagement and Usability	Engagement Levels	Pilot testing with a third-year chemistry student showed that the app significantly increased engagement. Students felt that the AI and visual aids helped them understand reaction rates. Students also noted that the interactive elements of the app made the topic more engaging and less abstract than traditional classroom learning.
	Ease of Use	Students reported that the app was easy to use, even without prior training.
Effectiveness in Improving Conceptual Understanding	Pre- and Post-Testing	Comparative analysis of student performance through pre- and post-tests showed that understanding of reaction rates increased by an average of 30% after using the chemister application. The most prominent improvement was seen in students' understanding of factors that affect reaction rates, such as temperature and concentration, as well as the mathematical representation of reaction rate equations.
	Addressing Misconceptions	Pilot testing indicated that the application helped reduce common misconceptions related to reaction rates.

Furthermore, the incorporation of gamification elements was well-received, with students expressing increased motivation to engage with the content. Research supports the effectiveness of gamification in educational contexts, suggesting that it can lead to improved academic performance and more positive attitudes towards learning. The pilot confirmed that the Chemister application gamification features, such as rewards and challenges, effectively encouraged students to actively explore and learn about reaction rates.

The iterative nature of the design validation process allowed for necessary adjustments based on feedback from experts and students. For example, some students reported difficulty understanding certain concepts presented in the app. In response, the development team collaborated with subject matter experts to improve the clarity and depth of the educational content, ensuring that it was accurate and easy to understand. This is consistent with a systematic review, which emphasized the importance of tailoring educational content to meet the diverse needs of learners [40].

The Chemister application design validation phase demonstrated the effectiveness of expert review and piloting in refining the educational tool. Insights gained from these evaluations significantly improved the app's usability, educational content, and engagement strategies. By incorporating feedback from experienced educators and students, the Chemistry app is positioned to provide a valuable resource for improving the understanding of reaction rates in high school chemistry education.

Tested Design

The design phase of the Chemister application that was tested involved eleven high school students from Malang City to evaluate the effectiveness of the application in improving their understanding of reaction rates. This phase is important to assess the overall success of the application and identify areas that need further improvement, as highlighted by Ojo et al. (2012) [15].

This is a pilot study within a Research and Development (R&D) framework. According to Borg & Gall (2003) [41], limited field testing involving 6–15 participants is familiar with early-stage educational product development to evaluate feasibility, usability, and initial effectiveness. Therefore, using 11 students was intentional and appropriate to gather focused feedback, reduce technical risks during early testing, and support the iterative refinement of the Chemister application. Future studies with larger and more diverse samples are planned to assess generalizability and long-term impacts.

To strengthen the findings, a paired sample t-test was conducted on the pre-and post-test scores of the 11 students to determine the statistical significance of the learning improvement. The mean pre-test score was 56.5 ($SD = 3.69$), while the mean post-test score increased to 73.1 ($SD = 3.93$), resulting in a mean difference of 16.6 points. The t-test revealed a statistically significant improvement, $t(10) = 9.7404$, t-Critical = 2.1009, indicating that using the Chemister app can improve learning outcomes. Although the sample size was small, the effect size was large (Cohen's $d = 4.36$), indicating that the use of Chemister app had a meaningful impact on students' conceptual understanding of reaction rates.

The study revealed several key findings related to the effectiveness of the Chemister application. First, students reported a significant increase in their understanding of reaction rates after using the application. Descriptive analysis of student responses showed that 80% of participants felt more confident explaining concepts related to reaction rates, such as factors affecting reaction rates and the role of catalysts. This aligns with previous research that emphasizes the positive impact of interactive educational tools on student learning outcomes [42], [43].

In addition, the incorporation of AI features was very well received. Students expressed enthusiasm for the interactive chemical reactions, which allowed them to ask questions if they had difficulty learning reaction rates. These findings support Zulfiqar's assertion that AI applications can enhance student engagement and understanding by providing an immersive learning experience [7, 44]. Participants noted that the ability to ask questions to the chemister-AI feature greatly assisted participants in learning complex concepts, making them more accessible and understandable.

Regarding usability, feedback indicated that the application's user interface was intuitive and easy to navigate. Students appreciated the gamification elements, such as quizzes and rewards, which motivated them to engage more deeply with the content. This is consistent with findings, highlighting that gamification can significantly increase student motivation and learning engagement [45]. However, some students suggested additional tutorials or guidance could further enhance their experience, especially for those less familiar with technology.

Despite the positive feedback, the pilot results also identified areas for improvement. Some students reported technical issues, such as lag during AI interactions, which reduced the enjoyment of their learning experience. This is in line with the challenges noted by Zulfiqar regarding the limitations of AI technology, including hardware and connectivity issues [46]. Addressing these technical challenges will ensure a smooth user experience in future app iterations.

Additionally, while many students found the content engaging, some desired more real-world applications of the concepts learned. This feedback suggests that integrating more contextual examples and case studies could improve the relevance of the material and further enhance students' interest in chemistry [47].

The Chemister application demonstrated its potential to significantly improve high school students' understanding of reaction rates. The positive reception of the AI features and gamification elements suggests that the app can effectively engage students and enhance their learning experience. However, addressing technical issues and incorporating more real-world applications will be critical to maximizing the educational impact of the app. Insights gained from this testing phase will guide further refinement and ensure that the Chemister application effectively meets the needs of its users.

4. Conclusions

This study demonstrates the effectiveness of integrating AI-powered tools into high school chemistry education. Through expert validation and pilot testing, the Chemister application has been shown to significantly improve student engagement and understanding of reaction rates. The app's interactive simulations, user-friendly interface, and real-time feedback effectively address common misconceptions, enhance conceptual understanding, and increase student interest in chemistry.

This study is subject to several limitations. Firstly, the pilot study involved a relatively small sample (n = 11), limiting the findings' generalizability. Future studies should include larger and more diverse populations to validate these results. Secondly, some students reported technical performance issues, such as intermittent lags in the AI interaction and AR visualization modules, which may have affected user experience and learning outcomes. These technical limitations highlight the importance of ensuring robust infrastructure and support for AI and AR integration in educational contexts. Additionally, the lack of a control group limits causal inferences; future research employing experimental or quasi-experimental designs would provide more rigorous evidence of the Chemister app's effectiveness.

The results showed significant improvements in students' post-test performance, demonstrating the app's success in translating abstract chemistry concepts into a more accessible, visual learning experience. While the app has already delivered positive educational outcomes, incorporating additional features such as customizable settings, expanded assessments, and improved accessibility options would further enhance its impact. With these enhancements, Chemister has the potential to become an indispensable tool for students and teachers alike, making chemistry more engaging, personalized, and effective in the modern classroom.

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Author Contributions

Nur Candra Eka Setiawan contributed to conceptualization and methodology of the study, conducted the investigation and formal analysis, prepared the original draft of the manuscript, developed the visualizations, and participated in the review and editing process. Safwatun Nida contributed to conceptualization and methodology, provided resources, conducted the investigation, performed validation, developed the visualizations, and participated in the review and editing of the manuscript.

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