JEGEO
Journal of Environment and Geography Education
JEGEO 2(2): 96–113
ISSN 3062-8938

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

MolekulAR: A conceptual design of interactive chemistry learning based on augmented reality to improve science literacy

Febiola Irashai Siti Mawla Yuri[1,*]
[1] *Department of Chemistry, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Central Java 50275, Indonesia.*
*Correspondence: febiolaismy@gmail.com

Received Date: July 18, 2025 Revised Date: August 26, 2025 Accepted Date: August 31, 2025

ABSTRACT

Background: Chemistry education in Indonesia faces persistent challenges in improving science literacy due to the abstract nature of chemical concepts and limited access to interactive, effective learning tools. Augmented Reality (AR) technology offers a promising approach by providing immersive, visual learning experiences that facilitate comprehension of complex topics such as molecular structures and chemical reactions. **Methods:** This study designs and develops MolekulAR, an AR-based interactive chemistry learning application aligned with the national curriculum. The development process incorporates a Pentahelix collaboration model involving educators, government, industry, communities, and media to ensure pedagogical relevance and technical feasibility. The application integrates interactive 3D molecular models, real-time reaction simulations, and customized learning modules. Evaluation was conducted through expert validation, classroom trials, and user feedback. **Findings:** Results demonstrate that MolekulAR significantly improves student motivation, engagement, and conceptual understanding of challenging chemistry subjects. Features including Scan to Structure, Lab Simulation, and Explore Molecules enable hands-on, exploratory learning, making abstract content more tangible. The study also identifies barriers such as technological infrastructure limitations, unequal device accessibility, and teacher readiness. **Conclusion:** MolekulAR represents a scalable and sustainable educational tool that aligns AR technology with curriculum goals and addresses pedagogical and infrastructural challenges, fostering improved science literacy across Indonesian classrooms. Sustained cross-sector collaboration is essential for effective implementation. **Novelty/Originality of this article:** This research uniquely combines AR technology, curriculum alignment, and a systemic multi-stakeholder (Pentahelix) collaboration model to deliver an innovative and contextually relevant solution that advances interactive chemistry learning and science literacy in Indonesia.

KEYWORDS: augmented reality; chemistry education; interactive learning media; science literacy.

1. Introduction

The rapid development of technology has brought substantial advancements across various sectors, including education, creating new opportunities to improve teaching quality and learning outcomes. In particular, digital innovations have opened the door to more engaging, accessible, and interactive learning experiences for diverse learners. Despite these positive developments, challenges in literacy, especially science literacy, remain a critical issue requiring urgent action. Science literacy is essential for fostering critical thinking, problem-solving abilities, and the capacity to apply scientific knowledge in

Cite This Article:
Yuri, F. I. S. M. (2025). MolekulAR: A conceptual design of interactive chemistry learning based on augmented reality to improve science literacy. *Journal of Environment and Geography Education, 2*(2), 96-113. https://doi.org/10.61511/jegeo.v2i2.2025.2199

Copyright: © 2025 by the author. This article is distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

real-life contexts. However, data from the Programme for International Student Assessment (PISA) in 2022 reveal that Indonesia scored 366 in mathematics, 359 in reading, and 383 in science (Figure 1). These scores represent a decline from the 2022, 2018, and 2015 assessments and remain significantly below the average of Organisation for Economic Cooperation and Development (OECD) countries (OECD, 2023). This persistent gap reflects ongoing challenges in equipping students with the necessary skills to thrive in a technology-driven, knowledge-based global environment.

This low level of literacy, particularly in science, significantly affects students' ability to think critically, reason logically, and approach problems with creativity. It also limits their capacity to apply scientific concepts to practical situations, reducing their effectiveness in addressing issues that arise in everyday life. Furthermore, inadequate science literacy contributes to a lack of awareness and understanding of pressing environmental concerns, as well as the social and economic challenges faced within local communities. These limitations hinder the development of informed, responsible, and solution-oriented citizens. If left unaddressed, such gaps in knowledge and skills will continue to impede both individual and national progress, particularly in preparing future generations to respond effectively to the increasingly complex demands of the 21st century. Therefore, strategic educational interventions that are engaging, relevant, and interactive are essential to enhance students' understanding and application of science in real-world contexts.

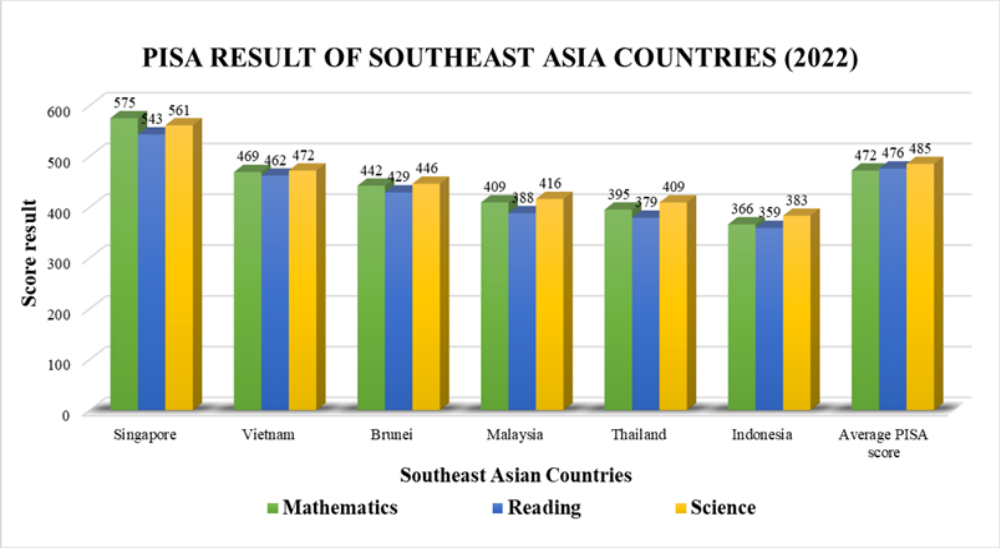


Fig. 1. PISA result of southeast asia countries (2022)
(OECD, 2023)

Science literacy is the ability to understand and apply scientific knowledge to develop critical thinking patterns towards scientific issues and environmental phenomena in everyday life (Cahyani et al., 2025). The low level of science literacy can be caused by several factors, including the use of teaching materials that are not relevant, difficulties in understanding scientific concepts, as well as passive learning methods that are one-sided and centered on the instructor, making it less interactive for students (Audina et al., 2024). One of the fields of study impacted by low science literacy is chemistry. Chemistry is often perceived as abstract, too complex, and difficult for students to understand, which affects their interest in studying it (Priliyanti et al., 2021). In fact, chemistry is a fundamental science that is very important in various other fields of study, such as medicine, pharmacy, food technology, energy, and the environment (Tarng et al., 2022). With a good understanding of chemistry, students will have a strong foundation to contribute to development based on science in the future.

The advancement of technology in the field of education provides new opportunities to improve science literacy skills through learning approaches that are more interactive, engaging, and visually stimulating. One promising innovation is the integration of

Augmented Reality (AR) technology into the learning process. Augmented Reality is an interactive technology that merges virtual elements with the real-world environment in real time (Alfitriani et al., 2021). Through AR, users can view and interact with digital objects such as images, animations, or three-dimensional (3D) models as if they physically exist within their surroundings (Suharso et al., 2020). These visual elements are displayed through devices like smartphones or tablets, creating an immersive experience that enhances understanding and retention. By bridging abstract scientific concepts with concrete and interactive visualizations, AR technology offers an effective way to increase student engagement, motivation, and comprehension, particularly in complex subjects such as chemistry where molecular structures and reactions are often challenging to grasp through traditional methods.

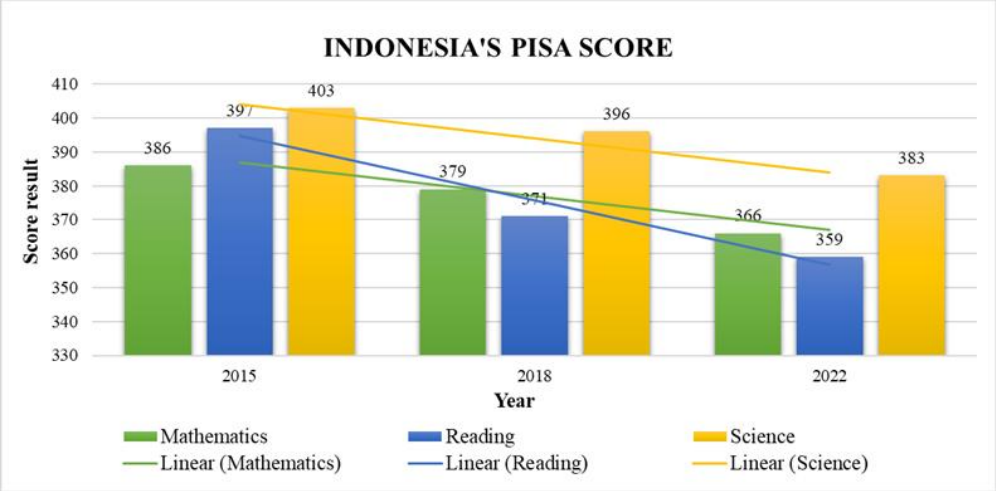


Fig. 2. Indonesia's PISA score (2015, 2018, 2022)
(OECD, 2023)

Various studies have demonstrated that the use of Augmented Reality (AR) in education can significantly improve learners' conceptual understanding, engagement, and motivation. AR enables the visualization of abstract and complex concepts that are often difficult to convey through conventional teaching methods, allowing students to explore learning material independently, interactively, and in real time. This technology promotes active learning, encourages curiosity, and supports different learning styles, making it highly adaptable in diverse classroom settings. Findings from Saepudin & Wulandari (2023) support the integration of AR into the national curriculum as an effective strategy to improve the quality of science education, particularly at the elementary school level. Similarly, Bau et al. (2022) reported that AR-based learning media not only increased students' motivation and comprehension compared to traditional methods but also improved post-test scores, enhanced learning activities, and generated highly positive student feedback, with an average response rate of 86%, indicating strong acceptance and effectiveness.

Although the use of technology in education continues to advance, the number of AR-based innovations specifically designed to improve science literacy in the context of chemistry learning remains limited. In reality, AR technology has strong potential to assist learners in understanding abstract concepts such as molecular structures, chemical bonds, and reaction mechanisms in a clearer and more accessible way. Despite this potential, its implementation in learning environments still encounters various challenges. These include the readiness and digital competence of educators and students, limited availability of adequate digital infrastructure, unequal access to compatible devices, and unstable internet connectivity (Dendodi et al., 2024). Addressing these barriers is essential to ensure the effective integration of AR in chemistry education.

Therefore, this writing aims to design and present an innovative approach to chemistry learning that is both visual and interactive through the development of the MolekulAR

application, which is based on Augmented Reality (AR) technology. This innovation is specifically intended to support efforts to improve science literacy in Indonesia by providing students with an engaging and accessible way to understand complex chemical concepts. The MolekulAR application differs from other platforms because it integrates AR technology with a variety of supporting features for learning chemistry in a single, cohesive application. All of its content and functionalities are designed to align with the national education curriculum, allowing it to be directly implemented in formal educational settings across Indonesia. In addition, MolekulAR addresses the challenges of low science literacy by delivering learning experiences that are visual, interactive, and relevant to the real world, while also adapting to the characteristics, preferences, and learning styles of today's digital-native generation of students.

2. Methods

2.1 Type, approach, and analysis of the study

This writing employs a qualitative approach with a descriptive analysis method, focusing on the formulation and development of innovative ideas without conducting an empirical research process (Ambarwati et al., 2021). The approach emphasizes an in-depth examination of the persistent issue of low science literacy in Indonesia through a comprehensive review of literature and conceptual analysis. The findings are then systematically synthesized into a proposed solution design, namely MolekulAR—an interactive chemistry learning application based on Augmented Reality (AR) technology. According to Sugiyono (2022), the descriptive qualitative approach is rooted in post-positivist philosophy and is aimed at examining objects in their natural conditions, with the researcher serving as the main instrument in data interpretation and analysis. This method allows for a thorough exploration of the problem, capturing its multifaceted nature, while enabling the design of a solution that is pedagogically sound. Consequently, this approach was deemed suitable for formulating a contextual, technology-based AR innovation framework aligned with the learning needs and characteristics of today's learners.

The stages in this writing consist of several systematic steps, including problem identification, literature review, formulation of objectives, collection of supporting data, information analysis, and the preparation of the proposed innovation in the form of a structured and easily understandable narrative (Figure 3). Once the relevant data is gathered, the analysis process is carried out by conducting a thorough review of the literature, classifying information based on key themes, comparing findings with previous studies (Qomaruddin & Sa'diyah, 2024), and evaluating the literature content in relation to the development of the MolekulAR concept. This process enables the identification of research gaps (Juliansyah et al., 2024), such as the minimal availability of AR-based media specifically designed for chemistry learning in accordance with the national curriculum. By following these stages, the writing not only compiles and synthesizes relevant insights but also constructs a comprehensive conceptual framework for AR-based educational innovation that can provide tangible contributions toward enhancing science literacy in Indonesia.

2.2 Data collection technique and source

The data collection process in this writing was conducted using a literature study method, focusing on secondary data obtained from a variety of credible and relevant scientific sources. This method involved systematically searching, reviewing, and analyzing references that align with the core theme of the writing, namely the enhancement of science literacy through the application of Augmented Reality (AR) technology in chemistry education. The sources consulted included peer-reviewed academic journals, research articles, educational textbooks, official policy reports, ministry publications, and reputable online resources (Nur et al., 2025). Data gathering was carried out by accessing multiple

scientific databases such as Google Scholar, ScienceDirect, and ResearchGate, as well as national journal repositories including Garuda and Sinta. The selection of sources prioritized recent publications to ensure the relevance and accuracy of the information. This approach provided a comprehensive foundation of evidence and theoretical perspectives to support the conceptual development of the MolekulAR innovation framework.

The selection of literature in this writing is carried out selectively and systematically, ensuring that each reference meets several key criteria, including topical relevance, source credibility, publication recency, and contextual alignment with the Indonesian educational setting (Jabnabillah et al., 2023). Priority is given to works published within the last five years to maintain the currency and applicability of the information. The chosen references primarily consist of recent research findings that directly support the advancement of technology-based learning innovations, particularly in the field of chemistry education. The insights gained from this literature study serve as the foundation for formulating the conceptual framework of MolekulAR. This framework addresses the urgency of improving science literacy, explores the potential of integrating Augmented Reality (AR) technology, and proposes the design of interactive learning features that are aligned with the national curriculum and tailored to the needs, characteristics, and learning styles of today's students (Adlini et al., 2022).

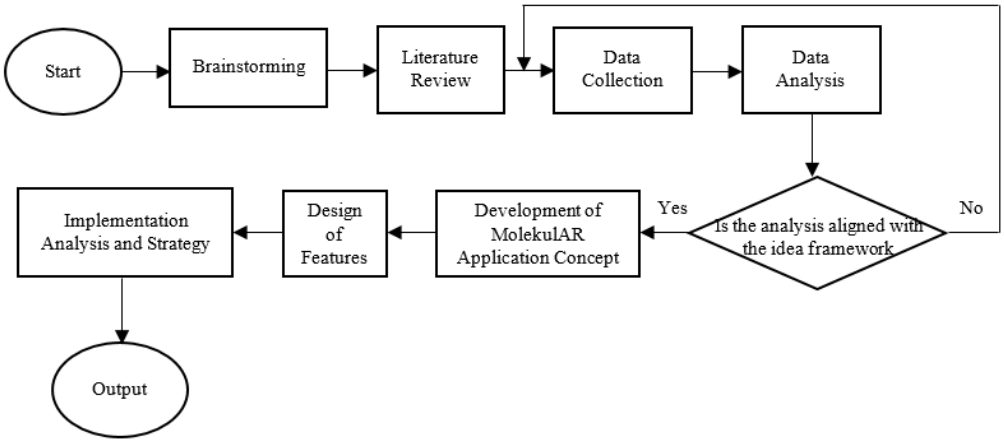


Fig. 3. Conceptual framework flowchart

3. Results and Discussion

3.1 Rationale for AR based learning innovation

Based on the previously outlined issue of low science literacy in Indonesia, there is an urgent need for a learning approach that can effectively address the demands of 21st-century education. This need is especially important in the field of chemistry, which is often perceived by students as difficult, abstract, and less engaging. The complexity of chemical concepts such as molecular structures, reaction mechanisms, and chemical bonding poses significant challenges to comprehension, particularly when taught using conventional methods and static learning materials. In many schools, the limited availability of innovative and technology-based learning media worsens this problem, leading to low levels of interest and understanding among students. To address these challenges, the implementation of a more visual, interactive, and technology-driven learning strategy is necessary. This approach can make abstract concepts more concrete, encourage curiosity, and improve students' motivation to explore and master complex topics in chemistry.

Augmented Reality (AR) technology is chosen as the primary foundation for this innovation because of its ability to integrate digital objects seamlessly into the real world through widely accessible devices such as smartphones or tablets. This capability allows learners to interactively explore molecular structures, atomic arrangements, and chemical reaction mechanisms in the form of highly detailed and accurate 3D models. These models

can be rotated, zoomed in, and examined from various perspectives, enabling students to grasp complex chemical concepts that are often difficult to visualize through conventional methods such as textbooks or static images. The immersive nature of AR helps bridge the gap between abstract theory and tangible understanding, fostering greater engagement, curiosity, and retention of knowledge. By making learning more interactive, AR also encourages active participation, allowing students to construct their own understanding of chemistry concepts in ways that align with the learning preferences of the digital generation.

Such immersive visualization not only bridges the gap between theoretical knowledge and practical comprehension but also transforms learning into a more engaging, dynamic, and memorable process. By enabling students to directly interact with 3D representations of molecular structures and chemical processes, Augmented Reality (AR) fosters active learning and deeper cognitive processing. A growing body of research confirms that AR can significantly enhance student engagement, intrinsic motivation, and conceptual understanding in science education (Ibáñez & Delgado-Kloos, 2018; Saepudin & Wulandari, 2023). The integration of AR into chemistry learning through the MolekulAR application is particularly well-suited to the learning styles of the digital-native generation, who are accustomed to visual, interactive, and technology-driven experiences. Beyond its pedagogical benefits, MolekulAR offers a practical, scalable, and curriculum-aligned solution for overcoming challenges in delivering complex and abstract scientific content, thereby contributing to the improvement of science literacy and the advancement of innovative educational practices in Indonesia.

Table 1. List of recent studies applying augmented reality in chemistry learning

No	Journal title	Summary
1.	Development of learning media diaroma and 3d hydrocarbons (homolog series) using edu assembler in chemistry learning on hydrocarbon material (Sadam et al., 2025)	This research developed a learning media of physical dioramas and 3D hydrocarbon models based on the Assembler Edu application to visualize homologous series interactively. The expert validation results (≥85%) and the student trial (94.7%) indicate that this media is very feasible, effective in enhancing understanding of abstract concepts, and motivating for learning, although there were technical constraints related to file size.
2.	Development of augmented reality-based chemistry learning media on carbon compound material (Sahidi et al., 2025)	This research focuses on the development of Augmented Reality (AR)-based chemistry learning media for the topic of carbon compounds, utilizing the 4D development model up to the development stage. The resulting media demonstrated a high level of validity with a score of 0.68 and very high practicality, achieving 87.5% in practicality assessments. These results indicate that the media is both feasible and effective for use in the learning process. By enabling the visualization of abstract and complex concepts in carbon chemistry, the AR-based media helps bridge the gap between theoretical material and student comprehension. Furthermore, it significantly enhances students' interest, engagement, and understanding, making it a valuable tool for improving learning outcomes in chemistry.
3.	Factors influencing teachers' adoption of augmented reality in high school chemistry education (Mau-Duc et al., 2025)	This research investigates the factors that influence the adoption of Augmented Reality technology by high school chemistry teachers through a mixed-methods approach of surveys and interviews. The results indicate that technological proficiency, pedagogical relevance, availability of resources, training, institutional support, and perceptions of effectiveness are key determinants, thus targeted interventions such as specialized training programs and resource provision are necessary to effectively encourage AR implementation.

4.	Student perceptions using augmented reality and 3d visualization technologies in chemistry education (Abdinejad et al., 2021)	This research combines 3D modeling, animation, and augmented reality through the ARchemy application to enhance students' 3D spatial visualization skills in understanding molecules and chemical reactivity. The results indicate the effectiveness of ARchemy in addressing the limitations of traditional methods, and future development will include an iOS version, markerless AR, as well as image-to-3D model conversion, accompanied by quantitative evaluation to assess its impact on understanding and learning performance.
5.	Development of augmented reality-based chemistry learning media on carbon compound material (Supriadi et al., 2023)	This research develops Augmented Reality-based chemistry learning media on acid-base material using the 4D development model (define, design, develop, disseminate). The results of expert validation (0.86), practicality testing (84.96%), and effectiveness testing indicate that this media is feasible, practical, and capable of enhancing the mental models of high school students, although the majority of students are still at the synthetic mental model level, not fully scientific.
6.	Development of teaching modules for acid-base solutions integrated with ethnochemistry based on augmented reality (Ariani et al., 2024)	This research develops an integrated ethnochemistry acid-base teaching module based on Augmented Reality (AR) using the 4D model, which was validated by experts and tested on 20 students. The results show that this module is highly valid (Aiken's V = 0.9), practical (86%), and effective in improving the understanding of abstract concepts, motivation, and student engagement through 3D visualization and local cultural context.
7.	Can typical game features have unintended consequences? A study of players' learning and reactions to challenge and failure in an educational programming game (Chase et al., 2021)	This study investigates the impact of mobile-based Augmented Reality (AR) in science learning on three key outcomes: learning achievement, motivation, and conceptual understanding. Through a comprehensive meta-analysis of multiple prior studies, the findings reveal that mobile AR consistently produces a significant positive effect across all three dimensions. The degree of effectiveness, however, varies depending on factors such as the learning design implemented, the type and complexity of the material taught, and the characteristics of the student population. These results highlight the potential of mobile AR as an innovative educational tool when appropriately adapted to specific learning contexts.
8.	Molecule World: Enhancing chemistry education through webbased augmented reality using Assemblr (Handoyo et al., 2024)	This research focuses on the development of the Augmented Reality based Molecule World application using the ADDIE framework to improve students' comprehension of molecular structures and complex chemistry concepts. The application integrates interactive 3D visualizations to bridge theoretical knowledge with practical understanding. Evaluation results indicate an excellent user experience, particularly in attractiveness, reliability, and novelty, demonstrating its strong appeal and engagement potential. Areas identified for further enhancement include clarity, efficiency, and stimulation, which could optimize its role as a learning tool. Overall, the Molecule World application shows significant promise for advancing chemistry education through immersive and technology-driven learning experiences.
9.	Augmented reality interactive experiences for multi-level chemistry understanding	This research evaluates the use of Augmented Reality in chemistry education and finds that AR significantly enhances the understanding of abstract concepts,

(Câmara Olim et al., 2024)	motivation, and student engagement. The data from the trials show an increase in understanding scores of over 20% compared to traditional methods, with the majority of participants reporting a more interactive learning experience and clearer visualization of concepts, although there are still technical constraints on devices and connectivity.

3.2 Concept design and features of MolekuAR

3.2.1 Prototype design of MolekulAR

MolekulAR is an innovative application based on Augmented Reality (AR) technology, created to provide immersive and interactive visualization in chemistry learning as a solution to enhance science literacy skills in Indonesia. This application is designed to transform the traditional way of learning and understanding chemistry concepts into a more engaging, clear, and practically applicable experience. Through MolekulAR, users can view molecules and compounds in detailed 3D, as well as simulate real-time interactions between reacting particles. To further enrich the learning process, the application offers several standout features, including Scan to Structure, Lab Simulation, Chem Module, Explore Molecules, and My Notes. These features are carefully designed to create a visual, interactive, and integrated learning environment tailored to the needs, interests, and curriculum of modern learners.

This application employs Augmented Reality (AR) methods with marker-based tracking, which displays digital objects based on the recognition of 2D images (markers) provided during learning activities (Fitriyanto & Gustalika, 2025). In the MolekulAR application, the marker presented as a visual representation of a chemical structure and scanned using the device's camera. The captured image is then processed in real time to generate and overlay a detailed 3D model of the molecule directly on top of the marker (Figure 4). This process relies on computer vision algorithms to precisely determine the position, orientation, and scale of the virtual object in relation to the physical marker. As a result, users can explore and manipulate molecular structures interactively within their real-world environment using mobile devices, enhancing engagement and conceptual understanding.

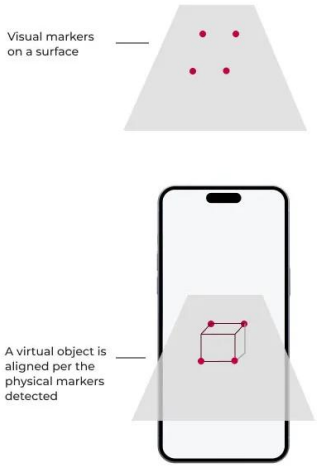


Fig. 4. Marker-based tracking illustration

The development of the MolekulAR application integrates multiple tools and software, namely Unity 3D, Vuforia SDK, and Blender, to create an engaging and functional augmented reality learning platform. Unity 3D serves as the primary development environment, enabling the design, structuring, and management of interactive 3D visualizations while optimizing object variables to ensure smooth functionality and user interaction. Vuforia

SDK functions as the AR engine, allowing 3D digital objects to be accurately recognized and seamlessly overlaid onto the real environment through live camera views, thus creating an immersive mixed-reality experience (Triyono et al., 2021). Blender is utilized for designing, modeling, and animating molecular models and chemical structures in high detail, covering the entire workflow from modeling and rendering to advanced visualization (Rini et al., 2024). The integration of these tools ensures that MolekulAR provides accurate, realistic, and interactive visual representations that support effective chemistry learning.



Fig. 5. Prototype Design of MolekulAR

3.2.2 Scan to structure and lab simulation

The Scan to Structure feature enables users to scan molecular images through a provided QR code, instantly generating and displaying an interactive 3D model of the corresponding molecule. Each displayed molecular structure is accompanied by detailed information, including the molecule's name, molecular mass, bond angles, melting point, and boiling point, providing both visual and textual learning support. Users can freely zoom, rotate, and examine the molecule from multiple angles in real time, allowing for an in-depth exploration of its geometry and properties. By combining interactive manipulation with informative data, this feature facilitates a more engaging and comprehensive understanding of complex chemical concepts, making abstract molecular structures more tangible and accessible for learners.

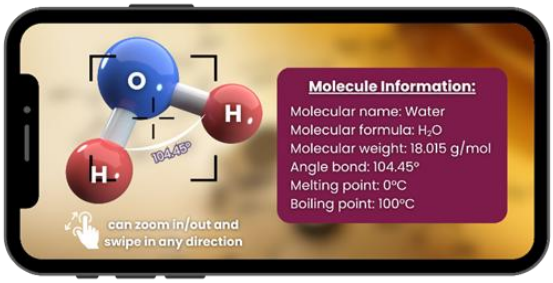


Fig. 6. Scan to structure feature display with AR technology

The Lab Simulation feature enables users to virtually conduct chemical experiments using atomic models, digital laboratory equipment, and interactive visualizations of reaction processes. Through this feature, learners can select from a variety of substances, combine them in a simulated environment, and observe real-time changes presented through animations, such as shifts in color, variations in temperature, gas evolution, or the formation of precipitates. These visual effects are designed to mimic actual laboratory outcomes, enhancing conceptual understanding. In addition, the feature introduces students to fundamental laboratory procedures and safety practices before engaging in real

experiments, thereby improving both their preparedness and confidence. By integrating visual interactivity with procedural learning, Lab Simulation offers a safe, engaging, and effective pre-lab experience.



Fig. 7. Lab simulation feature

3.2.3 Chem modul, explore molecules, and my notes

The Chem Module feature offers structured and comprehensive chemistry learning materials categorized according to the main branches of chemistry, including organic, inorganic, physical, analytical, and biochemistry. All content is carefully organized in alignment with the national education curriculum to ensure relevance and coherence with formal learning standards. The materials are presented through visually enriched formats, such as diagrams, illustrations, and interactive elements, to facilitate deeper understanding and retention of concepts.

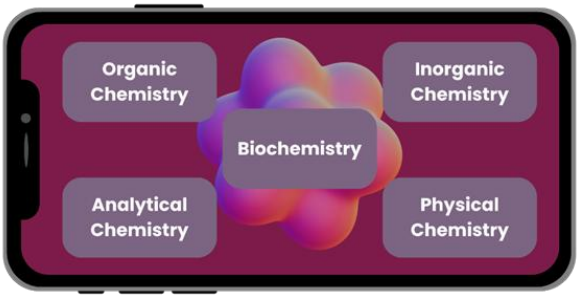


Fig. 8. Chem modul feature

By integrating clear explanations with engaging visuals, this feature supports diverse learning styles and encourages students to explore topics at their own pace. Ultimately, the Chem Module is designed to promote effective, self-directed learning while making the study of chemistry more accessible, enjoyable, and meaningful for learners. The Explore Molecules feature provides an interactive platform for users to engage with a dynamic periodic table, enabling them to learn about the properties, classifications, and relationships of chemical elements in a visually appealing way. Users can examine atomic models in detail, observe the structures of compounds formed, and visualize these processes in real time.

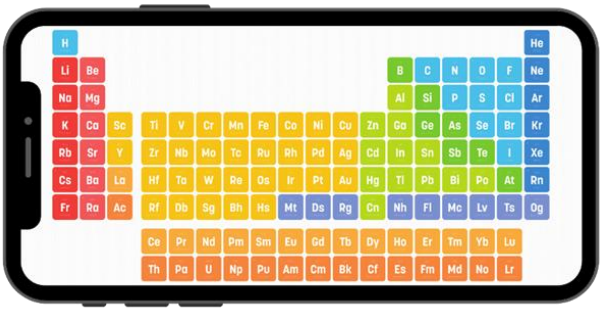


Fig. 9. Explore molecules feature

This feature also offers tools to explore electron configurations, identify groups and periods, and combine multiple elements to simulate the formation of chemical bonds. Through hands-on interaction, learners gain a deeper understanding of how elements relate to each other within the periodic table and how these relationships influence compound formation, thereby strengthening both conceptual knowledge and practical visualization skills in chemistry.



Fig. 10. My notes feature

The My Notes feature allows users to create, save, upload, and conveniently access personal notes related to the chemistry topics they have studied, providing a flexible and well-organized learning process. Users can highlight key points, summarize important concepts, and categorize their notes according to specific branches or themes in chemistry, making it easier to revisit and review materials when needed. This feature also supports the integration of text, images, or links to enhance note-taking and provide richer learning resources. By enabling students to personalize and manage their own study materials, My Notes fosters independent learning, improves retention, and helps learners build a clear, structured understanding of the concepts they have explored through the MolekulAR application.

3.3 Anticipated challenges

The integration of Augmented Reality (AR) technology in science learning offers numerous benefits; however, it also presents several challenges that must be addressed before large-scale implementation in educational settings. A major obstacle lies in the readiness of both teachers and students to adopt this relatively new technology (Mayasari et al., 2021). Many educators still lack sufficient digital competence to effectively integrate AR into classroom instruction, making targeted and ongoing professional training a critical priority. Additionally, access to compatible devices such as smartphones or tablets, along with reliable internet connectivity, remains limited particularly in schools situated in regions with underdeveloped infrastructure. These limitations hinder the consistent use of AR in learning activities. Furthermore, research highlights that the high costs associated with AR development and maintenance, coupled with the need for compatible hardware and updated software, present another significant barrier (Dunleavy & Dede, 2021). Addressing these challenges is essential to ensure that AR can be implemented effectively and sustainably to improve science education outcomes.

To overcome these challenges, a well-planned implementation strategy is required that incorporates both short-term and medium-term solutions. Key actions include providing continuous professional development programs for teachers to strengthen their technological competence and pedagogical skills in using AR. The development of a lightweight AR application, capable of operating offline, will help address limitations in internet access and device performance. Collaboration with local governments, private sector partners, and educational institutions is also essential for procuring necessary equipment, ensuring maintenance, and providing ongoing technical support. Additionally, schools should conduct thorough assessments of their technical readiness, infrastructure,

and available resources before fully integrating AR into the curriculum. By addressing these factors systematically, potential barriers can be minimized, allowing AR technology to be adopted more effectively. Gradually, this integration has the potential to significantly enhance students' motivation, engagement, and mastery of complex chemistry concepts, ultimately contributing to improved science literacy in the long term.

3.4 Sustainability collaboration

In implementing the MolekulAR innovation sustainably, strong cross-sector synergy is essential, which can be achieved through the Pentahelix collaboration model involving five key elements: government, industry, academia, society, and media (Vani et al., 2020). This collaboration serves as a strategic foundation to ensure that the innovation is not limited to the development phase but can be systematically integrated into the educational ecosystem (Pasaribu et al., 2023). By fostering active participation from all parties, MolekulAR has greater potential to be widely adopted, supported by policies, resources, and public awareness. Such synergy encourages collective responsibility in advancing technology-based science education and ensures that the application remains relevant, effective, and accessible (Prasetyanto et al., 2023). Through ongoing cooperation, MolekulAR can contribute to long-term educational transformation, aligning with national goals for improving science literacy and fostering innovation in learning practices across Indonesia.

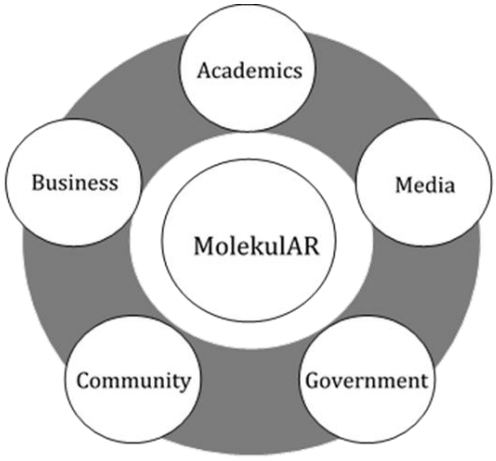


Fig. 11. Pentahelix model collaboration of MolekulAR

3.4.1 Academics and business

Academics include teachers, lecturers, and educational researchers who play a vital role in ensuring the academic quality and relevance of the MolekulAR application. They provide expert input on chemistry learning materials so that they align with the national education curriculum and meet pedagogical standards. Their contribution involves reviewing and validating the accuracy of scientific content, suggesting improvements for clarity, and ensuring that AR-based visualizations are effective in supporting conceptual understanding. By integrating their feedback, MolekulAR can present complex chemical concepts in a way that is both engaging and academically rigorous, ultimately supporting better learning outcomes for students at various educational levels.

The business sector, particularly application developers and edutech startups, is primarily responsible for the technical design, programming, and overall development of the MolekulAR application. Their tasks include ensuring smooth functionality, maintaining system stability, and implementing innovative features to enhance user experience and engagement. Beyond technical development, they play a strategic role in sustaining the application through regular updates, bug fixes, and compatibility improvements across diverse platforms. The business sector is also actively involved in managing distribution channels, licensing, and marketing strategies to ensure the application can reach a wide and

diverse audience. By ensuring both quality and widespread availability, they help MolekulAR remain a sustainable, effective, and impactful educational tool for learners everywhere.

3.4.2 Community and government

The community consists of students, university learners, and educational communities who are the primary users of MolekulAR. Their involvement is essential in providing direct, practical feedback on the application's usability, content clarity, and overall effectiveness in supporting chemistry learning. Through their experiences, developers can identify which features work well and which need improvement. This feedback loop ensures that MolekulAR remains relevant and user-friendly, meeting the actual needs of learners. The active participation of the community also fosters a sense of ownership and engagement, encouraging consistent use and continuous refinement of the platform for maximum educational benefit.

The government, through education ministries or related agencies, plays a regulatory and facilitative role in the implementation of MolekulAR. They ensure that the content and features comply with national curriculum standards and educational policies. The government can also provide funding, grants, or infrastructure support to promote the use of AR technology in schools and universities. Furthermore, their endorsement can encourage broader adoption by institutions, especially in public education. By collaborating with developers, academics, and communities, the government helps integrate MolekulAR into formal learning systems, ensuring equitable access for students across different regions and supporting digital transformation in education.

3.4.3 Media

Media partners, including education influencers, bloggers, and online learning platforms, play a critical role in promoting MolekulAR to a wider audience. They create awareness through reviews, tutorials, webinars, and social media campaigns, making the application more visible to both teachers and students. By showcasing its features, benefits, and practical applications, the media can inspire educators to adopt MolekulAR as a modern teaching tool. Their influence also extends to building trust and credibility, encouraging more schools and universities to integrate the application into their learning systems. This promotional effort helps accelerate adoption and supports the growth of educational innovation.

3.5 Implementation strategy

Table 1. Implementation strategy

No	Stage	Description
1.	Research	The research stage identifies the specific needs for improving science literacy in the education sector, with a particular focus on chemistry. This process involves reviewing curriculum standards, assessing student difficulties, and analyzing existing learning gaps. Findings from this stage form the foundation for designing the MolekulAR application, ensuring its features and content are relevant, accurate, and aligned with national curriculum objectives. By addressing these gaps, the application aims to enhance students' conceptual understanding and engagement in learning complex chemistry topics.
2.	Engangement	This stage involves active collaboration with diverse stakeholders, including academics, government bodies, community representatives, industry experts, and media partners. Such collaboration ensures that the MolekulAR application is developed with a comprehensive perspective,

		addressing both pedagogical needs and technical feasibility. By integrating insights from various sectors, the design aligns with national education goals, responds to real classroom challenges, and meets the technological requirements necessary for effective AR-based chemistry learning, fostering broader adoption and sustainable implementation in educational environments.
3.	Augmentation	The development team integrates AR features, including interactive 3D molecular models, animations, and simulations, to deliver engaging and immersive chemistry learning experiences. All content is designed to align with curriculum requirements while simplifying complex concepts for students. Regular updates are implemented to reflect the latest scientific advancements, ensuring accuracy and relevance. By combining technological innovation with pedagogically sound content, the application remains an effective, up-to-date teaching tool that supports both educators and learners in enhancing science literacy and conceptual understanding.
4.	Classroom	Trials of the MolekulAR application are carried out in actual classroom environments, engaging both teachers and students in its use for chemistry learning. Educators receive training to ensure effective integration of the technology into lesson plans, enabling optimal learning outcomes. These trials assess usability, engagement, and concept comprehension, while also gathering feedback to identify areas for refinement. The process ensures that MolekulAR can be seamlessly adopted in daily teaching activities, enhancing visualization of complex concepts and improving overall science literacy.
5.	Tracking	The effectiveness of MolekulAR is evaluated through feedback and observations in real classroom use, involving both teachers and students. This process measures its impact on engagement, comprehension, and learning outcomes while identifying strengths, improvement areas, and technical challenges. Collected insights guide targeted refinements in features, interface, and performance to enhance usability. Continuous evaluation ensures the application remains effective, user-friendly, and aligned with educational needs, ultimately supporting better visualization of complex chemistry concepts and improving overall science literacy.
6.	Scaling	After successful trials, the implementation of MolekulAR is scaled up nationally through large-scale production and strategic distribution. Promotion is sustained via educational networks, teacher communities, and media platforms to increase awareness and adoption. This stage prioritizes broad accessibility while ensuring consistent quality standards. Regular updates are introduced to align with curriculum changes, integrate new features, and address user feedback, ensuring the application remains relevant, effective, and capable of meeting the evolving demands of modern chemistry education.

4. Conclusions

The development of the MolekulAR application represents a strategic response to the urgent need for improving science literacy in Indonesia, particularly in chemistry education, which is often perceived as abstract and difficult. By integrating Augmented Reality (AR) technology into a structured learning framework, this innovation bridges the gap between complex chemical concepts and student comprehension through immersive, visual, and interactive experiences. The design aligns with the national education curriculum, ensuring its direct applicability in formal educational settings while supporting curriculum-based learning objectives. The conceptual framework of MolekulAR demonstrates how technology

can be effectively tailored to meet pedagogical needs and address contextual challenges, such as limited student engagement and difficulty in visualizing molecular structures or reaction mechanisms. The incorporation of features like Scan to Structure, Lab Simulation, Chem Module, Explore Molecules, and My Notes offers a comprehensive learning ecosystem that fosters self-directed learning, enhances conceptual understanding, and stimulates curiosity. Furthermore, the application accommodates the learning styles of the digital-native generation, promoting both active participation and deeper comprehension.

This study contributes to the growing body of literature on AR-based educational innovations by offering an example of a holistic design that integrates technical, pedagogical, and contextual considerations. The originality of MolekulAR lies not only in its technical implementation but also in its alignment with Indonesia's educational realities, including challenges related to infrastructure, teacher readiness, and equitable access. Through its flexible deployment on widely accessible mobile devices, the application has the potential to reduce barriers to advanced visualization tools in science education. In doing so, it supports the broader educational goal of equipping students with critical thinking, problem-solving, and scientific reasoning skills necessary for the 21st century.

In conclusion, MolekulAR serves as a conceptual proof of how AR technology can be harnessed to transform chemistry learning into an engaging and meaningful process. While this study focuses on the conceptual design, future research should empirically test its effectiveness in classroom contexts, assess its impact on student performance, and refine its features based on user feedback. The integration of AR in chemistry education, as exemplified by MolekulAR, not only addresses the national challenge of low science literacy but also contributes to the global discourse on educational innovation in STEM fields. With sustained collaboration among academia, industry, government, communities, and media, this innovation holds promise for long-term adoption and scalability, ultimately shaping a more scientifically literate generation prepared to face complex global challenges.

Acknowledgement

The author expresses sincere gratitude to the reviewers for their insightful and constructive feedback, and to the editorial team for their dedication in improving and publishing this work.

Author Contribution

F.I.S.M.Y. contributed to all aspects of this work, including conceptualization, methodology, literature review, data collection, data analysis, software development, visualization, writing – original draft preparation, and writing – review & editing.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

The author declare that no generative artificial intelligence tools were used in the

preparation, writing, analysis, or revision of this manuscript. All content, interpretations, and conclusions are the sole responsibility of the author.

Open Access

©2025. The author. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

References

Abdinejad, M., Talaie, B., Qorbani, H.S., & Dalili, S. (2021). Student perceptions using augmented reality and 3D visualization technologies in chemistry education. *Journal of Science Education and Technology*, *30*(1), 87–96. https://doi.org/10.1007/s10956-020-09880-2

Adlini, M. N., Dinda, A. H., Yulinda, S., Chotimah, O., & Merliyana, S. J. (2022). Metode penelitian kualitatif studi pustaka. *Edumaspul: Jurnal Pendidikan*, *6*(1), 974–980. https://doi.org/10.33487/edumaspul.v6i1.3394

Alfitriani, N., Maula, W. A., & Hadiapurwa, A. (2021). Penggunaan media augmented reality dalam pembelajaran mengenal bentuk rupa bumi. *Jurnal Penelitian Pendidikan*, *38*(1), 30–38. https://doi.org/10.15294/jpp.v38i1.30698

Ambarwati, D., Wibowo, U. B., Arsyiadanti, H., & Susanti, S. (2021). Studi literatur: Peran inovasi pendidikan pada pembelajaran berbasis teknologi digital. *Jurnal Inovasi Teknologi Pendidikan*, *8*(2), 173–184. https://jurnal.uny.ac.id/index.php/jitp/article/view/43560

Ariani, S., Hidayanti, E., Adiguna, S. P., & Supriadi, S. (2024). Development of acid base solution teaching module integrated ethnochemistry based on augmented reality. *Chemistry Education Practice*, *7*(1), 200–207. https://doi.org/10.29303/cep.v7i1.6083

Audina, K., Murni, A. W., Jannah, N. L., dan Kartikasari, H. L. (2024). The influence of problem-based learning models on students'scientific literacy abilities in class V heat transfer materials in primary schools. *Didaktika Jurnal Pemikiran Pendidikan*, *30*(1), 1-14. https://doi.org/10.30587/didaktika.v30i1.6896

Bau, C. P. E., Olii, S., dam Pakaya, N. (2022). Perbandingan motivasi belajar pada mata pelajaran kimia sebelum dan sesudah penerapan media pembelajaran augmented reality chemistry. *INVERTED: Journal of Information Technology Education*, *2*(1), 45-53. http://ejurnal.ung.ac.id/index.php/inverted

Cahyani, D. K., Nugroho, A. S., Nizaruddin, dan Hayat, M. S. (2025). Analisis kemampuan literasi sains dan berpikir kritis siswa SMP pada pembelajaran IPA. *PENDIPA: Journal of Science Education*, *8*(3), 593–600. https://doi.org/10.33369/pendipa.8.3.593-600

Câmara Olim, S., Nisi, V., & Romão, T. (2024). Augmented reality interactive experiences for multi-level chemistry understanding. *International Journal of Child-Computer Interaction*, *42*, 100681. https://doi.org/10.1016/j.ijcci.2024.100681

Chase, C. C., Malkiewich, L. J., Lee, A., Slater, S., Choi, A., & Xing, C. (2021). Can typical game features have unintended consequences? A study of players' learning and reactions to challenge and failure in an educational programming game. *British Journal of Educational Technology*. Advance online publication. https://doi.org/10.1111/bjet.13021

Dendodi, Simarona, N., Elpin, A., Bahari, Y., & Warneri. (2024). Analisis penerapan augmented reality dalam meningkatkan efektifitas pembelajaran sains di era digital.

ALACRITY: Journal of Education, *4*(3), 293–304. https://doi.org/10.52121/alacrity.v4i3.456

Dunleavy & Dede. (2021). Augmented reality teaching and learning. *Handbook of Research on Educational Communications and Technology*, 735-745. http://dx.doi.org/10.1007/978-1-4614-3185-5_59

Fitriyanto, P. I., & Gustalika, M. A. (2025). Implementation Augmented Reality On Banjarnegara culture as a learning media using marker-based tracking. *Journal of Informatics and Telecommunication Engineering*, *8*(2), 181-195. https://doi.org/10.31289/jite.v8i2.13623

Handoyo, K. J., Wisnuwardana, C. J., Austen, A., & Permana, F. (2024). Molecule world: Enhancing chemistry education through web-based augmented reality using assemblr. *Procedia Computer Science, 245*, 1249–1258. https://doi.org/10.1016/j.procs.2024.10.354

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education*, *123*, 109-123. https://doi.org/10.1016/j.compedu.2018.05.002

Jabnabillah, F., Aswin, A., & Fahlevi, M. (2023). Efektivitas situs web pemerintah sebagai sumber data sekunder bahan ajar perkuliahan statistika. *Jurnal Sustainable*, *6*(1), 59-70. https://doi.org/10.32923/kjmp.v6i1.3373

Juliansyah, H., Sari, C. P. M., Nailufar, F., & Trisniarti, N. (2024). Pelatihan identifikasi research gap dalam penelitian dengan menggunakan publish or perish dan vosviewer. *Jurnal Pengabdian Ekonomi dan Sosial (JPES)*, *3*(2), 28-39. https://doi.org/10.29103/jpes.v3i2.20290

Mau-Duc, N., Ngoc-Son, P., & Hoai-Minh, T. (2025). Factors influencing teachers' adoption of augmented reality in high school chemistry education. *Journal of Technology and Science Education, 15*(2), 346-363. https://doi.org/10.3926/jotse.3310

Mayasari, A., Supriani, Y., & Arifudin, O. (2021). Implementasi sistem informasi manajemen akademik berbasis teknologi informasi dalam meningkatkan mutu pelayanan pembelajaran di SMK. *JIIP - Jurnal Ilmiah Ilmu Pendidikan*, *4*(5), 340-345. https://doi.org/10.54371/jiip.v4i5.277

Nur, A., Pitri, D., Augustine, T. S., Versica, J., & Aulia, M. A. (2025). Peranan sistem pengendalian manajemen dalam meningkatkan efektivitas strategi bisnis: Studi data sekunder. *Journal ANC*, *1*(3), 61-69. https://journal.anc-aryantonurconsulting.com/tp

Organisation for Economic Co-operation and Development. (2023). *PISA 2022 Results (Volume I): The State of Learning and Equity in Education*. OECD Publishing. https://doi.org/10.1787/53f23881-en

Pasaribu, L. P., Apsari, N. C., & Sulastri, S. (2023). Kolaborasi penta helix dalam penanganan pasca bencana gempa bumi. *Share: Social Work Journal*, *13*(1), 140-149. https://doi.org/10.45814/share.v13i1.47909

Prasetyanto, N. W., Trimo, L., & Setiawan, I. (2023). Implementation of pentahelix framework on the development of Pujon Kidul tourism village, Pujon District, Malang Regency. *Agrisocionomics: Jurnal Sosial Ekonomi Pertanian, 7*(2), 235-249. https://ejournal2.undip.ac.id/index.php/agrisocionomics/article/view/17031

Priliyanti, A., Muderawan, I. W., & Maryam, S. (2021). Analisis kesulitan belajar siswa dalam mempelajari kimia kelas XI. *Jurnal Pendidikan Kimia Undiksha*, *5*(1), 11-18. https://doi.org/10.23887/jjpk.v5i1.32402

Qomaruddin, Q., & Sa'diyah, H. (2024). Kajian teoritis tentang teknik analisis data dalam penelitian kualitatif: Perspektif Spradley, Miles dan Huberman. *Journal of Management, Accounting, and Administration*, *1*(2), 77–84. https://doi.org/10.52620/jomaa.v1i2.93

Rini, D. S., Azrai, E. P., Khansa, A. A., & Kurnianto, M. B. (2024). The effect of augmented reality application (ARSINAPS) on learning motivation and outcomes in biology. *Biosfer: Jurnal Pendidikan Biologi*, *17*(1), 196–203. https://doi.org/10.21009/biosferjpb.37752

Sadam, P. A. P., Paristiowati, M., & Syaadah, R. S. (2025). Pengembangan media pembelajaran diaroma dan 3D hidrokarbon (deret homolog) menggunakan assembler

edu pada pembelajaran kimia materi hidrokarbon. *Jurnal Riset Pendidikan Kimia (JRPK)*, *15*(1), 54–59. https://doi.org/10.21009/JRPK.151.05

Saepudin, A., & Wulandari, F. (2023). Pemanfaatan Augmented Reality (Ar) Dalam Pembelajaran Sains Di Sekolah Dasar. *Jurnal Primary Edu*, *1*(3), 355-367. https://jurnal.rakeyansantang.ac.id/index.php/primary/article/view/102

Sahidi, S., Siahaan, J., & Supriadi, S. (2025). Development of augmented reality-based chemistry learning media on carbon compound material. *Chemistry Education Practice*, *8*(1), 85-93. https://doi.org/10.29303/cep.v8i1.6854

Sugiyono. (2022). *Metode Penelitian kuantitatif, kualitatif, dan R&D*. Alfabeta.

Suharso, A., Jaman, J. H., & Mulyana, A. (2020). Brosur digital fitur eksterior produk otomotif berbasis markless augmented reality. *Jurnal Teknologi Terpadu*, *6*(1), 11-16. https://doi.org/10.54914/jtt.v6i1.237

Supriadi, S., Wildan, W., Siahaan, J., Muntari, M., & Haris, M. (2023). Pengembangan media pembelajaran kimia berbasis teknologi augmented reality (AR) untuk melatih model mental siswa. *Chemistry Education Practice*, *6*(1), 8–14. https://doi.org/10.29303/cep.v6i1.4206

Tarng, W., Tseng, Y. C., & Ou, K. L. (2022). Application of augmented reality for learning material structures and chemical equilibrium in high school chemistry. *Systems*, *10*(5), 141. https://doi.org/10.3390/systems10050141

Triyono, A., Muhaqiqin, & Satria, M. N. D. (2021). Aplikasi pembelajaran biologi tentang tanaman berbasis augmented reality untuk kelas XI. *Jurnal Informatika dan Rekayasa Perangkat Lunak (JATIKA)*, *2*(4), 501-513. https://doi.org/10.33365/jatika.v2i4.1607

Vani, R.V., Priscilia, S. O., & Adianto. (2020). Model pentahelix dalam mengembangkan potensi wisata di Kota Pekanbaru. *PUBLIKAUMA: Jurnal Ilmu Administrasi Publik UMA*, *8*(1), 63-70. https://doi.org/10.31289/publika.v8i1.3361

Biography of Author

Febiola Irashai Siti Mawla Yuri, Department of Chemistry, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Central Java 50275, Indonesia.

- Email: febiolaismy@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A