

The role of augmented reality in supporting deep learning within the merdeka curriculum: A systematic literature review in chemistry education

Hastuti Agussalim^{1*}

¹ Chemistry Department, Universitas Negeri Makassar, Indonesia
Corresponding Author E-mail: hastuti.agussalim@unm.ac.id*

ARTICLE INFO:

Revised: 2025-11-02
Accepted: 2025-12-04
Published: 2025-12-05

Keywords:

Augmented reality,
chemistry education,
deep learning,
merdeka curriculum

ABSTRACT

Chemistry education frequently faces challenges due to the abstract nature of chemical concepts, limited visual media, and insufficient student engagement. In contrast, the Merdeka Curriculum highlights the importance of deep learning, emphasizing conceptual understanding, scientific reasoning, and meaningful learning experiences. Augmented Reality (AR) offers promising affordances for addressing these issues through interactive, context-rich three-dimensional representations. This study employed a PRISMA-based Systematic Literature Review (SLR) of 12 empirical articles published between 2015 and 2025 in Scopus-indexed databases, major international publishers, and accredited SINTA journals. The findings reveal a marked increase in AR research in chemistry education between 2023 and 2025, with research and development (R&D) and quasi-experimental designs predominantly conducted at the senior secondary level. Across studies, AR consistently enhances conceptual understanding, multi-level representational competence, higher-order thinking skills, and student engagement. Moreover, AR aligns strongly with the pedagogical principles of the Merdeka Curriculum, particularly project-based learning, authentic assessment, differentiated instruction, and the development of the Pancasila Student Profile. These insights position AR as a strategic innovation for advancing deep and meaningful chemistry learning. Further research is recommended to investigate the long-term effects of AR and its integration within inquiry-based and project-based instructional models.

©2025 Arfak Chem: Chemistry Education Journal
This is an open access article distributed under the CC BY-ND 4.0 license
(<https://creativecommons.org/licenses/by-nd/4.0/>)

How to cite: Agussalim, H. (2025). The role of augmented reality in supporting deep learning within the merdeka curriculum: A systematic literature review in chemistry education. *Arfak Chem: Chemistry Education Journal*, 8(2), 772-785. <https://doi.org/10.30862/accej.v8i2.1111>

1. INTRODUCTION

Chemistry education continues to face various challenges related to the abstract and difficult-to-visualize nature of chemical content. Students often struggle to understand molecular structures, chemical bonding, and the three levels of chemical representation (macroscopic, microscopic, symbolic). These difficulties are frequently reported as causes of low conceptual understanding and the emergence of misconceptions. Recent literature shows that students still experience significant barriers when attempting to connect complex chemical representations, particularly when the learning media used are predominantly two-dimensional and static (Khairani & Prodjosantoso, 2023). These limitations in conventional media call for innovative learning tools that can facilitate concept visualization in a more concrete, realistic, and interactive manner.

The Merdeka Curriculum emphasizes a transformation toward deep learning that aligns with these challenges. The curriculum focuses on the construction of understanding, critical reasoning, creativity, collaboration, and authentic problem-solving. Teachers are required to provide learning experiences that allow space for exploration, inquiry, and meaningful learning activities. Through these conditions, students are expected not only to recall information but also to interpret it in real contexts and apply it to solve problems (Kemendikbudristek, 2022). Research on the implementation of deep learning in Indonesia also indicates the need for learning media that support active student engagement, rich interactions, and learning activities that encourage reflection and conceptual synthesis (Feriyanto & Anjariyah, 2024; Hasanah et al., 2025).

Augmented Reality has attracted growing attention over the past decade as a potential technology in the field of education, including chemistry education. AR enables the integration of three-dimensional virtual objects into real environments, which provides more interactive and immersive learning experiences. Recent meta-analyses show that the use of AR in education consistently improves motivation, engagement, conceptual understanding, and student's cognitive skills (Chang et al., 2022). In chemistry learning, AR specifically assists students in visualizing molecular structures, electron configurations, and chemical processes that cannot be directly observed. This capability helps bridge the gap between conceptual abstraction and student understanding (Talib et al., 2022). These benefits are aligned with the principles of multimedia learning, which state that learning becomes more effective when students receive information through the integration of visual and verbal elements that mutually reinforce one another (Mayer, 2014).

Although research on AR in chemistry education shows promising results, most studies still focus on media development, product feasibility, and short-term learning outcomes. Studies that specifically evaluate how AR can be integrated to support deep learning, such as through project-based learning, inquiry, or authentic problem-solving, remain limited, especially in the context of the Merdeka Curriculum. Additionally, the connection between AR and the development of the dimensions of the Pancasila Student Profile in chemistry learning has received limited attention in empirical studies.

A systematic literature review is therefore needed to comprehensively examine the role of Augmented Reality in supporting deep learning in chemistry education, particularly within the framework of the Merdeka Curriculum. This review is important for mapping recent research

trends, analyzing the effectiveness of AR in enhancing higher-order thinking skills, and formulating practical recommendations for educators and policymakers to optimize AR as a learning medium that is relevant to the current curriculum demands.

2. METHODS

A. Research Design

This study employed a Systematic Literature Review (SLR) design guided by the PRISMA reporting framework (Liberati et al., 2009; Moher et al., 2009). The SLR approach was selected to ensure a structured, transparent, and replicable review of articles that examine the use of Augmented Reality (AR) in chemistry education and its relevance to deep learning within the context of the Merdeka Curriculum (Page et al., 2021).

B. Research Questions

This Systematic Literature Review was directed to answer three central research questions, namely:

- a. What are the characteristics and trends of research on the use of Augmented Reality in chemistry education over the past ten years (2015–2025)?
- b. How does the use of AR contribute to deep learning in chemistry education, particularly regarding conceptual understanding, multi-level representations, higher-order thinking skills, and learning engagement?
- c. How is the implementation of AR in chemistry education aligned with the principles of the Merdeka Curriculum in Indonesia?

C. Inclusion and Exclusion Criteria

a. Inclusion Criteria

The inclusion criteria for this review required that the selected articles be empirical studies employing quantitative, qualitative, research and development, or mixed-method designs. The articles had to be published in international journals indexed in Scopus Q1 to Q3 or in nationally accredited journals with a minimum of SINTA 3, appear between 2015 and 2025, focus specifically on chemistry education with clearly defined chemistry content, use Augmented Reality as the primary instructional media, and measure at least one aspect related to chemistry learning outcomes, motivation or attitudes toward chemistry or AR, learning activities, science process skills, higher-order thinking skills, problem-solving, engagement, or indicators of deep learning. Only full-text articles written in Indonesian or English were considered.

b. Exclusion Criteria

Articles were excluded if they were categorized as systematic literature reviews, literature reviews, conceptual analyses, overviews, or bibliometric studies; if they were unrelated to chemistry education; if they discussed only the technical development of AR without instructional application; if they were not journal articles; or if the full text was not

accessible.

D. Study Selection Procedure: PRISMA

The study selection procedure in this SLR followed the four main stages of the PRISMA guidelines, which include identification, screening, eligibility, and inclusion. The description of each stage is presented below.

a. Identification

The identification stage was carried out by retrieving articles from several credible scientific databases, namely Scopus (focusing on journals ranked Q1 to Q3), ScienceDirect, SpringerLink, Wiley Online Library, Taylor and Francis Online, and SINTA. The article search covered the period from 2015 to 2025 and used combinations of the following keywords: “augmented reality chemistry learning”, “AR in chemistry education”, “augmented reality in science learning”, “mobile AR chemistry”, “interactive AR molecular structure”, and “AR for chemical bonding”. The initial identification process yielded 379 articles related to the use of Augmented Reality in chemistry learning. Duplicate articles found across databases were removed, totaling 78 duplicates, resulting in 301 unique articles to be reviewed in the subsequent stage.

b. Screening

Screening was conducted based on the title and abstract to assess the preliminary relevance of each article to the SLR topic. The screening criteria included the following: 1) the article was published between 2015 and 2025; 2) it was published in a reputable journal (Scopus, SINTA, or nationally accredited journals); 3) it represented an empirical study such as experimental, quasi-experimental, research and development, or mixed methods; 4) it focused on the use of Augmented Reality in chemistry learning; 5) it used AR as the primary or integral instructional media; and 6) the study was situated within an educational context (junior high school, senior high school, vocational school, or higher education). At this stage, 82 articles met the criteria for further assessment in the eligibility stage.

c. Eligibility

The eligibility stage was conducted by reading the full text of each article to ensure complete alignment with the aims of the study. Articles were eliminated if they met any of the following conditions: 1) they did not directly address chemistry learning; 2) they did not substantially incorporate AR in the learning process; 3) they were categorized as literature reviews, SLRs, or theoretical overviews; or 4) the full text was inaccessible and thus could not be analyzed thoroughly. At this stage, 70 articles were excluded and 12 articles met all eligibility criteria.

d. Inclusion

In the final stage, 12 articles were included for in-depth analysis using content analysis techniques. The analysis focused on identifying the effectiveness of AR in improving conceptual understanding in chemistry, its influence on multi-level representational abilities at the macroscopic, microscopic, and symbolic levels, its contribution to the development of higher-order thinking skills (HOTS), the potential of AR to support deep learning in accordance with

the principles of the Merdeka Curriculum, and the suitability of AR as instructional media for projects, authentic assessment, and differentiated learning. The flow diagram of the study selection process is presented using the PRISMA model, illustrating the number of articles at each stage and the reasons for exclusion (Figure 1)

The flow diagram of the study selection process is presented using the PRISMA model, illustrating the number of articles at each stage and the reasons for exclusion (Figure 1)

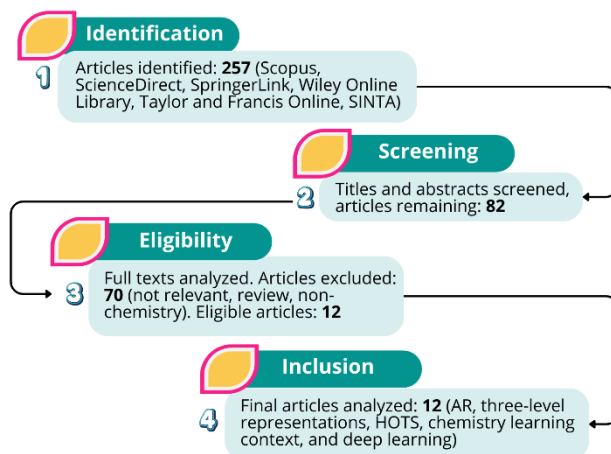


Figure 1. PRISMA Flow Diagram: The Role of AR in Supporting Deep Learning

3. RESULTS AND DISCUSSIONS

Based on the study selection procedure using the PRISMA model, a total of 12 articles met the inclusion criteria and were further analyzed as presented in Table 1.

Table 1. Analysis of Articles on the Use of Augmented Reality in Chemistry Education

No	Authors	Article Title	Journal	Topic
1	Ariska et al., 2023	Pengembangan <i>E-Book</i> Kimia Berbasis Augmented Reality (AR) pada Materi Bentuk Molekul	Orbital: Jurnal Pendidikan Kimia (SINTA 3)	Molecular Shapes
2	Zalukhu & Panggabean, 2025	Development of Augmented Reality-Based Mobile Learning Media on Molecular Shapes for High Scholl Students	JIPK: Jurnal Inovasi Pembelajaran Kimia (SINTA 3)	Molecular Shapes
3	Fadhilah & Nasution, 2025	Development of Chemistry E-Modules Based on Augmented Reality Technology on Hydrocarbon Material	JIPK: Jurnal Inovasi Pembelajaran Kimia (SINTA 3)	Hydrocarbons
4	Priyanto & Sumarwan, 2023	Development of Augmented Reality Learning Media in Chemistry Subject in High School	IJAIR: International Journal of Artificial Intelegence Research (SINTA 3)	Covalent Bonding
5	Nazar et al., 2024	Development of Augmented Reality as a Learning Tool to Improve Student Ability in Comprehending Chemical Properties of the Elements	CTI: Chemistry Teacher International (Scopus Q2)	Periodic Properties of Elements
6	Setiawaty et	Integrating Mobile Augmented Reality	JPPI: Jurnal Pendidikan IPA	Hydrocarbons

No	Authors	Article Title	Journal	Topic
	al., 2024	Applications Through Inquiry Learning to Improve Students Science Process Skills and Concep Mastery	Indonesia (Scopus Q3)	
7	Du & Dewitt, 2024	Technology Acceptance of a Wearable Collaborative Augmented Reality System in Learning Chemistry Among Junior High School Students	JPR: Journal of Pedagogical Research (Scopus Q2)	Atomic Structure and Molecular Formations
8	Lah et al., 2024	Mobile Augmented Reality in Learning Chemistry Subject: An Evaluation of Science Exploration	IJERE: International Journal of Evaluation and Research in Education (Scopus Q2)	Alkali Metal Reactivity
9	Ripsam & Nerdel, 2024	Augmented Reality for Chemistry Education to Promote the Use of Chemical Terminology in Teacher Training	Frontiers in Psychology (Scopus Q1)	Redox Reactions
10	Câmara Olim et al., 2024	Augmented Reality Interactive Experiences for Multi-Level Chemistry Understanding	Journal of Child-Computer Interaction (Scopus Q1)	Periodic Tables and Atomic Structure
11	Yamtinah et al., 2023	Augmented Reality Learning Media Based on Tetrahedral Chemical Representation: How Effective in Learning Process?	EURASIA Journal of Mathematics, Science and Technology (Scopus Q2)	Chemical Equilibrium
12	Tania & Sukarmin, 2025	Augmented Reality-Base Virtual Reality Laboratory Application as Chemistry Learning Media for Acid-Base Titration Material	Jurnal Eduscience: JES (SINTA 2)	Acid Base Titration

The summary of the characteristics and main findings of the articles is presented in Table 2. In general, the articles consistently demonstrate that the use of Augmented Reality (AR) in chemistry education has a positive impact on conceptual understanding, multi-level representational ability, the development of higher-order thinking skills (HOTS), and alignment with deep learning principles in the Merdeka Curriculum.

Table 2. Analysis of the Main Findings of Articles on the Use of Augmented Reality in Chemistry Education

No	Authors	Research Design	Main Findings	Limitations
1	Ariska et al., 2023	Research & Development with Validity Testing	The AR e-book demonstrated very high validity (94–97 percent) and was well-liked by students. The 3D visualization made molecular shapes more concrete and reduced misconceptions about bond angles and molecular forms. Students were more engaged and showed increased learning motivation.	Focused only on media feasibility. HOTS and long-term retention were not evaluated. Sample limited to one school.
2	Zalukhu & Panggabean, 2025	Research & Development and Quasi Experimental	AR improved learning outcomes (N-Gain: moderate to high), motivation, and student confidence. Students more easily understood the connection between VSEPR theory and molecular shapes.	Retention and collaboration were not measured. Short instructional duration.
3	Fadhilah & Nasution, 2025	Research & Development	AR supported students in understanding hydrocarbon structures, isomers, and	Lacked strong control group. HOTS not assessed.

No	Authors	Research Design	Main Findings	Limitations
			classifications. Students reported that learning became easier, more engaging, and provided deeper understanding.	
4	Priyanto & Sumarwan, 2023	Research & Development Effectiveness Study	AR made bonding concepts more concrete and minimized conceptual difficulties.	Collaboration not evaluated. Limited to one topic and one school.
5	Nazar et al., 2024	Research & Development And Experimental	AR improved student's analytical ability regarding element properties and understanding of periodic trends. Students were able to generalize patterns more accurately.	Participants were university students only. Motivation was not assessed.
6	Setiawaty et al., 2024	Research & Development, Quasi-experimental	AR improved learning outcomes and science process skills. Students showed strong acceptance of the technology. AR assisted in visualizing abstract hydrocarbon concepts.	AR content did not cover the full chemistry curriculum. Differences in student's technology skills. Teachers were not yet familiar with AR usage.
7	Du & Dewitt, 2024	Single-group Posttest Design	Students showed strong acceptance of WcAR for chemistry learning. Collaborative learning and collaborative authoring significantly influenced student's perceptions.	Conducted in only one school which limits generalization. No pretest-posttest, so improvement in learning outcomes was not measured.
8	Lah et al., 2024	Design & Development Research (DDR)	AR enhanced science exploration, curiosity, and significantly improved learning outcomes. The application was easy to use, navigation was responsive, and reaction visualizations were clear.	Focused on a single topic. Did not compare AR with other methods due to absence of a control group.
9	Ripsam & Nerdel, 2024	Experimental Pre-Post Design	AR increased the accuracy of understanding chemical terminology and provided visual representations that supported conceptual restructuring.	Very small sample size. Measured only chemical terminology, not conceptual understanding.
10	Câmara Olim et al., 2024	Experimental Pre-Post Design	AR improved multi-level representation, especially in visualizing complex molecular structures.	Motivation was not measured. Required compatible devices and stable connection.
11	Yamtinah et al., 2023	Research & Development	Tetrahedral-representation-based AR effectively improved learning outcomes. Students more easily understood submicroscopic phenomena and connections across representational levels. AR was perceived as engaging, motivating, and supportive for exploration.	AR not optimal for online learning. Camera could only detect markers on 2D surfaces, limiting rotation capability.
12	Tania & Sukarmin, 2025	Research & Development	AR helped students understand titration procedures, interpret titration graphs, observe indicator changes, and grasp neutralization concepts more concretely through interactive simulations similar to actual laboratory practice.	Limited number of participants, thus generalization is limited. Problem-solving ability not evaluated. HOTS indicators not measured.

This SLR was directed to answer three main research questions, namely: (A) what are the characteristics and trends of research on the use of Augmented Reality (AR) in chemistry education over the past ten years (2015–2025), (B) how the use of AR contributes to deep learning in chemistry education, particularly in relation to conceptual understanding, multi-level representations, higher-order thinking skills, and learning engagement, and (C) how the implementation of AR in chemistry education aligns with the principles of the Merdeka Curriculum in Indonesia.

A. Characteristics and Research Trends of AR in Chemistry Education

The mapping results show that although the timeframe of this SLR covers the period 2015 to 2025, the articles that met the inclusion criteria and were ultimately analyzed were concentrated between 2023 and 2025. This condition indicates a sharp increase in research on the use of AR in chemistry education within the past five years. This finding aligns with global review reports which highlight that research on AR in science education experienced acceleration after 2018 as mobile devices and AR platforms became increasingly available, stable, and accessible (Akçayır & Akçayır, 2017; Garzón & Acevedo, 2019). In the Indonesian context, several studies also indicate a shift from merely exploring AR technology toward more purposeful integration with the curriculum and the specific needs of chemistry learning (Wulandari et al., 2025).

Most of the analyzed articles originated from Indonesia and Malaysia, with several additional studies from Germany and other international contexts (Câmara Olim et al., 2024; Ripsam & Nerdel, 2024). This pattern reflects that Southeast Asian countries are actively developing and examining AR media for chemistry education, particularly at the senior high school and higher education levels. The dominance of senior high school studies is evident in research by Ariska et al. (2023), Fadhilah and Nasution (2025), Lah et al. (2024), Priyanto and Sumarwan (2023), Setiawaty et al. (2024), Tania and Sukarmin (2025), Zalukhu and Panggabean (2025). This indicates that the upper secondary level is viewed as critical for addressing student's difficulties in understanding abstract concepts such as molecular shapes, chemical bonding, hydrocarbons, science process skills, and titration. Meanwhile, studies at the university level (Câmara Olim et al., 2024; Nazar et al., 2024; Ripsam & Nerdel, 2024) generally emphasize strengthening multi-level representations, chemical literacy, and the professional readiness of preservice teachers or chemistry practitioners.

In terms of topic focus, most articles examined the use of AR in abstract and representational concepts, such as molecular shapes and VSEPR theory (Ariska et al., 2023; Zalukhu & Panggabean, 2025), chemical bonding (Priyanto & Sumarwan, 2023), hydrocarbons (Fadhilah & Nasution, 2025), periodic properties (Nazar et al., 2024), multi-level and tetrahedral representation (Câmara Olim et al., 2024; Yamtinah et al., 2023), chemical terminology (Ripsam & Nerdel, 2024), and acid-base titration in virtual laboratory contexts (Tania & Sukarmin, 2025). This pattern aligns with findings from international SLRs which emphasize that AR is most widely used for content requiring three-dimensional visualization and translation across representational levels (Garzón & Acevedo, 2019; Radu, 2014).

From the perspective of research design, the dominant combination consisted of media development (Research and Development or R and D) followed by feasibility and effectiveness testing using quasi-experimental designs. Studies such as those by Ariska et al. (2023), Fadhilah & Nasution (2025), Priyanto & Sumarwan (2023), Tania & Sukarmin (2025), Zalukhu & Panggabean

(2025) positioned R and D as the primary approach for producing AR prototypes which were later tested on a limited scale. This reflects that the field of AR use in chemistry education is still in the developmental and media-testing phase and has not yet progressed toward large-scale comparative evaluations or broader longitudinal studies, as noted in global analyses of AR research in science education (Akçayır & Akçayır, 2017).

Overall, these patterns indicate that the current use of AR in chemistry education is driven by pedagogical needs related to visualizing abstract concepts, strengthening multi-level representations, and enhancing chemical literacy. The publication trends show a significant increase in the last three years, as illustrated in Figure 2.

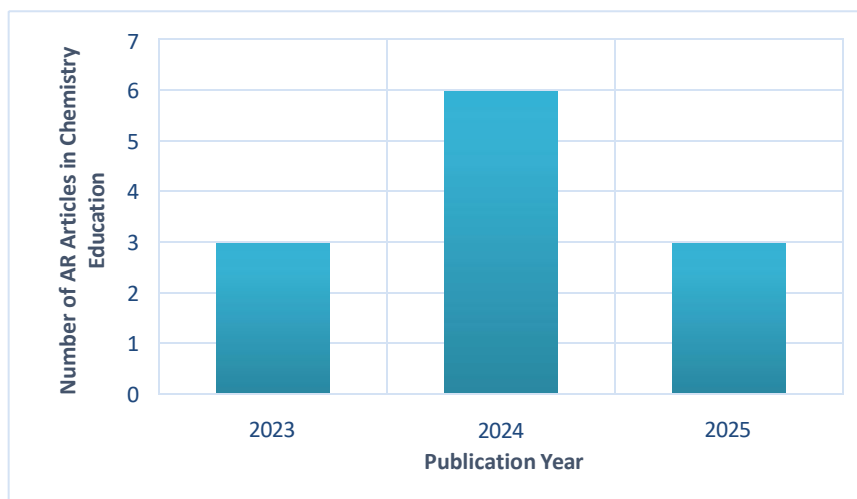


Figure 2. Trends in AR Research Publications in Chemistry Education

B. Contribution of AR to Deep Learning

The contribution of AR to deep learning, particularly regarding higher-order thinking skills and learning engagement, is evident across the analyzed studies. The synthesis of the 12 articles shows that AR consistently enhances conceptual understanding, strengthens multi-level representations, and in several cases contributes to the development of higher-order thinking skills (HOTS). The distribution of these contributions is presented in Table 3, which shows that all articles (100%) emphasize conceptual understanding, followed by learning engagement (66.7%), HOTS (50%), and multi-level representation (41.7%). This pattern indicates that AR is most effective for addressing conceptual difficulties in chemistry, while its integration with HOTS and multi-level representation is developing progressively.

Table 3. Distribution of Articles Based on Deep Learning Aspects

Deep Learning Aspect	Number of Articles	Percentage (%)
Conceptual Understanding	12	100
Multi-Level Representation	5	41,7
HOTS	6	50
Learning Engagement	8	66,7

In terms of conceptual understanding, studies on molecular shapes and VSEPR theory (Ariska et al., 2023; Zalukhu & Panggabean, 2025) demonstrate that AR facilitates three-dimensional visualization that allows students to observe molecular structures from various angles, manipulate models, and understand bond angles more accurately. This capability helps reduce common misconceptions that occur when instruction relies solely on static illustrations. In topics such as chemical bonding and hydrocarbons, AR helps clarify the relationships among electron structure, types of bonding, and compound properties (Fadhilah & Nasution, 2025; Priyanto & Sumarwan, 2023). For periodic properties, AR improves student's ability to identify periodic trends and generalize concepts more accurately (Nazar et al., 2024). These findings show that AR is highly effective in strengthening conceptual understanding in chemistry, consistent with constructivist theory which emphasizes active learning through concrete experiences (Piaget, 1973; Vygotsky, 1980).

Regarding multi-level representation, five articles (Ariska et al., 2023; Câmara Olim et al., 2024; Nazar et al., 2024; Ripsam & Nerdel, 2024; Yamtinah et al., 2023) show that AR enhances student's ability to connect macroscopic, submicroscopic, symbolic, and theoretical representations. Yamtinah et al., (2023) showed that tetrahedral chemical representation-based AR supports simultaneous understanding of relationships across representational levels, while Câmara Olim et al., (2024) found that AR reduces misconceptions when students transition from the macroscopic to the microscopic and symbolic levels. This multi-level integration is central to deep learning because students move beyond memorizing facts toward linking concepts, analyzing cause and effect relationships, and developing more mature scientific reasoning.

In relation to learning engagement, most articles reported that AR increases motivation, interest, and learning activity. The immersive and interactive learning environment encourages active participation, curiosity, and independent exploration (Du & Dewitt, 2024; Lah et al., 2024; Setiawaty et al., 2024). This aligns with previous reviews showing that AR enhances student engagement and learning experiences across educational contexts (Akçayır & Akçayır, 2017; Garzón & Acevedo, 2019). Within the framework of deep learning, increased engagement becomes a prerequisite for complex cognitive activities such as analysis, evaluation, and reflection.

Overall, the contribution of AR to deep learning is strongest in the aspect of conceptual understanding, followed by learning engagement, HOTS, and multi-level representation. This indicates that AR functions not only as a visual tool but as a pedagogical instrument capable of fostering knowledge integration, scientific reasoning, and learning experiences oriented toward depth of understanding.

C. Relevance of AR Implementation to the Principles of the Merdeka Curriculum in Indonesia

The Merdeka Curriculum emphasizes student-centered learning that is project-based, contextual, differentiated, and oriented toward the development of the Pancasila Student Profile (Kemendikbudristek, 2022). The findings of this SLR indicate that AR has strong potential to support instructional practices aligned with these principles.

First, AR can be effectively integrated into project-based learning and authentic assessment. Learning products such as three-dimensional molecular models, virtual laboratory simulations, or

AR-based visualizations of periodic properties can serve as components of student projects or portfolios. The study by Tania & Sukarmin (2025) showed that an AR-based virtual laboratory for acid–base titration not only improved students understanding of procedures and learning outcomes but also generated digital artifacts, such as titration graphs and virtual laboratory reports, which could be used as evidence for authentic assessment. This aligns with the Merdeka Curriculum, which encourages assessment practices that evaluate both learning processes and products comprehensively rather than relying solely on written tests.

Second, AR supports the implementation of differentiated learning. AR media provide flexibility for teachers in determining the depth of content, variation of activities, and forms of learning products. High-achieving students can be guided to conduct advanced analyses, such as examining more complex structure–property relationships or analyzing virtual experimental data. Meanwhile, students who require reinforcement can use AR to repeatedly explore basic concepts until a more stable understanding is formed. This approach is consistent with the principles of content, process, and product differentiation mandated in the Merdeka Curriculum (Kemendikbud, 2024).

Third, AR plays an important role in expanding access to laboratory experiences in schools with limited science facilities. Through AR-based virtual laboratories, students can still engage in concept-rich practical experiences, observe phenomena, analyze graphs, and draw scientific conclusions without relying solely on the availability of laboratory equipment and chemical materials. Studies by Setiawaty et al. (2024), Tania & Sukarmin (2025) demonstrate that AR in virtual laboratory contexts enhances science process skills and conceptual understanding while supporting safety and efficiency. This contributes to the equitable provision of quality science learning expected by the Merdeka Curriculum.

Fourth, AR implementations designed to promote collaboration are relevant to strengthening the Pancasila Student Profile, particularly the dimensions of critical thinking, creativity, and cooperation. Several studies integrating AR with group discussions, presentations, and scientific argumentation (Du & Dewitt, 2024; Ripsam & Nerdel, 2024) show that students were not only observing models but were also required to explain, compare, and justify arguments based on visual evidence from AR. This process supports the development of critical and creative thinking, as well as practice in scientific communication and teamwork.

However, the use of AR within the framework of the Merdeka Curriculum requires teacher readiness and institutional support. Research on AR in education emphasizes that successful AR implementation depends not only on the sophistication of the technology but especially on how AR is pedagogically integrated into the curriculum and assessment (Akçayır & Akçayır, 2017; Cheng & Tsai, 2013). Teachers need to design instructional scenarios that explicitly guide students to think critically, solve problems, and reflect on their learning through interactions with AR media. In addition, teacher training, the development of structured AR-based learning materials, and adequate technological infrastructure are essential for AR to genuinely contribute to deep learning as envisioned by the Merdeka Curriculum.

Common limitations across the 12 analyzed articles include small sample sizes, the frequent use of quasi-experimental designs that limit generalizability, and the lack of long-term retention and concept transfer measurements. Several studies did not explicitly measure HOTS indicators or

examine the integration of AR in Merdeka Curriculum learning scenarios such as projects, authentic assessment, and differentiated instruction.

Future research needs to adopt stronger experimental designs, involve larger samples, and measure the long-term impact of AR. Furthermore, the integration of AR into project-based learning and authentic assessment requires deeper investigation to determine its effectiveness in supporting student's holistic competency development.

4. CONCLUSIONS

This systematic review shows that the use of Augmented Reality (AR) in chemistry education has continued to increase over the past five years and provides significant contributions to conceptual understanding, multi-level representational ability, and student learning engagement. AR consistently addresses the abstract nature of chemical concepts through interactive three-dimensional visualizations that reduce misconceptions and strengthen knowledge construction. The findings also indicate that AR implementation aligns with the characteristics of deep learning promoted by the Merdeka Curriculum, including independent exploration, scientific reasoning, and more contextual learning experiences. Therefore, the objectives of this study to map trends, pedagogical contributions, and the relevance of AR in chemistry education have been comprehensively achieved.

The results of this SLR open opportunities for further research that more deeply investigates the longitudinal effects of AR on concept retention, knowledge transfer, and higher-order thinking skills through inquiry-based, project-based, or authentic assessment-oriented instructional designs. At the practical level, AR can be utilized by teachers as a tool for differentiated instruction, as support for virtual laboratory activities, and as a medium to enrich contextual learning experiences in accordance with the principles of the Merdeka Curriculum. Teacher training and the availability of adequate digital infrastructure are key factors to ensure that the integration of AR can contribute optimally to meaningful and sustainable chemistry learning.

REFERENCES

- Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, 20, 1–11. <https://doi.org/10.1016/j.edurev.2016.11.002>
- Ariska, N. N., Sholeh, M. I., & Laksono, P. J. (2023). Pengembangan e-book kimia berbasis augmented reality (AR) pada materi bentuk molekul. *Orbital: Jurnal Pendidikan Kimia*, 7(2), 197–207. <https://doi.org/10.19109/ojpk.v7i2.20159>
- Câmara Olim, S., Nisi, V., & Romão, T. (2024). Augmented reality interactive experiences for multi-level chemistry understanding. *International Journal of Child-Computer Interaction*, 42(September). <https://doi.org/10.1016/j.ijcci.2024.100681>
- Chang, H. Y., Binali, T., Liang, J. C., Chiou, G. L., Cheng, K. H., Lee, S. W. Y., & Tsai, C. C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers and Education*, 191(C). <https://doi.org/10.1016/j.compedu.2022.104641>
- Cheng, K. H., & Tsai, C. C. (2013). Affordances of augmented reality in science learning: suggestions for future

- research. *Journal of Science Education and Technology*, 22(4), 449–462. <https://doi.org/10.1007/s10956-012-9405-9>
- Du, J., & Dewitt, D. (2024). Technology acceptance of a wearable collaborative augmented reality system in learning chemistry among junior high school students. *Journal of Pedagogical Research*, 8(1), 106–119. <https://doi.org/10.33902/JPR.202425282>
- Fadhilah, N. F., & Nasution, H. A. (2025). Development of chemistry e-modules based on augmented reality technology on hydrocarbon material. *Jurnal Inovasi Pembelajaran Kimia*, 7(1), 124–133. <https://doi.org/10.24114/jipk.v7i1.67921>
- Feriyanto, F., & Anjariyah, D. (2024). Deep learning approach through meaningful, mindful, and joyful learning: A library research. *Electronic Journal of Education, Social Economics and Technology*, 5(2), 208–212. <https://doi.org/10.33122/ejeset.v5i2.321>
- Garzón, J., & Acevedo, J. (2019). Meta-analysis of the impact of augmented reality on students' learning gains. *Educational Research Review*, 27, 244–260. <https://doi.org/10.1016/j.edurev.2019.04.001>
- Hasanah, U., S, R. P., W, L. A., & K, D. Y. (2025). Implementation of deep learning approach in Indonesian education. *International Journal of Educational Technology and Society*, 2(2), 37–41. <https://international.aspirasi.or.id/index.php/IJETS/article/view/358>
- Kemendikbud. (2024). Kajian akademik: Kurikulum merdeka. In *Kemendikbud* (1st ed.). Pusat Kurikulum dan Pembelajaran.
- Kemendikbudristek. (2022). Panduan Implementasi Kurikulum Merdeka Pada Madrasah. In *Direktorat KSKK Madrasah RI*. Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi.
- Khairani, R. N., & Prodjosantoso, A. K. (2023). Application of augmented reality on chemistry learning: A Systematic Review. *Jurnal Penelitian Pendidikan IPA*, 9(11), 1221–1228. <https://doi.org/10.29303/jppipa.v9i11.4412>
- Lah, N. H. C., Senu, M. S. Z. M., Jumaat, N. F., Phon, D. N. E., Hashim, S., & Zulkifli, N. N. (2024). Mobile augmented reality in learning chemistry subject: an evaluation of science exploration. *International Journal of Evaluation and Research in Education*, 13(2), 1007–1020. <https://doi.org/10.11591/ijere.v13i2.25198>
- Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ (Clinical Research Ed.)*, 339. <https://doi.org/10.1136/bmj.b2700>
- Mayer, R. E. (2014). *The cambridge handbook of multimedia learning*. Cambridge University Press. <https://books.google.co.id/books?id=r3rsAwwAQBAJ>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P. C., ... Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*, 6(7), 1–6. <https://doi.org/10.1371/journal.pmed.1000097>
- Nazar, M., Zulfadli, Rahmatillah, Puspita, K., Setiawaty, S., & Sulastri. (2024). Development of augmented reality as a learning tool to improve student ability in comprehending chemical properties of the elements. *Chemistry Teacher International*, 6(3), 241–257. <https://doi.org/10.1515/cti-2023-0070>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Bmj*, 372. <https://doi.org/10.1136/bmj.n71>
- Piaget, J. (1973). To understand is to invent: the future of education; right to education in the modern world. In *Unesco*. Penguin Books. <https://unesdoc.unesco.org/ark:/48223/pf0000006133>
- Priyanto, P., & Sumarwan, S. (2023). Development of augmented reality learning media in chemistry subject high school. *International Journal of Artificial Intelligence Research*, 7(2), 123. <https://doi.org/10.29099/ijair.v6i2.912>
- Radu, I. (2014). Augmented reality in education: A meta-review and cross-media analysis. *Personal and Ubiquitous Computing*, 18(6), 1533–1543. <https://doi.org/10.1007/s00779-013-0747-y>

- Ripsam, M., & Nerdel, C. (2024). Augmented reality for chemistry education to promote the use of chemical terminology in teacher training. *Frontiers in Psychology*, 15(July), 1–23. <https://doi.org/10.3389/fpsyg.2024.1392529>
- Setiawaty, S., Lukman, I. R., Imanda, R., Sudirman, S., & Rauzatuzzikrina, R. (2024). Integrating mobile augmented reality applications through inquiry learning to improve students' science process skills and concept mastery. *Jurnal Pendidikan IPA Indonesia*, 13(1), 90–102. <https://doi.org/10.15294/jpii.v13i1.48891>
- Talib, C. A., Romainor, N., & Aliyu, F. (2022). Augmented reality in chemistry education: A literature review of advantages on learners. *Journal of Natural Science and Integration*, 5(1), 126. <https://doi.org/10.24014/jnsi.v5i1.16805>
- Tania, A. P., & Sukarmin, S. (2025). Augmented reality-based virtual laboratory application as chemistry learning media for acid-base titration material. *Jurnal Eduscience*, 12(5), 1354–1366. <https://doi.org/10.36987/jes.v12i5.7641>
- Vygotsky, L. . (1980). Mind in society: Development of higher psychological processes. In *Science & Society: A Journal of Marxist Thought and Analysis* (Vol. 44, Issue 1). Harvard University Press. <https://doi.org/10.1177/003682378004400121>
- Wulandari, R., Mariska, R., Hairunisa, P., Yobee, A., Supriyadi, S., & Hermawan, J. S. (2025). Studi literatur: Analisis pembelajaran berbasis teknologi augmented reality (AR). *JGK (Jurnal Guru Kita)*, 9(2), 555–570. <https://doi.org/10.24114/jgk.v9i2.65335>
- Yamtinah, S., Elfi Susanti, V. H., Saputro, S., Ariani, S. R. D., Shidiq, A. S., Sari, D. R., & Ilyasa, D. G. (2023). Augmented reality learning media based on tetrahedral chemical representation: How effective in learning process? *Eurasia Journal of Mathematics, Science and Technology Education*, 19(8). <https://doi.org/10.29333/ejmste/13436>
- Zalukhu, F. A. C., & Panggabean, F. T. M. (2025). Development of augmented reality-based mobile learning media on molecular shapes for high school students fandel. *Jurnal Inovasi Pembelajaran Kimia*, 7(2), 276–281. <https://doi.org/https://jurnal.unimed.ac.id/2012/index.php/jipk/issue/view/3517>
-