Integrated Science Education Journal
Vol. 7, No. 2, March 2026, pp. 244~254
ISSN: 2716-3725, DOI: 10.37251/isej.v7i2.2669

Research Article

Integrating Augmented Reality into the FERA (Focus-Explore-Reflect-Apply) Learning Model to Improve Students' Conceptual Understanding of Atomic Theory

Arjuna Pramana[1,*], Agung Rahmadani[1], Nurlaili Nurlaili[1], Fitriah Khoirunnisa[2]
[1] Department of Chemistry Education, Universitas Mulawarman, Kalimantan Timur, Indonesia
[2] Department of Chemistry Education, Universitas Raja Ali Haji Maritim, Kepulauan Riau, Indonesia

Article Info

Article history:

Received Jan 14, 2026
Revised Feb 21, 2026
Accepted Mar 11, 2026
OnlineFirst Mar 23, 2026

Keywords:

Atomic Theory
Augmented Reality
FERA Learning Model

ABSTRACT

Purpose of the study: This study aims to examine the effectiveness of the FERA (Focus-Explore-Reflect-Apply) learning model integrated with Augmented Reality (AR) in improving students' conceptual understanding of atomic theory.

Methodology: This was a pre-experimental study employing a one-group pretest–posttest design. The sample was 32 tenth-grade students selected through cluster random sampling from ten classes in the public high school in East Kalimantan. The instruments consisted of essay-based pretest and posttest questions, teacher and student observation sheets, and AR-integrated reading materials. The data were analyzed by using descriptive statistics, normality test, Wilcoxon Signed Rank Test, normalized gain (N-Gain), and effect size (r).

Main Findings: The results indicated a statistically significant improvement in students' conceptual understanding after the intervention. The average N-Gain score was 0.67 (moderate category). Meanwhile, the effect size ($r = 0.88$) showed a large effect. The greatest improvement was found in the classification indicator, whereas the application indicator demonstrated relatively lower gains. Overall, the integration of FERA and AR effectively improved conceptual understanding of atomic theory.

Novelty/Originality of this study: The novelty of this study lies in systematically embedding augmented reality within the structured stages of the FERA (Focus-Explore-Reflect-Apply) learning model to improve the students' conceptual understanding of atomic theory. Unlike previous studies that often employ augmented reality as a supplementary visualization tool, this study integrated AR into a coherent pedagogical framework, aligning interactive 3D representations with specific cognitive processes in each instructional stage.

Corresponding Author:
Arjuna Pramana,
Department of Chemistry Education, Universitas Mulawarman,
Jl. Kuaro, Gn. Kelua, Kec. Samarinda Ulu, Kota Samarinda, Kalimantan Timur 75117, Indonesia
Email: arjunapramana46@gmail.com

1. INTRODUCTION

Advances in technology and information have brought about major changes in various aspects of life, including education, by creating efficient and accessible learning [1]. The main challenge in 21st-century education is how to create learning that not only emphasizes content mastery but also fosters critical, creative, collaborative, and communicative thinking skills. Therefore, innovative and contextual learning approaches are a must so that the learning process is not only informative but also transformative [2], [3].

In the context of science education, particularly chemistry, this challenge is even greater because most of the material is abstract and cannot be observed directly [4]. One aspect of chemistry that students find difficult to understand is atomic theory. Concepts such as atomic structure, subatomic particles, and atomic models require a high level of visualization and reasoning skills [5]. This can lead to low conceptual understanding among students and a high likelihood of misconceptions in learning [6],[7]. Understanding a concept is the ability of students to comprehend the meaning of the information received, use definitions in accordance with the information provided, and be able to convey ideas with creative and innovative explanations [8]. Good conceptual understanding enables students to accept, understand, and remember the material for a long period of time [9], [10].

Atomic theory is an abstract chemical concept that is often tough for students to grasp and understand. Lectures and a lack of visual media are some of the reasons why students do not actively participate in the learning process [11]. To overcome this, a learning model is needed that encourages active student involvement in constructing their own understanding. One relevant model is FERA (Focus-Explore-Reflect-Apply). This model provides a structured and reflective learning flow. Students are invited to explain their basic understanding of a concept (focus), explore the material independently or in groups (explore), reflect on the results of their exploration to build concepts (reflect), and finally apply the concepts in real-life contexts (apply) [12]. This structured progression supports meaningful learning and facilitates deeper conceptual understanding by encouraging students to reconstruct their mental models rather than passively receiving information. However, despite its reflective structure, the FERA model alone may still face challenges in addressing highly abstract chemical concepts such as atomic theory, which require strong visualization support.

Previous studies have demonstrated that augmented reality (AR) enhances students' motivation and conceptual understanding in chemistry learning, particularly in abstract topics such as atomic structure [13], [14]. AR provides three-dimensional and interactive representations that help students visualize submicroscopic phenomena more concretely [15]. Nevertheless, most AR-based studies have implemented the technology as a standalone instructional medium without integrating it into a specific pedagogical framework [16]. Conversely, studies on the FERA model have not incorporated immersive visualization technologies to address abstract chemical concepts. Therefore, empirical research examining the integration of augmented reality within the FERA learning model in atomic theory instruction remains limited.

Considering the persistent difficulties that students experience in understanding atomic theory and the need for both structured learning guidance and meaningful visualization, integrating augmented reality (AR) into the FERA learning model becomes pedagogically significant. Although previous studies have demonstrated the effectiveness of augmented reality (AR) in enhancing visualization and others have implemented structured learning models independently, limited research has systematically integrated AR within a reflective instructional framework such as FERA. This indicates the absence of a unified pedagogical model that simultaneously supports immersive visualization and structured conceptual reconstruction in abstract chemistry learning [17], [18]. To address this issue, this study proposed an integrated FERA–AR instructional design in which AR-based three-dimensional atomic representations are strategically embedded into each stage of the FERA learning cycle. The novelty of this study lies in conceptualizing and implementing the FERA model in combination with AR as an integrated pedagogical approach, in which AR is not merely used as a supplementary tool but is strategically embedded within each stage of the FERA learning cycle (Focus-Explore-Reflect-Apply). This structured integration enables visualization support during exploration, guided reflection for conceptual reconstruction, and application activities reinforced by immersive representations.

This study aims to examine the effectiveness of integrating augmented reality into the FERA learning model in enhancing the students' conceptual understanding of atomic theory and to determine the magnitude of its instructional impact. Accordingly, this study addresses the following research questions: (1) Does the integration of augmented reality into the FERA learning model significantly improve the students' conceptual understanding of atomic theory? and (2) What is the magnitude of the effect of the integrated FERA–AR intervention on the students' conceptual understanding?

2. RESEARCH METHOD

This study employed a pre-experimental quantitative design with a one-group pre-test and post-test design. This design was selected to examine the effectiveness of integrating augmented reality into the FERA learning model on the students' conceptual understanding of atomic theory. Despite its suitability for preliminary effectiveness testing, this study has methodological limitations. The use of a one-group pretest–posttest design without a control group limits the ability to attribute causal effects exclusively to the intervention. Additionally, the relatively short duration of the intervention may not fully capture long-term conceptual retention or sustained learning effects. The students' conceptual understanding was measured before and after the intervention to determine the changes attributable to the treatment. The FERA learning model was in accordance with the syntax in Figure 1 [19], [20].

Figure 1. Syntax of the FERA Learning Model

In addition, the population of this study consisted of ten tenth-grade classes at the public high school in East Kalimantan. The sample was selected by using the cluster random sampling technique, in which one intact class was randomly chosen from the ten available classes. This technique was employed because the population was naturally organized into existing classroom clusters. Based on the random selection process, class X-4 was chosen as the research sample, consisting of 32 students. This study employed three main instruments: the teacher observation sheets, student observation sheets, a conceptual understanding test administered as a pretest and posttest, and integrated reading materials AR. The conceptual understanding test consisted of essay-based questions designed to measure the students' mastery of atomic theory concepts. The test items were content-validated by 2 the academic supervisors as subject-matter experts to ensure alignment with the learning objectives and conceptual indicators. The AR-integrated reading materials used in this study were adopted from previously developed instructional materials. The materials had undergone expert validation by two educational practitioners, resulting in a final validation score of 97.85%, categorized as very valid. The validated aspects included content feasibility, presentation, language use, and graphical design. Therefore, the materials were considered appropriate for use in the learning process. The data from the Likert-scale observation sheet were analyzed by using a scoring formula implemented in Microsoft Excel. The calculation procedure followed the formula proposed by Islami et al. [21], as presented in Formula 1.

$$Percentage\ of\ Observation\ Sheets = \frac{Score\ obtained}{Maximum\ Score} \times 100\% \ldots (1)$$

The results were interpreted according to Table 1, which lists teacher and student activities, to evaluate the extent to which the learning process was carried out well, as reported by Islami et al. [21].

Table 1. Teacher and student activity categories

Activity (X, %)	Criteria
$80 < X \leq 100$	Very High Quality
$60 < X \leq 80$	Quality
$40 < X \leq 60$	Enough
$20 < X \leq 40$	Low Quality
$0 < X \leq 20$	Very Low Quality

The analysis of data involved descriptive statistics (mean and standard deviation). To determine the difference in learning outcomes between before and after the treatment, the pretest and posttest data were analyzed by using a paired t-test after fulfilling tests of normality for score differences. This test was calculated by using the formula and then interpreted based on the categories used by Wahab et al. [22], in Formula 2 and Table 2. To measure the magnitude of the treatment effect, an effect size test (r) was used. Furthermore, the effectiveness of learning was analyzed by using normalized gain (N-gain) values descriptively [23].

$$Normal\ Gain = \frac{Score\ Post\ Test - Score\ Pre\ Test}{Score\ Ideal - Score\ Pre\ Test} \ldots (2)$$

Table 2. N-Gain Level Criteria

Average	Criteria
$g \geq 0.8$	Very High
$0.6 < g < 0.8$	High
$0.4 < g < 0.6$	Medium
$0.2 < g < 0.4$	Low
$0 < g < 0.2$	Very Low

The next test used the effect size. This test was used to assess the success rate of a learning model. This term may also refer to the process of evaluating the impact of learning models that have been implemented and tested on students [24],[25]. Then, the values were calculated by using the effect size formula described by Zahirah et al. [26], as shown in Formula 3.

$$r = \frac{Z}{\sqrt{n}} \ldots (3)$$

The resulting value was interpreted by using the effect size r, established criteria to determine the practical significance of the intervention. The classification framework applied in this study is summarized in Table 3, as described by Rohmatika et al. [27].

Table 3. Effect Size r Level Criteria

Average	Criteria
$r \geq 0.50$	Large effect
$0.30 \leq r < 0.50$	Medium effect
$0.10 \leq r < 0.30$	Small effect
$r < 0.10$	Negligible effect

3. RESULTS AND DISCUSSION

The use of this FERA model helps students focus on the core material (focus) while teachers focus on the basic concepts of atomic theory through reading materials that have been integrated by AR, giving students a strong initial focus [28]. The learning process continues with exploration, where students directly explore the 3D atomic model using AR and utilize reading materials and worksheets, which will increase their active involvement and curiosity [29]. Students reflect on the results of their exploration (reflect) by comparing their understanding through group discussions. This stage will strengthen their conceptual understanding and ultimately apply this knowledge in a new context (apply) to solve problems or real-world issues [30].

From a theoretical perspective, three-dimensional visualization through augmented reality supports conceptual change by enabling students to form clearer and more concrete mental representations of atomic structures that cannot be directly observed. Interactive visual elements allow learners to reorganize new information and relate it to prior knowledge, facilitating gradual conceptual restructuring [31], [32]. This visualization becomes more pedagogically powerful when embedded within a structured instructional sequence such as FERA.

The use of this FERA learning model supported by AR-integrated reading materials on the research subjects, resulted in a average pre-test score of 27.50, a post-test score of 72.18. Meanwhile, the standard deviation was 14.08, as shown in Table 4. Based on these data, there was an increasing understanding of these concepts among students after receiving the treatment. The diagram shows the increase of pre-test and post-test scores, as shown in Figure 2.

Table 4. Average Results and Standard Deviation

μ Post-test	μ Pretest	μ Post-Pre	Std. Deviation
72.18	27.50	44.68	14.08

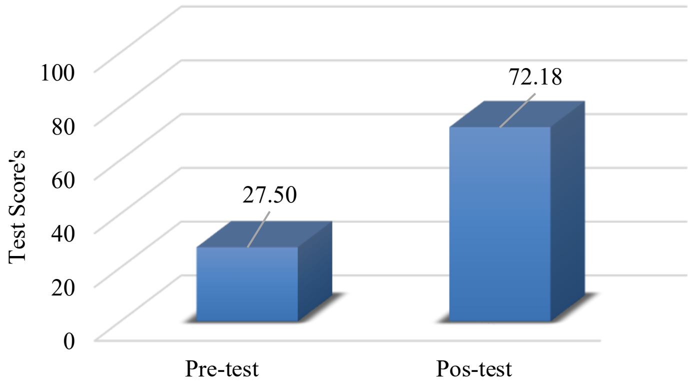

Figure 2. Comparison of students' pretest and posttest scores.

The rise in the average score indicates an enhancement in the students' conceptual understanding after the application of the FERA learning model integrated with AR. The increased average score on the pre- and post-tests showed that students experienced better conceptual understanding after following through the learning process [33].

Table 5. Teacher and the Student Activities

Teacher Activity	Criteria	Student Activity	Criteria
98.66%	Very High Quality	85.80	Very High Quality

Furthermore, the results of the teacher observation sheet, assessed by three observers using a Likert scale, showed an average implementation percentage of 98.66%, categorized as very high quality. This indicates that the stages of the AR-assisted FERA learning model were implemented almost entirely according to the instructional plan. The student observation results showed an overall percentage of 85.80%, also categorized as very high quality. This finding reflects students' active participation, positive responses, and engagement during the learning process.

Clearly, a normality test was conducted in order to define the appropriate type of inferential statistical test for analyzing the pre-test and post-test score differences. When the data followed a normal distribution, a paired t-test was used, whereas the Wilcoxon Signed-Rank test was employed when the data did not meet the normality assumption. The results obtained from the statistical test are shown in Table 6.

Table 6. Results of Normality Test and t-test

Normality Test				Wilcoxon test	
Class	Data	Sig	Description	Asymp.sig .(2-Tailed)	Description
X	*Pre-test*	0.012	Not Normally Distributed	0.000	Significant
	Post-test	0.010	Not Normally Distributed		

Based on the analysis, the pre-test produced a significance value of 0.012, while the post-test yielded 0.010. Since both values were below 0.05, the data did not meet the normality assumption. As a result, the appropriate inferential analysis used was the Wilcoxon Signed Rank Test as a substitute for the t-test. The obtained Asymp. Sig. (2-tailed) A value of 0.000 confirms that a significant difference existed between pre-test and post-test scores following the application of the FERA learning model enhanced with AR-integrated reading materials.

Table 7. Results of N-Gain Test and Effect Size r Test

N-Gain	Criteria	Effect-Size	Criteria
0.67	Medium	0.88	Large Effect

Based on Table 7, the N-Gain value obtained was 0.67, which was classified as moderate. This showed that the increased conceptual understanding of the students after applying the FERA learning model assisted by AR-integrated reading materials was at a good level. In the context of atomic theory, an abstract and conceptually demanding topic, a moderate gain indicates that students made measurable improvements in understanding core concepts and demonstrated meaningful conceptual refinement. Educationally, although the normalized gain may fall into a moderate category, the large effect size suggests that the structured integration of augmented reality within the FERA stages contributed meaningfully to conceptual improvement. This level of improvement is particularly meaningful in the context of atomic theory, which is widely recognized as an abstract and conceptually challenging topic. Therefore, the findings answered the first research question by confirming that the integration of augmented reality into the FERA learning model significantly improved the students' conceptual understanding. Furthermore, the second research question was addressed by demonstrating that the magnitude of the intervention effect was large (r = 0.88), indicating a large effect.

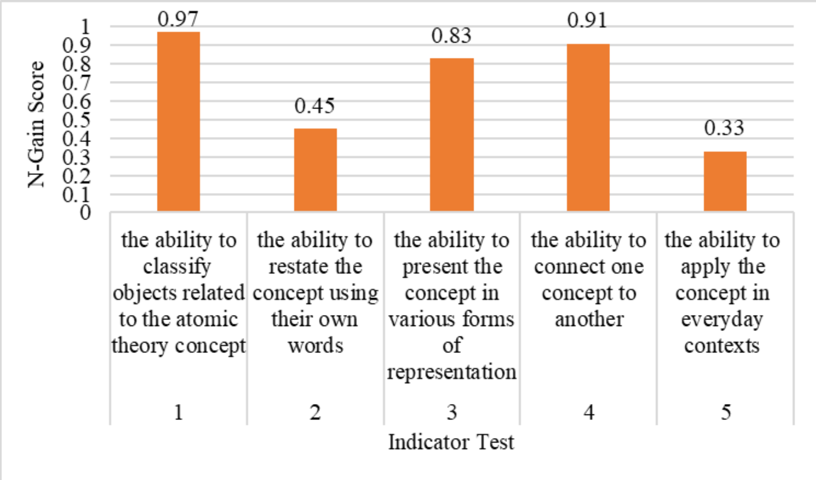

Figure 3. Distribution of students' N-Gain scores after the implementation of the AR-assisted FERA model.

However, the measurement of the students' conceptual understanding in this study was conducted through five indicators. These indicators included: (1) the ability to classify objects related to the atomic theory concept, (2) the ability to restate the concept using their own words, (3) the ability to present the concept in various forms of representation, (4) the ability to connect one concept to another, and (5) the ability to apply the concept in everyday contexts [34]. These five indicators were used in order to acquire a comprehensible overview of the level of students' conceptual understanding upon completing the learning process using the FERA model supported by augmented reality. The results of conceptual understanding measurements for each indicator are shown in Figure 3.

Obviously, indicators classify objects, demonstrating students' ability to group or distinguish objects based on properties or characteristics relevant to the concepts being studied. Students are asked to sequence the development of atomic models from Dalton's atomic model to quantum mechanics based on images. This process will enable students to remember atomic models so that they can classify them [35]. The post-test results showed that students had excellent ability in classifying atomic models, as indicated by the N-Gain score, which was 0.97, falling into the very high category. In an exploration stage, the use of AR allows students to visualize atomic models interactively, making the learning experience more concrete and interesting. This improves students' memory, making it easier for them to observe, distinguish, and classify the objects in each atomic model [36], [37].

Re-stating concepts in their own words is an indicator that assesses the extent to which students can explain or re-formulate the concepts they have learned using their own words. This indicator shows a deep understanding because students did not just memorize definitions, but can express ideas in a way that they understand [38]. In the post-test questions, the students had to determine the atomic model based on the image provided, then explain the review of the discovery experiment conducted in accordance with that atomic model. This resulted in an N-Gain score of 0.45, which falls into the category of moderate. In the FERA learning model, the reflect stage greatly supports the achievement of this indicator because students are encouraged to reflect on the exploration experiences they have had in the explore stage. With the help of augmented reality, students can see a three-dimensional representation of atoms visually and interactively. This visualization makes it easier for students to grasp abstract concepts, so they are better prepared to restate these concepts in their own words and strengthen their conceptual understanding [39].

Indicators are presented in diverse representation forms, requiring students to be able to convey their understanding of a concept in visual, verbal, or symbolic form [40]. In the context of post-test questions, the students were asked to identify the distinctions between Rutherford's and Niels Bohr's atomic models, enabling them to present the differences between the two models in the form of atomic model diagrams, comparison tables, or coherent verbal explanations. The ability to present concepts in various forms of representation has an N-Gain value of 0.83, which is classified as very high. Through the implementation of the FERA learning model supported by augmented reality (AR), especially at the exploration stage, students can directly observe the three-dimensional visual form of the Rutherford and Bohr atomic models [41]. This exploratory experience helps them understand concretely how the structure and arrangement of electrons differ in the two models [42]. Furthermore, in the reflect stage, students represent their observations in various forms, such as atomic sketches, written explanations, or verbal descriptions of the location of electrons and atomic nuclei [43]. Thus, AR assistance in the FERA model not only made it easier to understand the differences between these two atomic models, but also trained students' ability to express concepts in various forms of representation more clearly and meaningfully.

Indicators connecting concepts, students are expected to be able to link one concept to another relevant concept to form a complete understanding [44]. The context of post-test questions that required the students to explain the advantages and disadvantages of Rutherford and Niels Bohr's atomic theories, the ability to connect concepts can be seen from how students were able to trace the relationship between Rutherford's experimental results and Bohr's refinement of the atomic model. The ability to connect learned concepts had an N-Gain indicator score of 0.91, which was classified as a very high category. The implementation of the assisted FERA learning model (AR) greatly supported achieving this indicator. During the exploration stage, the students used AR to observe the structural differences between two atomic models visually and interactively. Three-dimensional visualization helped the students understand why Rutherford's model was unable to explain electron stability and how Bohr improved it with the concept of electron orbits. Furthermore, in the reflect stage, the students were asked to compare the two models and relate them to the principle of energy so that they can explain the relationship between the two concepts logically [45], [46]. Through this learning experience, the students not only learn about the advantages and disadvantages of each atomic model, but also understand the conceptual relationships that underlie the development of atomic theory. Thus, the use of AR-assisted FERA learning models was effective in training the students' ability to connect the chemical concepts in a deep and meaningful way.

In the indicator of applying concepts in daily life, students should be able to apply the conceptual knowledge they have learned to explain phenomena or technologies around them [47]. In the context of the post-test questions that presented explanations about nanofertilizers, the students were required to relate the concept of atomic theory, particularly the principles of quantum mechanics, to the role of atoms and nanoparticles in increasing the efficiency of nutrient absorption by plants [48]. The ability to apply concepts in daily life has an N-Gain value of 0.33, which is classified as low category. This low N-Gain score may be due to several factors. *First*, the concepts of atomic theory and quantum mechanics are abstract and complex, making it difficult for students to relate the theory to real-world applications, such as the role of atoms in nanofertilizers [49], [50]. *Second,* although the augmented reality-assisted FERA learning model provides a visual and interactive experience, students may not be fully accustomed to applying their observations to real-life situations [51]. *Third*, limited learning time may reduce opportunities for students to practice applying concepts in depth through the apply stage [52].

Based on five conceptual understanding indicators, these indicators classified the objects into the best improvement category with an N-Gain value of 0.97. Conversely, indicators that showed the lowest improvement were the application of concepts in everyday life, which have an N-Gain value of 0.33. In general, this can occur because the application stage requires the ability to transfer concepts to new situations, which is cognitively more complex than the exploration or reflection stages. Transfer skills require an in-depth understanding and flexibility of thinking, which generally develop gradually. Overall, the implementation of the FERA learning model with AR assistance on atomic theory material had the N-Gain value of 0.67 so that the students' conceptual understanding level after receiving the treatment was in the moderate category. The resulting effect size ($r = 0.88$) indicated a large effect [53], [54].

These results are consistent with previous studies reporting that augmented reality enhances the visualization of abstract chemical concepts and improves students' conceptual understanding. A study conducted by Olim et al., [55] show that augmented reality interactive experiences support multi-level understanding in chemistry by helping learners connect different forms of representation. The Research by Amirbekova et al., [56] also shows that the integration of virtual and augmented reality in chemistry instruction significantly improves students' ability to visualize abstract concepts. Furthermore, Agussalim [57] reports that augmented reality plays a substantial role in fostering deeper learning in chemistry by strengthening students' conceptual comprehension through immersive visualization tools.

In addition, studies on constructivist-based instructional models have demonstrated that structured phases of exploration and reflection promote conceptual change. The present findings not only corroborate those earlier studies but also extend them by systematically integrating AR within the structured framework of the FERA learning model [58], [59]. The improvement in students' conceptual understanding can be interpreted as the result of a synergistic interaction between the pedagogical structure of FERA and the visual affordances of augmented reality. While FERA provides a systematic learning progression that scaffolds conceptual construction, AR enhances this process by offering concrete and dynamic representations of abstract phenomena.

The combination of these elements resulted in significant learning gains and a large magnitude of effect, indicating that technology integration is most effective when aligned with a structured pedagogical framework.

The novelty of this study lies in the systematic integration of augmented reality into the FERA learning model rather than employing AR as a standalone instructional medium. This integrated approach demonstrates that the educational impact of technology is strengthedyned when embedded within a structured learning sequence. Nevertheless, this study is limited by the use of a pre-experimental design without a control group, which restricts the ability to establish stronger causal inferences. Future research is therefore recommended to employ a quasi-experimental design with a comparison group to enhance internal validity and provide more robust evidence regarding the effectiveness of the intervention.

4. CONCLUSION

Overall, the FERA learning model supported by Augmented Reality (AR) proved to be effective and relevant for chemistry learning. This study concluded that the integration of the FERA learning model with Augmented Reality was effective in improving students' conceptual understanding of atomic theory, with an effect size of 0.88 in the large effect category. These findings confirm that the intervention significantly improved students' conceptual understanding, with meaningful learning gains and a large effect magnitude. Practically, these results suggest that chemistry teachers can improve the quality of learning by integrating visualization technology into clearly structured pedagogical models, rather than using technology as an additional tool. From a technology integration perspective, the effectiveness of augmented reality appears to be stronger when aligned with clear instructional stages that guide the cognitive process. Although the findings show positive results, future research is recommended to use controlled or quasi-experimental designs involving comparison groups to provide stronger causal evidence regarding the effectiveness of augmented reality integrated into the FERA model.

ACKNOWLEDGEMENTS

The author would like to thank all parties who have contributed to the completion of this research. Particular thanks are extended to the Principal of State Senior High School in East Kalimantan for the permission and support provided.

AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing-Original Draft Preparation, & Visualization, Arjuna Pramana, Nurlaili Nurlaili; Writing – Review & Editing, Agung Rahmadani, Fitriah Khoirunnisa; Supervision & Project Administration, Agung Rahmadani and Nurlaili Nurlaili.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

REFERENCES

[1] C. Sulistyowati, and N. Asriati, “Pemanfaatan teknologi untuk meningkatkan efektivitas pembelajaran dan keterlibatan belajar di era digital [Utilizing technology to improve learning effectiveness and engagement in the digital age],” *Jurnal Ilmiah Pendidikan Citra Bakti*, vol. 11, no. 4, pp. 1176–1188, 2024, doi:10.38048/jipcb.v11i4.4542.

[2] U. Haryaka, N. K. Razak, F. Rachman, K. Y. Tung, and L. Judijanto, “Integrating digital literacy, critical thinking, and collaborative learning: Addressing contemporary challenges in 21st century education,” *Jurnal of Hunan University*, vol. 52, no. 3, pp. 102–112, 2025, doi:10.55463/issn.1674-2974.52.3.9.

[3] A. Whindayati, R. N. Fauziah, S. Fatimah, Yusmaini, and D. Handayani, “Penguatan kompetensi abad 21 dalam pembelajaran di era digital: Tantangan dan strategi pendidik Indonesia [Strengthening 21st century competencies in learning in the digital age: Challenges and strategies for Indonesian educators],” *Jurnal Ilmiah Pendidikan Dasar,* vol. 10, no. 4, pp. 240–262, 2025. doi:10.23969/jp.v10i04.35543.

[4] S. Nickel, S. Brockmüller, W. J. Boone, and S. Habig, “Measuring representational competence – analyses of dimensionality and the relationship to general content knowledge knowledge,” *Int. J. Sci. Educ*, vol. 0693, pp. 1-25, 2025, doi: 10.1080/09500693.2025.2515621.

[5] N. Afrianis and L. Ningsih, “Analisis kesulitan belajar siswa pada materi struktur atom [Analysis of student learning difficulties in atomic structure material],” *Jurnal Pendidikan Kimia dan Terapan*, vol. 6, no. 2, pp. 102–108, Jul. 2022. doi: 10.24014/konfigurasi.v6i1.18617.

[6] R. U. Fauziah and D. Novita, “Conceptual profile in chemistry: The matter of atomic theories,” *Journal of Chemistry Education Research* , vol. 6, no. 2, pp. 119–123, 2022, doi:10.26740/jcer.v6n2.p119-123.

[7] T. Tanti, W. Utami, D. Deliza, and M. Jahanifar, “Investigation in vocation high school for attitude and motivation students in learning physics subject”, *Journal Evaluation in Education (JEE),* vol. 6, no. 2, pp. 479-490, 2025, doi: 10.37251/jee.v6i2.1452.

[8] F. F. N. H. A. Haq and M. I. R. Raicudu., “Pemahaman konsep peserta didik kelas vii pada materi segiempat [Understanding of seventh grade students' concepts on quadrilateral material],” *Prosiding Seminar Nasional Pendidikan Matematika*, vol. 3, pp. 82-89, 2023.doi: 10.30872/psnpm.v1i0.2470.

[9] N. Murniati, H. Susilo, and D. Listyorini “Retention achievement in brain-based whole learning is supported by students’ scientific literacy and concept mastery,” *Journal of Education and Instruction*, vol. 13, no. 3, pp. 294–303, 2023, doi: 10.47750/pegegog.13.03.30.

[10] D. Corral and S. K. Carpenter, “Effects of retrieval practice on retention and application of complex educational concepts,” *Learn. Instr*, vol. 100, p. 102219, 2025, doi: 10.1016/j.learninstruc.2025.102219.

[11] C. Lin and H. Wu, “Effects of different ways of using visualizations on high school students’ electrochemistry conceptual understanding and motivation towards chemistry learning,” *Chemistry Education Research and Practice*, pp. 786–801, 2021, doi: 10.1039/d0rp00308e.

[12] T. Tanti, A. Astalini, D. A. Kurniawan, D. Darmaji, T. O. Puspitasari, and I. Wardhana, “Attitude for physics: The condition of high school students,” *Jurnal Pendidikan Fisika Indonesia,* vol. 17, no. 2, pp. 126-132, 2021, doi: 10.15294/jpfi.v17i2.18919.

[13] E. Laila dan S. Atun, “Augmented reality sebagai media inovatif dalam pembelajaran kimia untuk meningkatkan motivasi belajar siswa: Sebuah systematic literature review [Augmented reality as an innovative medium in chemistry learning to improve student motivation: A systematic literature review],” *J. Pendidikan Matematika dan Sains*, vol. 14, no. 1, 2024, doi:10.21831/jpms.v14i1.90940.

[14] A. I. Fazrin, D. N. Agnafia, and A. Mashuri, “Development of augmented reality (AR) media to improve learning outcomes on earth structure for eighth grade students,” *In. Sci. Ed. J,* vol. 6, no. 2, 2025, doi: 10.37251/isej.v6i2.1762.

[15] M. Ripsam and C. Nerdel, “Augmented reality for chemistry education to promote the use of chemical terminology in teacher trainings,” *Frontiers in Psychology*, vol. 13, Art. no. 1037400, 2022, doi:10.3389/fpsyg.2022.1037400.

[16] H. S. Fernandes, N. M. F. S. A. Cerqueira, and S. F. Sousa, “Developing and using BioSIMAR, an augmented reality program to visualize and learn about chemical structures in a virtual environment on any internet-connected device,” *J. Chem. Educ.*, vol. 98, no. 5, pp. 1789–1794, 2021, doi: 10.1021/acs.jchemed.0c01317.

[17] A. Chairunnisa, R. Al Rian, and E. Ismanto, “Pengembangan media pembelajaran augmented reality (AR) berbasis android pada materi struktur atom sma kelas x [Development of android-based augmented reality (AR) learning media for high school 10th grade atomic structure material]” *Jurnal Ilmiah PGSD STKIP Subang*, vol. 11, no. 3, pp. 225–230, 2025, doi:10.36989/didaktik.v11i03.7710.

[18] T. Tanti, A. Astalini, D. Darmaji, D. A. Kurniawan, and R. Fitriani, “Student perception review from gender: Electronic moduls of mathematical physics,” *JPI (Jurnal Pendidikan Indonesia)*, vol. 11, no. 1, pp. 125-132, 2022, doi: 10.23887/jpiundiksha.v11i1.35107.

[19] I. Wahyunita and W. T. Subroto, “Efektivitas model pembelajaran blended learning dengan pendekatan STEM dalam upaya meningkatkan kemampuan berfikir kritis peserta didik [The effectiveness of the blended learning model with a STEM approach in efforts to improve students' critical thinking skills],” *Jurnal Ilmu Pendidikan Research & Learning in Education*, vol. 3, no. 3, pp. 1010–1021, 2021.

[20] J. W. Creswell and J. D. Creswell, “Quantitative Methods,” in *in Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 5th Ed. Los Angeles, CA, USA: SAGE Publication, 2018, ch. *1*, pp. *206–253.*

[21] A. A. Islami, R. Gunawan, F. Erika, and A. Rahmadani, “Development of learning videos on the atomic model concepts based on multilevel representation,” *Jambura J. Educ. Chem.*, vol. 8, no. 1, pp. 99–103, 2026, doi: 10.37905/jjec.v8i1.36535

[22] A. Wahab, Junaedi, and M. Azhar, “Efektivitas pembelajaran statistika pendidikan menggunakan uji peningkatan n-gain di PGMI [Effectiveness of statistics education learning using the n-gain improvement test in PGMI],” *JURNAL BASICEDU Research & Learning in Elementary Education,* vol. 5, no. 2, pp. 1039-1045, 2021, doi: 10.31004/basicedu.v5i2.845.

[23] C. O. Fritz, P. E. Morris, and J. J. Richler, “Effect size estimates: Current use, calculations, and interpretation,” *Journal of experimental psychology,* vol. 141, no. 1, pp. 2–18, 2012, doi: 10.1037/a0024338.

[24] N. Fauziah, A. Asrizal, and U. Usmeldi, “Meta analisis effect size pengaruh bahan ajar terhadap kemampuan berpikir kritis dan hasil belajar peserta didik [Meta-Analysis effect size of teaching materials on critical thinking skills and student learning outcomes],” *Jurnal Pendidikan Tambusai,* vol. 7, no. 3, pp. 32103–32109, 2023, doi: 10.31004/jptam.v7i3.12241.

[25] N. F. Diannisa, E. Erlina, A. I. Harun, R. Sahputra, and M. Ulfah, “Deskripsi pemahaman konsep pada materi struktur atom di kelas x sma negeri 01 Ngabang [Description of conceptual understanding of atomic structure material in grade x at ngabang state high school 01],” *HYDROGEN: Jurnal Kependidikan Kimia,* vol. 11, no. 4, pp. 497–512, 2023, doi: 10.33394/hjkk.v11i4.8091.

[26] A. A. Zahirah, M. P. Sindiawati, Z. Mufidah, and S. F. Giwangsa, “Program kampus mengajar 7: Efektifkah terhadap kemampuan numerasi siswa di SDN Kertasari? [Teaching campus program 7: is it effective in improving students' numeracy skills at SDN Kertasari?],” *Jurnal Ilmiah Pendidikan Dasar*, vol. 9, no. 4, pp. 244–255, 2024, doi: 10.23969/jp.v9i04.20651.

[27] R. Rohmatika, H. Yuliani, and J. Annovasho, “Meta-Analysis: The impact of PjBL on students’ creative thinking skills in physics education,” *Jurnal Kependidikan Fisika*, vol. 12, no. 1, pp. 116–134, 2024, doi: 10.33394/j-lkf.v12i1.11793.

[28] F. Prasetya, A. Fortuna, A. Dwinggo, S. Rawas, S. Mystakidis, and R. Ema, "Social sciences & humanities open the impact of augmented reality learning experiences based on the motivational design model: A meta-analysis," *Soc. Sci. Humanit. Open*, vol. 10, pp. 100926, 2024, doi: 10.1016/j.ssaho.2024.100926.

[29] J. Levy, I. C. Chagunda, V. Iosub, D. C. Leitch, and J. S. Mcindoe, "MoleculAR: An augmented reality application for understanding 3d geometry," *Elsevier Ltd,* pp. 2533–2539, 2024, doi: 10.1021/acs.jchemed.3c01045.

[30] K. Komarudin, N. D. Rahmawati, B. S. Anggoro, Suherman, and S. Arfina, "Meningkatkan kemampuan metakognitif dan penalaran adaptif matematis: Dampak model FERA berbantuan video pembelajaran [Improving metacognitive abilities and adaptive mathematical reasoning: The impact of the FERA model assisted by learning videos]," *Jurnal Cendekia: J. Pendidikan Mat*, vol. 06, no. 02, pp. 1419–1432, 2022, doi: 10.31004/cendekia.v6i2.1268.

[31] R. Anggraini, L. Marlina, and S. M. Siahaan, "Augmented reality–based flashcard media: A study of foster senior high school students' critical thinking skills on atomic models," *Integrated Sci. Educ. J.*, vol. 7, no. 1, pp. 18–24, 2026, doi: 10.37251/isej.v7i1.2374.

[32] A. Ramadhani, I. Ismet, and K. Wiyono, "Solar system learning innovation through augmented reality: Increasing student concept solar system," *Integrated Sci. Educ. J.*, vol. 7, no. 1, 2026, doi: 10.37251/isej.v7i1.2443.

[33] A. Sugianingsih, "Analisis model problem based learning untuk meningkatkan keberhasilan belajar siswa pada mata pelajaran kimia [Analysis of problem-based learning models to improve student learning outcomes in chemistry]," *Chemistry Education Journal,* vol. 3, no. 1, pp. 166–172, 2020, doi: 10.30862/accej.v3i1.294.

[34] R. Anggraini, L. Marlina, and S. M. Siahaan, "Augmented Reality–Based flashcard media: A study of foster senior high school students' critical thinking skills on atomic models," *Integrated Science Education Journal*, vol. 7, no. 1, pp. 18-24, 2026, doi: 10.37251/isej.v7i1.2374.

[35] A. I. Fazrin, D. N. Agnafia, and A. Mashuri, "Development of augmented reality (AR) media to improve learning outcomes on earth structure for eighth grade students," *Integrated Science Education Journal*, vol. 6, no. 2, pp. 115-122, 2026, doi: 10.37251/isej.v6i2.1762.

[36] S. Sutrisno, S. Sudargo, dan R. A. Titi, "Analisis kemampuan representasi matematis siswa SMK Kimia Industri Theresiana Semarang [Analysis of the mathematical representation abilities of students at Theresiana Industrial Chemistry Vocational School in Semarang]," *Jurnal Ilmiah Pendidikan Matematika,* vol. 4, no. 1, pp. 65–76, 2019, doi: 10.26877/jipmat.v4i1.3626.

[37] K. R. L. Marbun, M. Siregar, M. M. Boangmanalu, L. Simamora, R. G. P. Silaban, and J. R. Saragih, "Development of augmented reality-based learning media to improve students' conceptual understanding in chemistry," *In. Sci. Ed. J*, vol. 6, no. 1, pp. 1–12, 2025, doi: 10.37251/isej.v6i1.

[38] P. Hulu, A. O. Harefa, and R. N. Mendrofa, "Studi model pembelajaran inkuiri terhadap pemahaman konsep matematika siswa [Study of inquiry learning models on students' understanding of mathematical concepts]," *Jurnal Pendidikan,* vol. 2, no. 1, pp. 152–159, 2023, doi: 10.56248/educativo.v2i1.97

[39] Lubis, N., Risnawati, R., & Hamdani, M. F., "Pengaruh media pembelajaran berbasis augmented reality terhadap pemahaman konsep dan minat membaca siswa kelas 5 sekolah dasar [The effect of augmented reality-based learning media on conceptual understanding and reading interest of fifth grade elementary school students]," *Junal Ilmiah Pendidikan Dasar,* vol. 10, no. 2, pp. 376–384, 2025, doi:10.23969/jp.v10i2.27176.

[40] M. Isnaini and W. P. Ningrum, "Hubungan keterampilan representasi terhadap pemahaman konsep kimia organik [The relationship between representation skills and understanding of organic chemistry concepts]," *Orbital: Jurnal Pendidikan Kimia*, vol. 2, no. 2, pp. 12–25, 2018, doi: 10.19109/ojpk.v2i2.2637.

[41] M. Qibtiyah and S. Sukarmin, "Development of augmented reality-based interactive 'element card' media on electron configuration submaterial according to Niels Bohr," *Jurnal Pengkajian Ilmu dan Pembelajaran Matematika dan IPA IKIP Mataram*, vol. 10, no. 2, pp. 252–261, 2022, doi: 10.33394/j-ps.v10i2.4916.

[42] S. Wulandari, J. Jusniar & A. F. Majid, "Development of augmented reality-based learning media in the form of cards on atomic structure material," *UNESA Journal of Chemical Education*, vol. 12, no. 2, pp. 83–91, 2023, doi: 10.26740/ujced.v12n2.p83-91.

[43] A. Aris, A. Fitria, and L. Ihtisyamuddin, "Chemistry structure sheet as augmented reality-based chemistry learning media on atomic structure material development design obtained is based on the assessment of material experts, and media," *Jurnal Pendidikan Matematika dan Sains,* vol. 8, no. 2, pp. 77–81, 2020, doi: 10.21831/jpms.v8i2.42773.

[44] A. V. Zandroto and K. Sinaga, "Analisis kemampuan literasi kimia siswa pada materi senyawa hidrokarbon melalui pendekatan kontekstual [Analysis of students' chemical literacy skills in hydrocarbon compounds material through a contextual approach]," *Jurnal Pendidikan MIPA,* vol. 12, no. 2, pp. 349–358, 2022, doi: 10.37630/jpm.v12i2.596.

[45] F. Rahmi, "Augmented reality sebagai inovasi teknologi dalam pengajaran kimia di tingkat universitas: Tinjauan literatur [Augmented reality as a technological innovation in chemistry teaching at the university level: A literature review]," *Jurnal Pendidikan Tambusai,* vol. 8, pp. 43657–43662, 2024. doi: 10.31004/jptam.v8i3.20833.

[46] J. S. Akbar and D. Djakariah, "Efektivitas penggunaan media pembelajaran berbasis augmented reality dalam pembelajaran kimia di era society 5.0 [The effectiveness of using augmented reality-based learning media in chemistry education in the society 5.0 era]," *UNESA Journal of Chemical Education*, vol. 13, no. 2, pp. .86–99, 2024, doi: 10.26740/ujced.v13n2.p86-99.

[47] R. Wahyuni and N. C. Prihatiningtyas, "Kemampuan pemahaman konsep matematika terhadap kemampuan koneksi matematika siswa pada materi perbandingan [Mathematical concept comprehension ability on students' mathematical connection ability in comparison material]," *VARIABEL,* vol. 3, no. 2, pp. 66–73, 2020. doi: 10.33084/variabel.v3i2.2269.

[48] A. Nongbet, A. K. Mishra, Y. K. Mohanta, S. Mahanta, and M. K. Ray, "Nanofertilizers: A smart and sustainable attribute to modern agriculture," *Plants,* vol. 11, no. 19, pp. 1–20, 2022, doi: 10.3390/plants11192587.

[49] A. Pramana, F. Z. Fransiska, E. D. Nurrohimi, S. Sukmawati, M. Ridwansyah, and A. Rahmadani, "Kajian literatur model pembelajaran dalam meningkatkan keterampilan metakognitif pada pembelajaran kimia [Literature review of

learning models in improving metacognitive skills in chemistry learning]," *ALOTROP,* vol. 8, no. 2, pp, 79-96, 2024, doi: 10.33369/alo.v8i2.37599.
[50] R. N. Firuz, "Nanotechnology integration into chemistry education for development-oriented learning and the formation of scientific thinking and creative potential in secondary school students," *Scientific Collection,* pp. 55–60, 2025, doi: 10.51582/interconf.19-20.08.2025.008.
[51] A. Astafani, R. F. Resmawati, dan M. E. Luqmanul Hakim, "Systematic review: Faktor-faktor kesulitan belajar materi kimia [Systematic review: Factors contributing to difficulties in learning chemistry material]," *Jurnal Inovasi Pendidikan Kimia,* vol. 18, no. 2, pp. 81–88 2024, doi: 10.15294/qm1ym619.
[52] M. E. Apriani, H. Huda, and S. Prasetyaningsih, "Pengembangan modul berbasis multipel representasi dengan bantuan teknologi augmented reality untuk membantu siswa memahami konsep ikatan kimia [Development of multiple representation-based modules with augmented reality technology to help students understand chemical bonding concepts]," *Jurnal IPA dan Pembelajaran IPA,* vol. 5, no. 4, pp. 305–330, 2021, doi: 10.24815/jipi.v5i4.23260.
[53] A. Priliyanti, I. W. Muderawan, and S. Maryam, "Analisis kesulitan belajar siswa dalam mempelajari kimia [Analysis of students' learning difficulties in studying chemistry]," *Jurnal Pendidikan Kimia,* vol. 5, no. 1, pp. 11–18, 2021, doi:10.23887/jjpk.v5i1.32402.
[54] S. Urrahmah, E. Tasrif, V. I. Delianti, and L. Mursyida, "Analysis of the use of augmented reality-based learning media on conceptual understanding ability," *Jurnal Vokasi Informatika,* vol. 5, no. 1, pp. 80–99, 2025, doi: 10.24036/javit.v5i1.239.
[55] S. C. Olim, V. Nisi, and T. Romão, "Augmented reality interactive experiences for multi-level chemistry understanding," *Int. J. Child-Comput. Interact,* vol. 42, 2023, 2024, doi: 10.1016/j.ijcci.2024.100681.
[56] E. Amirbekova, N. Shertayeva, and E. Mironova, "Teaching chemistry in the metaverse : the effectiveness of using virtual and augmented reality for visualization," *Front. Educ*, no. vol. 8, pp. 1–9, 2024, doi: 10.3389/feduc.2023.1184768.
[57] H. Agussalim, "The role of augmented reality in supporting deep learning within the merdeka curriculum: A systematic literature review in chemistry education," *ACCEJ,* vol. 8, no.2. pp. 772–785, 2025. doi.org/10.30862/accej.v8i2.1111
[58] N. S. Rahmadona, N. Nana, and R. Rizal, "Pengaruh model pembelajaran focus, explore, reflect, dan apply (FERA) dengan pendekatan scientific terhadap keterampilan proses sains peserta didik pada materi fluida Dinamis [The effect of the focus, explore, reflect, and apply (FERA) learning model with a scientific approach on students' science process skills in dynamic fluids material]," Spektra: *J. Pendidikan & Kajian Sains*, vol. 9, no. 2, pp. 312–323, 2023, doi: 10.32699/spektra.v9i2.349.
[59] S. Nurhalimah and R. Rizal, "Implementation of focus explore reflect apply (FERA) learning model assisted crocodile physics in improving students' critical thinking skills," *J. Ilmu Pendidik. Fisika (JIPF)*, vol. 9, no. 2, 2024, doi: 10.26737/jipf.v9i2.4771