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THE EFFECT OF AUGMENTED REALITY GAME-BASED LEARNING ON STUDENTS' CRITICAL THINKING DISPOSITION AND ACADEMIC ACHIEVEMENT

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Abstract

This study aimed to examine the effect of augmented reality game-based learning (ARGBL) on students' critical thinking disposition and academic achievement in the topic of green chemistry. The research employed a quasi-experimental method with a pretest-posttest design. The sample consisted of 72 tenth-grade students from a senior high school in Jakarta during the 2023/2024 academic year, divided into two classes: one designated as the experimental group and the other as the control group. The critical thinking disposition scale and the academic achievement test were employed to collect the data. The experimental group was taught using ARGBL, while the control group received conventional instruction. The data were analyzed using analysis of covariance (ANCOVA). The results showed that the implementation of ARGBL positively influenced students' critical thinking disposition and academic achievement. Students in the experimental group demonstrated higher scores in both critical thinking disposition and academic achievement compared to the control group. It can be concluded that ARGBL is effective in enhancing students' critical thinking disposition and academic achievement. Based on these findings, it is recommended that teachers adopt ARGBL to improve students' critical thinking disposition and academic achievement in chemistry.

Keywords – Game-based learning, Augmented reality, Critical thinking disposition, Green chemistry, Academic achievement.

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1. Introduction

The rapid advancement of digital technology has substantially increased smartphone use among students, making internet-enabled devices an integral part of their daily lives. In line with this trend, student ownership of mobile devices has grown significantly, and the use of smartphones and the internet has become ubiquitous in educational contexts (Pratama & Scarlatos, 2020). Empirical evidence indicates that students spend a considerable amount of time online, with Yakinci, Gurbuz and Yetis (2018) reporting an internet usage rate of 67.8% and an average daily use of approximately five hours. Although students access a wide range of online platforms, including social media, entertainment, gaming, and informational websites, these activities are predominantly oriented toward entertainment rather than meaningful learning experiences (Yakinci et al., 2018). This pattern highlights the need to redirect students' extensive technology use toward pedagogically meaningful purposes.

In parallel with technological developments, the framework of 21st-century skills underscores critical thinking as a core competency required for effective problem-solving and decision-making (Dwyer, Hogan & Stewart, 2014). Students with strong critical thinking dispositions are better equipped to analyze information, evaluate evidence, and respond to complex problems. However, empirical studies consistently indicate that students' critical thinking dispositions remain insufficient. In Indonesia, high school students demonstrate low levels of critical thinking, particularly in the domains of analysis and evaluation (Utami, Saputro, Ashadi, Masykuri, Probosari & Sutanto, 2018), with Sari, Karyanto and Muzzazinah (2019) reporting an overall average score of only 55% among eleventh-grade students. Similar trends have been observed internationally, as evidenced by low critical thinking dispositions among Turkish high school students (Çelik-İskifoğlu, Çerkez & İskifoğlu, 2022). These findings collectively suggest an urgent need for instructional innovations that can more effectively foster students' critical thinking dispositions.

One contributing factor to this persistent issue is the continued dominance of teacher-centered instructional practices. In Indonesia, classroom instruction remains largely teacher-centered, with teachers functioning primarily as transmitters of knowledge rather than facilitators of active learning (Maulana, Helms-Lorenz, Irnidayanti & van-de-Grift, 2016). Also, Khairuddin, Masrun, Bakhtiar and Syahruddin (2023) similarly reported the persistence of teacher-centered instruction in Indonesian junior high schools. Such teaching practices are deeply rooted in what has been described as "heritage education," in which learning is achieved mainly through observing and emulating teachers (Tweed & Lehman, 2002). Consequently, students often assume passive roles in the learning process, which may reduce engagement and hinder the development of higher-order thinking skills in science (Teppo, Soobard & Rannikmäe, 2021). In response to these challenges, this study focuses on green chemistry as a learning context with the potential to promote critical thinking. Green chemistry is included in the Indonesian high school curriculum to encourage students to consider sustainability and environmental responsibility in chemical practices (Armstrong, Rivas, Douskey & Baranger, 2018). Through green chemistry education, students are expected to build environmental awareness, develop positive attitudes toward environmental issues, and be motivated to adopt more sustainable behaviors (Chen, Jeronen & Wang, 2020; Mellor, Coish, Brooks, Gallagher, Mills, Kavanagh et al., 2018). However, achieving these goals requires instructional approaches that actively engage students and support conceptual understanding, rather than relying solely on conventional, teacher-centered methods.

Augmented reality (AR) offers promising affordances to address these instructional needs. AR is a technology that overlays virtual objects onto real-world environments, enabling students to visualize abstract or complex concepts that are difficult to comprehend through traditional instruction alone (Çetin & Türkan, 2022; Kalemkuş & Kalemkuş, 2023; Sakr & Abdullah, 2024). According to Statista (2025), the number of mobile AR users reached 983 million in 2023 and is projected to increase to 1.106 billion users by 2026. This growth reflects that mobile AR applications can effectively enhance students' understanding of scientific concepts (Abdullah, Baskaran, Mustafa, Ali & Zaini, 2022; Çetin & Türkan, 2022; Kalemkuş & Kalemkuş, 2023). By bridging physical and virtual realities, AR also facilitates meaningful interactions between real and digital elements, thereby enriching students' learning experiences (Alkhabra, Ibrahem & Alkhabra, 2023; Peikos & Sofianidis, 2024). In educational settings, AR has been shown to provide interactive and engaging learning environments that encourage active participation, problem-solving, and decision-making (Faridi, Tuli, Mantri, Singh & Gargrish, 2020; Hanggara, Qohar & Sukoriyanto, 2024).

Prior studies have highlighted the potential of AR to promote students' active engagement within inquiry-based learning environments while fostering a greater sense of autonomy (Peikos & Sofianidis, 2024). Furthermore, research suggests that AR applications are effective in increasing knowledge and motivation to learn chemistry, as they promote engagement and interest in learning activities (Liu, Ma, Yu, Wang & Xu, 2023). Despite these promising findings, limited empirical studies have been conducted on students' critical thinking disposition and achievement, particularly within the context of school chemistry and game-based learning approaches. Accordingly, this study seeks to address this gap by investigating whether AR game-based learning (ARGBL) can enhance students' critical thinking disposition and academic achievement in green chemistry. Based on existing empirical evidence, the researchers therefore hypothesize that ARGBL will enhance students' critical thinking disposition and improve their academic achievement in the topic of green chemistry.

1.1. Purposes and Research Questions

The purpose of this study is to examine the effect of ARGBL on tenth-grade students' critical thinking disposition and academic achievement in the topic of green chemistry. Based on the identified research gaps, the study seeks to answer the following questions:

- Is there a significant difference in critical thinking disposition scores between students in the experimental group, who are taught using ARGBL, and those in the control group, who are taught using conventional methods?
- Is there a significant difference in academic achievement scores between students in the experimental group, who are taught using ARGBL, and those in the control group, who are taught using conventional methods?

2. Methodology

2.1. Ethical Approval

This study was approved by the Bureau of Academic Affairs, Student Affairs, and Public Relations, Universitas Negeri Jakarta (2112/UN39.12/KM/2024). Students participated voluntarily without any coercion. All participant data and responses were kept confidential.

2.2. Research Design

This study employed a quasi-experimental design, which was used to compare two nonequivalent groups based on the treatment provided (Creswell, 2012). The research design followed a pretest-posttest nonequivalent control group design. This approach involved administering a pretest to both groups, namely the control group and the experimental group, applying the treatment exclusively to the experimental group, and subsequently administering a posttest to measure differences between the two groups. The control group did not receive the treatment and engaged in conventional learning instead (Creswell, 2012).

2.3. Participants

The sample for this study consisted of 72 tenth-grade students from a senior high school during the 2023/2024 academic year. Of the 72 participants, 36 were assigned to the experimental group (18 males and 18 females), while the remaining 36 were assigned to the control group (19 males and 17 females). The average age of the participants ranged between 17 and 19 years. The sampling technique employed was convenience sampling.

2.4. Measuring Tools

2.4.1. Critical Thinking Disposition

The Critical Thinking Disposition Scale (CTDS), adapted from Sosu (2013), was used to measure students' critical thinking disposition. The questionnaire comprised 11 items, administered both before and after the treatment. The instrument employed a 5-point Likert scale, ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"). The maximum score obtained by students was 55, while the minimum was 11. Students were allocated 15 minutes to complete both the pretest and posttest. The reliability of the instrument was calculated through a pilot test using Cronbach's alpha. The calculated α value for the CTDS was 0.869, which is categorized as high (Cohen, Manion & Morrison, 2018).

2.4.2. Academic Achievement

The Academic Achievement Test (AAT) was employed to assess students' understanding of green chemistry concepts. The AAT consisted of 15 multiple-choice questions, each with five options. The maximum score achievable by students was 15, while the minimum score was 0. In this study, the α value for the AAT was 0.840, which is also categorized as high (Cohen et al., 2018).

2.5. Procedure

The advancement of AR media in chemistry education necessitates the use of three-dimensional modeling tools and interactive application development platforms. Autodesk Maya is employed in the initial phases to create intricate and scientific chemical molecular models, considering geometric structures, interatomic connections, and visual attributes such as textures and lighting that accurately reflect the original molecular form (see Figure 1). Accurate 3D visual representations of virtual items in augmented reality are generated by modeling, texturing, and rendering procedures. The modeling results are subsequently loaded into Unity, which functions as a development platform for augmented reality applications. Unity employs software development kits (SDKs) like Vuforia to link virtual objects with the physical environment via device cameras, facilitating dynamic interactions. Moreover, Unity enables user interface configurations, interactive control mechanisms, and performance enhancement, allowing applications to operate responsively across diverse platforms. The integration of Autodesk Maya and Unity produces immersive and interactive augmented reality learning material, enabling students to view molecular structures within their environment, thereby augmenting conceptual comprehension, learning motivation, and providing a more profound cognitive experience.

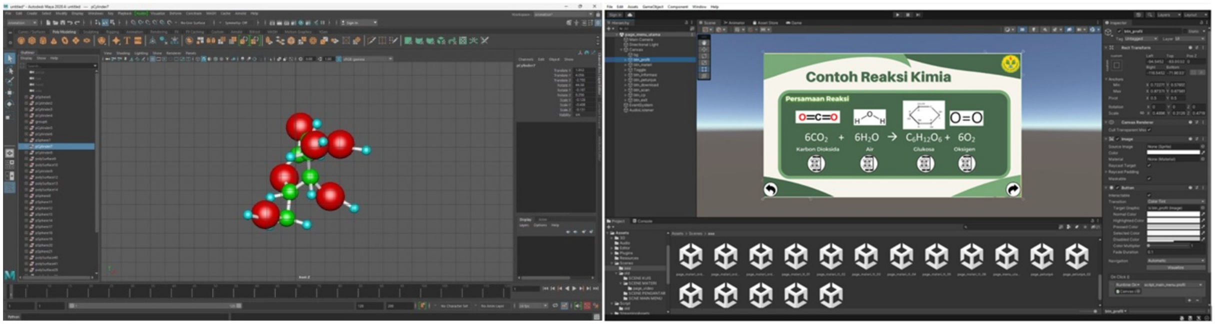

Figure 1. The development of the AR app

This study was conducted using a two-group procedure, with each group receiving a pretest and posttest. The experimental group was provided with AR media, while the control group employed conventional learning methods. The experimental class was divided into six groups to utilize augmented reality. The study was carried out over four sessions, with each session lasting 90 minutes. External variables were controlled through several procedural steps to ensure the validity of the results. Both the experimental and control groups were taught the same instructional content, followed the same curriculum objectives, and were allocated an equal amount of instructional time. The lessons were delivered by the same chemistry teacher to minimize teacher-related variability, including differences in teaching style, classroom management, and instructional quality.

Before the treatment, both classes were administered a pretest. Subsequently, the experimental group received the AR media, whereas the control group followed conventional teaching methods. After the treatment, both classes were given a posttest to measure differences in outcomes before and after the intervention (see Figure 2).

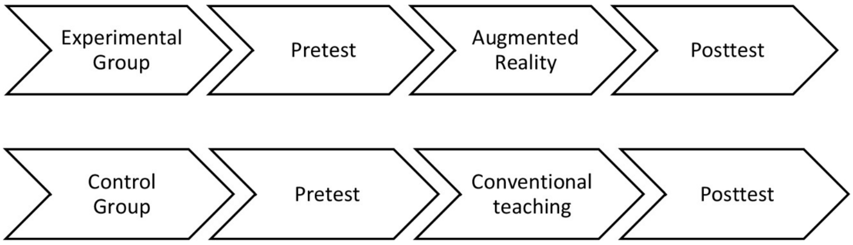

Figure 2. Research procedure in the present study

In the experimental group, students engaged in learning using ARGBL. Students were divided into six groups to conduct the learning process. At the beginning of the intervention, students were presented with thought-provoking questions to capture their attention and focus, such as "*What comes to your mind when you hear the term 'go green'?*", "*What is meant by green chemistry?*", and "*How do natural disasters caused by environmental pollution affect community activities?*" Subsequently, students were given a contextual reading describing the preservation of fish by fishermen in Indonesia using ice and salt to prevent rapid spoilage. They were then asked the question, "*Why do fish stored in a container with ice and salt last longer?*" Afterward, the teacher provided students with opportunities to ask questions that stimulated their curiosity.

In the next stage, students were instructed to study green chemistry materials available within the AR application (see Figures 3-4). During this phase, students also engaged in small-group discussions on the green chemistry topic. The teacher monitored and facilitated the learning process by addressing any issues or misconceptions related to conceptual understanding as well as difficulties in using the AR application. Students were also required to complete quizzes embedded in the AR application. Subsequently, students, working in small groups of five to six members, were required to solve problems presented in the student worksheets provided by the teacher. Finally, students were assigned to present the results of their small-group discussions based on the completed worksheets. The teacher provided feedback on the explanations and presentations delivered by the students.

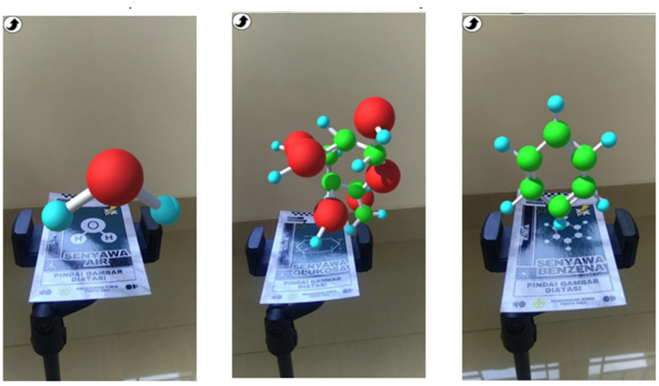

Figure 3. AR markers

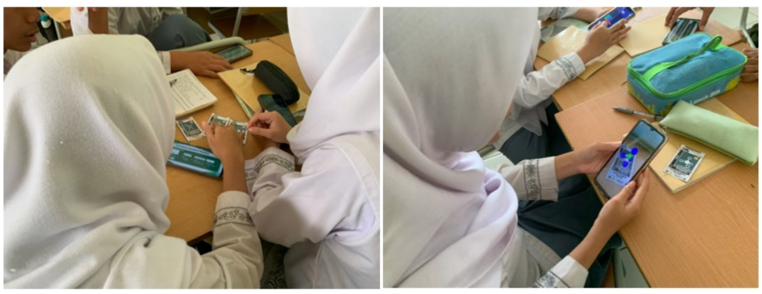

Figure 4. Students using AR applications

In the control group, students engaged in learning through conventional teaching using lecture and interactive discussion methods. Students received instruction on green chemistry delivered by the teacher, followed by a discussion between students and the teacher regarding the material studied.

2.6. Data Analysis

The data were analyzed using descriptive and inferential statistical methods with SPSS Version 27. Descriptive statistics were applied to examine the mean differences and standard deviations for each group across the dependent variables. To compare post-test scores between the experimental group (EG) and the control group (CG), an analysis of covariance (ANCOVA) was conducted, with pre-test scores treated as a covariate to control for initial group differences and to more accurately estimate the effect of the intervention, as recommended by Howell (2012). Before performing the ANCOVA, several assumptions were tested. The normality of post-test score distributions was verified using the Kolmogorov–Smirnov test, with results indicating normal distributions within each group ($p > 0.05$). Homogeneity of variances was assessed through Levene's test, which produced non-significant results ($p > 0.05$), confirming that the assumption of equal variances was met and that ANCOVA was appropriate for the analysis. Effect sizes were calculated using partial eta-squared (η^2) and interpreted based on Cohen's (1988) criteria for small (0.01), moderate (0.06), and large (0.14) effects. A significance level of 0.05 was set, consistent with common practice in educational research.

3. Results

3.1. Critical Thinking Disposition

Descriptive statistical analysis was employed to compare the pre-test and post-test results of critical thinking disposition between the EG and the CG. The results are presented in Table 1.

	Pre-test		Post-test		
Groups	**M**	**SD**	**M**	**SD**	**Mean Gain**
EG	3.716	0.519	4.266	0.443	0.550
CG	3.541	0.374	3.762	0.418	0.221

Table 1. Descriptive statistics of pre- and post-test critical thinking disposition scores

According to Table 1, the mean critical thinking disposition scores in both the EG and CG exhibited an increase from the pretest to the posttest. The EG, which received instruction through ARGBL, demonstrated a substantial increase in mean scores from 3.716 ($SD = 0.519$) in the pre-test to 4.266 ($SD = 0.443$) in the post-test, yielding a mean gain of 0.550. This improvement suggests that the ARGBL intervention was effective in fostering students' disposition toward critical thinking. In contrast, the CG exhibited a more modest increase, with mean scores rising from 3.541 ($SD = 0.374$) to 3.762 ($SD = 0.418$), resulting in a mean gain of 0.221.

An ANCOVA was employed to examine whether a statistically significant difference existed in the mean scores between the CG and the EG. This analysis was conducted to assess the effect of ARGBL on students' critical thinking disposition. A comparison of the pretest mean scores for critical thinking disposition between the EG and CG is presented in Table 2.

A statistically significant difference was observed in students' mean critical thinking disposition between those taught using ARGBL and those receiving conventional instruction ($F = 21.007$, $p < 0.001$; see Table 2). The effect size, as indicated by partial eta squared ($\eta^2 = 0.233$), reflects a strong impact of ARGBL on enhancing the critical thinking disposition of students in the EG compared with the CG. In addition, the instructional approach accounted for approximately 40% of the variance in critical thinking disposition related to the green chemistry topic ($R^2 = 0.402$).

Source	Type III Sum of Squares	df	Mean Square	F	p-value	Partial Eta Squared
Corrected Model	7.050[a]	2	3.525	23.145	<0.001	0.402
Intercept	6.707	1	6.707	44.036	<0.001	0.390
Pre-test	2.495	1	2.495	16.381	<0.001	0.192
Group	3.199	1	3.199	21.007	<0.001	0.233
Error	10.509	69	0.152			
Total	1177.653	72				
Corrected Total	17.559	71				

Note. [a]R Squared = .402 (Adjusted R Squared = .384)

Table 2. ANCOVA results for critical thinking disposition

3.2. Academic Achievement

A descriptive statistical analysis was conducted to compare the pre-test and post-test academic achievement results of the EG and the CG, as presented in Table 3.

Groups	Pre-test		Post-test		Mean Gain
	M	SD	M	SD	
EG	0.567	0.922	0.761	0.108	0.194
CG	0.494	0.107	0.574	0.104	0.080

Table 3. Descriptive statistics of pre- and post-test achievement scores

Prior to the intervention, the EG recorded a mean pre-test score of 0.567 (SD = 0.922), which increased substantially to a mean post-test score of 0.761 (SD = 0.108). This improvement is reflected in a moderate mean gain of 0.194, suggesting that ARGBL had a meaningful positive effect on students' academic performance. In contrast, the CG showed a smaller increase in achievement, with the mean score rising from 0.494 (SD = 0.107) in the pre-test to 0.574 (SD = 0.104) in the post-test, resulting in a relatively low mean gain of 0.080.

An ANCOVA was employed to examine whether a statistically significant difference existed in the mean academic achievement scores between the EG and CG. This analysis was conducted to evaluate the effect of ARGBL on students' academic achievement. Before the treatment, both groups completed a pretest. The comparison of the mean pretest scores of the EG and CG, as measured by the academic achievement test, is presented in Table 4.

Source	Type III Sum of Squares	df	Mean Square	F	p-value	Partial Eta Squared
Corrected Model	0.632[a]	2	0.316	27.762	<0.001	0.446
Intercept	0.974	1	0.974	85.587	<0.001	0.554
Pre-test	0.002	1	0.002	0.216	0.644	0.003
Group	0.530	1	0.530	46.573	<0.001	0.403
Error	0.730	69	0.011			
Total	33.507	72				
Corrected Total	1.418	71				

Note. [a]R Squared = .446 (Adjusted R Squared = .430)

Table 4. ANCOVA results for academic achievement

As presented in Table 5, the analysis revealed a statistically significant difference in students' mean achievement between those taught using the ARGBL approach and those receiving conventional instruction ($F = 46.573$, $p < 0.001$). The partial eta squared value ($\eta^2 = 0.403$) indicates a strong effect size, demonstrating that ARGBL substantially enhanced the academic achievement of students in the EG compared to the CG. Furthermore, the instructional approach accounted for 44.6% of the variance in students' achievement in the topic of green chemistry ($R^2 = 0.446$).

4. Discussion

The primary objective of this study was to examine the effect of ARGBL on tenth-grade students' critical thinking disposition in green chemistry. The results of the ANCOVA revealed a statistically significant difference between the experimental and control groups. Although both groups demonstrated improvements in critical thinking disposition after the intervention, the EG exhibited a significantly greater increase compared to the CG. These findings indicate that ARGBL is effective in enhancing students' critical thinking disposition. The EG also demonstrated a notably high effect size, suggesting that the ARGBL had a strong impact on students' critical thinking disposition. This finding may be explained by the interactive features and 3D visualizations afforded by AR, which allow students to explore chemical concepts more easily (Faridi et al., 2020). Another possible reason may be attributed to the immersive and engaging nature of AR learning environments, which capture students' attention and encourage active cognitive engagement during the learning process (Dutta, Mantri, Singh & Singh, 2023; Hanggara et al., 2024). The results are consistent with previous studies reporting positive effects of AR-based learning on critical thinking (Alkhabra et al., 2023; Dutta et al., 2023; Faridi et al., 2020; Hanggara et al., 2024).

AR-based learning supports students in accessing and processing information more effectively, particularly by visualizing abstract chemical concepts that are otherwise difficult to grasp (Alkhabra et al., 2023; Faridi et al., 2020). AR also provides richer learning experiences by allowing students to interact directly with virtual objects, thereby fostering higher-order thinking processes (Alkhabra et al., 2023). Within AR-supported learning environments, students are actively involved in problem-solving, analysis, and exploration of green chemistry concepts, which contributes to the development of critical thinking (Hanggara et al., 2024). The integration of real and virtual elements encourages students to engage more deeply with learning content, reinforcing the effectiveness of AR in promoting critical thinking dispositions, as demonstrated in this study. Moreover, AR-based learning facilitates interactive learning experiences that encourage data analysis and reflection, which are essential components of critical thinking (Hanggara et al., 2024). Classroom observations revealed that students in the experimental group exhibited high levels of enthusiasm and engagement, supporting previous findings that AR applications offer flexibility and accessibility for learning anytime and anywhere through smartphone use (Dutta et al., 2023). Consequently, AR creates a more interactive and learner-centered environment.

In addition to critical thinking dispositions, this study also investigated the effect of ARGBL on students' academic achievement in green chemistry. The results of the ANCOVA indicated a statistically significant difference between the two groups, with the EG achieving higher academic performance. These findings confirm that AR technology positively influences students' academic achievement in green chemistry. The higher academic achievement observed in the experimental class may be attributed to the use of 3D models that allow students to directly observe and manipulate abstract concepts rather than relying solely on mental visualization (Çetin & Türkan, 2022). Supporting this explanation, Cetintav and Yilmaz (2023) and Chen, Zhou, Wang, Oubibi and Li (2025) reported that AR technology enhances academic performance by increasing active participation and engagement in learning activities. This result is supported by existing literature demonstrating the effectiveness of AR in improving academic achievement (Abdullah et al., 2022; Çetin & Türkan, 2022; Kalemkuş & Kalemkuş, 2023). For instance, Sokmen, Sarikaya and Nalçacı (2023) and Kalemkuş and Kalemkuş (2023) reported that students exposed to AR-based learning outperformed those in conventional settings. Although Gün and Atasoy (2017) found no significant differences, such inconsistencies may be explained by variations in age, context, and students' characteristics.

Chemistry learning often involves abstract and complex concepts that pose challenges for students. As noted by Rahmawati, Dianhar and Arifin (2021), students frequently perceive chemistry as requiring advanced visualization. In this study, AR technology therefore helped transform abstract green chemistry concepts into more concrete and observable representations, thereby facilitating comprehension and contributing to improved academic achievement. AR also enhances students' interest, attention, and active participation during learning, as supported by findings from Ciloglu and Ustun (2023). Additionally, AR enables teachers to observe student interactions more closely and promote responsibility and accountability in learning activities (Sakr & Abdullah, 2024). The integration of AR technology into school curricula supports the development of interactive classrooms that enhance both academic achievement and student participation (Abdullah et al., 2022). AR-based applications stimulate students' curiosity, increase interest in challenging subjects such as chemistry, and provide meaningful learning experiences that are difficult to achieve through conventional instruction alone (Çetin & Türkan, 2022). These findings are consistent with Sakr and Abdullah (2024), who reported that AR can enhance motivation and focus while addressing limitations of traditional teaching methods.

In the context of widespread smartphone use among students, AR-based learning offers flexibility and accessibility, allowing students to learn at their own pace and according to their individual learning styles using devices they already own (Ferrari, Teijón & Ruiz, 2024). From a pedagogical perspective, the findings highlight the substantial potential of AR technology to enhance chemistry instruction when integrated strategically into classroom practice. Teachers can utilize AR as a visualization tool to explain abstract and submicroscopic chemical concepts that are difficult to convey through conventional instructional media such as textbooks or PowerPoint presentations. By bridging the gap between macroscopic phenomena and microscopic chemical processes, AR supports conceptual understanding while reducing cognitive load during instruction (Şimşek, Direkci, Koparan, Canbulat, Gülmez & Nalçacıgil, 2025). Moreover, AR facilitates exploratory and discovery learning by allowing students to interact with virtual objects, analyze visual representations, and construct knowledge (Liu et al., 2023). Such learning environments encourage students to generate ideas, question assumptions, and critically examine environmental issues related to green chemistry, thereby fostering critical and creative thinking skills (Chen et al., 2025).

5. Conclusions

Based on the research findings, it can be concluded that ARGBL has a positive impact on both the critical thinking disposition and academic achievement of grade 10 students in the context of green chemistry. Students in the experimental group demonstrated significant improvements in critical thinking disposition and academic achievement from pre-intervention to post-intervention following the implementation of ARGBL. The use of AR applications provides an interactive and engaging learning environment by actively involving students in the learning process. Through realistic three-dimensional visualizations, particularly at the submicroscopic level, AR enables students to learn green chemistry concepts in greater depth. This interactive learning experience supports students in generating new ideas, thinking critically, and developing a deeper conceptual understanding of green chemistry. These findings underscore the substantial potential of AR technology in chemistry education. By shifting the instructional focus from teacher-centered to student-centered, teachers can use AR applications to promote active student participation and higher-order thinking. In general, AR-supported instruction represents an effective pedagogical approach for enhancing both academic achievement and critical thinking disposition in green chemistry learning.

6. Limitation and Suggestions

The present study examined the impact of ARGBL on students' learning outcomes in green chemistry. While the findings demonstrate positive effects, several limitations should be acknowledged. First, the study was conducted within a relatively short intervention period. Future research is therefore encouraged to employ longitudinal designs to examine the persistence and development of students' critical thinking disposition and academic achievement over extended periods. In addition, this study focused exclusively on the green chemistry topic. Future investigations could apply ARGBL to other chemistry topics or different science disciplines. Comparative studies examining the effectiveness of AR-based learning in relation to other emerging educational technologies, such as virtual reality (VR), mixed reality (MR), simulations, or adaptive learning platforms, would also provide valuable information. Such studies would contribute to a more comprehensive understanding of the conditions and pedagogical contexts in which emerging educational technologies can be most effectively implemented to enhance students' critical thinking disposition and achievement. Another limitation concerns the use of self-administered questionnaires as the primary data collection instrument, which may introduce self-report bias and potentially affect response accuracy. To address this issue, future studies are recommended to adopt mixed-methods approaches by incorporating qualitative data sources, such as interviews, classroom observations, and think-aloud protocols. The integration of these methods could strengthen the validity of the findings and provide a more comprehensive understanding of students' learning processes and experiences in AR-supported environments.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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