



Research article

Fostering students' digital literacy and academic achievement using augmented reality-enriched inquiry learning

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Abstract: Despite the increasing use of Augmented Reality (AR) in education, there remains a gap regarding its impact on digital literacy and academic achievement in secondary school chemistry, particularly in the context of global warming. This study examined the effect of AR-enriched Questioning-Investigating-Making-Synthesising (QIMS) inquiry learning on the digital literacy and academic achievement of tenth-grade students in chemistry. A total of 72 students (37 males and 35 females) participated in the study, which employed a quantitative approach with a quasi-experimental design. Two intact classes from a public high school in Jakarta during the 2023/2024 academic year were assigned as the experimental and control groups. Data were collected using a digital literacy scale and an academic achievement test and were analyzed using an analysis of covariance (ANCOVA). The findings revealed that students in the experimental group who were taught using AR demonstrated significantly higher levels of digital literacy and academic achievement compared to those in the control group who received instruction without AR. These results suggest that AR-based learning has a meaningful impact on students' learning outcomes on the topic of global warming. The study highlights the potential of AR-enriched QIMS inquiry learning as an effective teaching method to enhance a student's performance in chemistry education.

Keywords: augmented reality, digital literacy, academic achievement, chemistry, inquiry learning

1. Introduction

In the 21st century, the role of technology in daily life has substantially increased over the past few decades [1–3]. The use of modern digital devices, particularly smartphones, continues to grow each year. As of 2023, the total number of smartphone users worldwide reached 7.33 billion, representing approximately 90% of the global population [4]. In Indonesia, Statista [5] reported that the number of smartphone users exceeded 190 million in 2023. This widespread digitalization has not only transformed communication and social interaction but has also significantly reshaped teaching and learning processes across educational contexts [6–8]. The integration of technology into educational practices has been shown to enhance learning experiences and increase student engagement [9–11], primarily because technology-based learning offers flexibility in accessing information anytime and anywhere [12,13].

The growing presence of digital technology in education is closely linked to the development of digital literacy, which plays a critical role in determining the quality of technology use as a learning support tool [14]. Despite its importance, several studies indicate that students' digital literacy remains inadequate and requires further improvement [15]. Consequently, the effective implementation of digital literacy to enhance the learning quality remains a persistent challenge in contemporary education [16]. Digital literacy extends beyond basic technical skills; it encompasses the ability to critically interpret, evaluate, create, and share information in digital environments [17]. In the current technological era, traditional reading and writing skills are no longer sufficient for meaningful participation in society, as individuals must also be able to navigate complex digital information landscapes [17]. This issue is particularly concerning in Indonesia, where the 2022 PISA report revealed that Indonesian students' performance and literacy levels remain among the lowest globally, ranking 75th out of 81 countries [18].

Insufficient digital literacy has broader implications for a student's learning and cognitive development. Research suggests that a student's digital literacy influences their digital competence, digital self-efficacy, learning engagement, and learning performance [3,19]. However, many students remain vulnerable to digital misinformation and often struggle to critically evaluate online content [20,21], largely due to limited digital literacy skills. As a result, students require more comprehensive digital competencies to avoid misconceptions and misinformation [22]. Additionally, low levels of digital literacy have been associated with weaker communication skills, problem-solving abilities, critical thinking, and decision-making capacities [23]. Therefore, strengthening digital literacy necessitates more opportunities for students to practice digital skills within authentic learning environments, supported by appropriate technological tools [24].

In addition, instructional approaches in science education, particularly in chemistry, used in Indonesia remain largely teacher-centered [25,26]. This may hinder a student's conceptual understanding and academic performance. In many learning contexts, visual-spatial understanding heavily depends on images or verbal explanations provided by teachers rather than interactive learning experiences [27]. Teacher-centered instructional beliefs continue to dominate science classrooms [28], including chemistry education, where teachers often serve as the primary source of knowledge while students assume passive roles. However, contemporary educational paradigms emphasize the need to integrate interactive, technology-enhanced learning models that actively engage students in knowledge construction [29,30]. Accordingly, leveraging digital technologies is considered essential to address existing weaknesses in chemistry instruction and improve both

academic achievement and digital literacy [31–33].

One promising technology to enhance science learning is Augmented Reality (AR). AR provides an innovative, cost-effective, and engaging learning environment that bridges the gap between physical and virtual experiences [34–36]. It is widely recognized as a transformative tool that enables real-time visual representation and allows students to interact with real-world environments through more immersive experiences [27,34,37]. AR facilitates creative learning by overlaying virtual objects onto real-world environments, thereby generating immersive mixed-reality experiences [38–40]. By integrating 3D visual representations with real-world contexts, AR can enhance a student's conceptual understanding in meaningful ways [41,42]. Furthermore, AR supports flexible and self-paced learning, as students can access digital content anytime and anywhere [33,37].

Chemistry, as a discipline, is inherently complex and often perceived as difficult by students [43]. Many chemical concepts are abstract and invisible at the macroscopic level, making them challenging to comprehend solely through traditional instructional methods [44]. This situation highlights the need to shift from predominantly abstract, lecture-based teaching toward more technologically enriched instructional approaches [45–47]. Integrating 3D visualization into chemistry education has been shown to improve a student's conceptual understanding and learning outcome [46], thus reinforcing the potential value of AR as a pedagogical tool in this field.

In the Indonesian secondary school curriculum, global warming is included as a key topic within chemistry education. However, prior research indicates that many students possess limited understanding and hold misconceptions about global warming and related phenomena [48,49]. Moreover, Kurup et al. [50] found that school curricula have not yet sufficiently integrated socio-scientific issues, despite their relevance to students' real-world experiences. Topics such as global warming, climate change, and the greenhouse effect require a strong foundation in scientific principles [51], yet students often struggle to connect these concepts to underlying chemical processes [52]. The lack of effective instructional strategies for teaching global warming may contribute to low environmental awareness and responsibility among students. Consequently, incorporating advanced visualization tools such as AR into global warming instruction may offer a more effective approach to enhancing a student's conceptual understanding and engagement [2,11,53].

1.1. Purpose and research questions

Despite a growing body of research on the use of AR in education [27,30,54], an empirical gap remains regarding its impact on digital literacy and academic achievement in chemistry, particularly in relation to the topic of global warming at the secondary school level. Although AR has been increasingly integrated into educational settings, relatively few studies have examined how AR-based learning shapes students' digital literacy and their academic achievement in chemistry topics. Moreover, existing empirical evidence has largely been confined to either elementary education [40,55] or university contexts [32,56]. In this context, and in light of students' rapidly expanding use of digital technologies alongside persistent challenges in both digital literacy and chemistry learning, this study investigates the role of AR as an instructional tool in teaching the topic of global warming. Evidence regarding AR implementation in environmental chemistry topics, particularly global warming, also remains limited. Global warming is an important environmental issue because it requires students to understand molecular processes, interpret environmental data, and evaluate

socioscientific issues that connect chemical concepts to real-world problems. Then, given the low level of students' digital literacy and conceptual understanding, we examine whether AR-enriched Questioning-Investigating-Making-Synthesising (QIMS) inquiry learning can foster students' digital literacy and improve their academic achievement related to global warming. Accordingly, this study addresses the following research questions (RQs):

RQ1. What is the effect of AR-enriched QIMS inquiry learning on students' digital literacy on the topic of global warming?

RQ2. What is the effect of AR-enriched QIMS inquiry learning on students' academic achievement on the topic of global warming?

In this study, AR-enriched QIMS inquiry learning serves as the independent variable, while the students' digital literacy and academic achievement are treated as the dependent variables. This study is grounded in the Cognitive Theory of Multimedia Learning [57], Cognitive Load Theory [58], and the Digital Literacy Framework [59]. According to the multimedia learning theory [57], students learn more effectively when verbal and visual information, including text, images, and audio, are integrated. AR provides interactive three-dimensional representations that can make invisible chemical phenomena more observable and understandable. Within the QIMS inquiry learning [60], students actively participate in a series of AR-based learning activities by formulating questions related to global warming (Questioning), exploring and reflecting on scientific phenomena through AR simulations (Investigating), applying their acquired knowledge in new contexts by creating artefacts (Making), and presenting their artefacts to communicate conclusions while consolidating their understanding of the learned concepts (Synthesising). AR-supported visualizations are expected to facilitate conceptual understanding by enabling students to explore chemistry from multiple perspectives. Participation in digital inquiry activities may also foster the technical, cognitive, and socio-emotional dimensions of digital literacy [59]. Technical literacy is developed through interaction with digital devices and applications, cognitive literacy through digital information evaluation and problem solving, and socio-emotional literacy through digital communication and responsible technology use. This study contributes to the literature by exploring how a student's engagement in an AR-supported QIMS inquiry learning environment is associated with their digital literacy and academic achievement in chemistry. While earlier studies examined AR as a tool to enhance conceptual understanding and engagement in science learning [2,11,47,53], the present study integrates the Cognitive Theory of Multimedia Learning [57], Cognitive Load Theory [58], and the Digital Literacy Framework [59] to explain how AR-enriched inquiry-based learning can affect the students' academic achievement and digital literacy. Accordingly, we hypothesize that AR-enriched QIMS inquiry learning will improve digital literacy and lead to higher academic achievement compared to conventional teaching.

2. Methodology

2.1. Research design

This study employed a quasi-experimental method to examine the effects of AR-enriched QIMS inquiry learning on tenth-grade students' digital literacy and academic achievement using a pre-test–post-test non-equivalent control group design [61]. In this design, two intact classes were

selected and assigned as the experimental and control groups. Both groups undertook a pre-test to establish their baseline levels before the intervention. Prior to the treatment, students in both groups had comparable access to digital devices and internet connectivity required for instructional activities. None of the participants had previously used AR applications in chemistry learning. Subsequently, the experimental group received instruction which integrated AR, whereas the control group was taught using the same instructional model without AR integration. Upon completion of the intervention, both groups completed a post-test to examine differences in digital literacy and academic achievement between the two groups following the intervention [61].

2.2. Participants

A total of seventy-two students (37 males and 35 females), aged between 13 and 16 years, participated in this study. They were enrolled in a public senior high school in Jakarta, located in the central region of Indonesia. The study was conducted during the second semester of the 2023/2024 academic year. The participating school was selected through convenience sampling, and two intact classes within the school were assigned to the experimental group ($n = 36$; 18 males and 18 females) and the control group ($n = 36$; 19 males and 17 females). To minimize potential instructional bias, both groups were taught by the same teacher throughout the study. All participants voluntarily took part in the research, and no personal data were disclosed. All data were confidentially treated and solely used for research purposes. Ethical approval for the study was obtained from Jakarta State University [8470/UNJ39.12/KM/2024].

Prior to data collection, an a priori power analysis was performed using G*Power 3.1.9.7 [62] to determine the minimum required sample size. For the analysis of covariance (ANCOVA), which involved one covariate and two groups, the parameters were set at $f = 0.40$ to detect a large effect size based on the previous research, $\alpha = 0.05$, and statistical power = 0.80. The analysis indicated that a minimum of 52 participants was required, confirming that the sample size of 72 students was adequate for the study.

2.3. Instruments

2.3.1. Digital literacy

The students' digital literacy was assessed using the self-reported Digital Literacy Scale (DLS). The instrument was originally adapted from Ng [59] and subsequently translated into Indonesian by the researchers. The DLS used in this study was comprised of 10 statements which covered three dimensions of digital literacy: technical (6 statements), cognitive (2 statements), and socio-emotional (2 statements). Example items included the following: "*I can learn new technologies easily*" (technical), "*I am confident with my search and evaluate skills in regards to obtaining information from the web*" (cognitive), and "*ICT enables me to collaborate better with my peers on project work and other learning activities*" (socio-emotional). The responses were recorded using a five-point Likert scale ranging from 5 (strongly agree) to 1 (strongly disagree), yielding a possible total score between 10 and 50. The students were allocated 15 minutes to complete the questionnaire. Subsequently, several statements were contextualized to reflect chemistry learning and digital learning environments involving AR technology. The adapted instrument was evaluated by three lecturers in chemistry education and two chemistry teachers for content relevance, clarity, and

cultural appropriateness. A pilot study that involved 36 students was conducted to assess the item clarity, reliability, and construct appropriateness. Minor wording revisions were implemented based on the participant's feedback prior to the main study. Following translation, expert review, and pilot testing, all items were deemed valid and retained for the main study. The internal consistency of the scale was high, as indicated by a Cronbach's alpha coefficient of 0.89.

2.3.2. Academic achievement

The Academic Achievement Test (AAT) was developed to assess the students' understanding of the global warming topic covered during the instruction. The test consisted of 15 multiple-choice questions, each with five response options, with one point awarded for each correct answer and zero for incorrect responses. The students were given 30 minutes to complete the test. The items were constructed based on senior high school chemistry textbooks and chemistry examination questions, thus ensuring alignment with the curriculum. The content of the test represented the learning objectives addressed in the instructional unit, including environmental changes resulting from climate change, the causes of the greenhouse effect, strategies to address environmental problems, and the balancing of chemical equations. The inclusion of balancing chemical equations was justified because students were required to interpret and represent chemical reactions associated with greenhouse gas formation and atmospheric chemistry processes. The items were designed to assess different cognitive levels based on the revised Bloom's taxonomy, including understanding (10 items), applying (4 items), and analyzing (1 item). The reliability of the AAT was confirmed with a Cronbach's alpha coefficient of 0.84, indicating a high level of internal consistency. Preliminary testing of the instrument on 36 tenth-grade students demonstrated acceptable psychometric properties, with item difficulty indices ranging from 0.50 to 0.67 and discrimination indices ranging from 0.67 to 1.00. The pre-test and post-test employed the same set of items to ensure consistency in measuring the students' academic achievement. To minimize potential recall effects, the order of the questions and the sequence of answer options were rearranged in the post-test.

2.4. Procedures

The study was conducted after obtaining formal approval, assigning the participants to the experimental and control groups, and developing the required learning materials. To ensure procedural fidelity and instructional equivalence between the experimental and control groups, a lesson plan was developed prior to the intervention. Both groups participated in four instructional sessions of equal duration (90 minutes per session) and followed the same sequence of learning activities. At the outset, a pre-test was administered to both groups to assess the students' digital literacy and academic achievement. Then, each class was organized into six groups consisting of six students each. Subsequently, the two groups received different instructional treatments: the experimental group was taught using AR, whereas the control group received instruction without AR. However, both groups followed the same pedagogical approach, namely inquiry-based learning using the QIMS framework [60], and covered the same topic (i.e., global warming). Moreover, to ensure instructional equivalence, all students were taught by the same teacher and received identical learning objectives, worksheets, and instructional durations. During the investigation stage, the teacher provided equivalent guidance regarding chemical principles and global warming phenomena

for both groups. The primary difference between the groups was the learning medium used to access and explore instructional content. In this case, the experimental group utilized AR, whereas the control group used educational videos from YouTube. At the end of the intervention, a post-test was administered to both groups to measure changes in the students' academic achievement and digital literacy.

2.4.1. Treatment in the experimental group

The students in the experimental group engaged in inquiry-based chemistry learning on the topic of global warming through the QIMS framework. In the *Questioning* stage, the teacher presented a phenomenon in the students' worksheet, such as rising sea levels as a consequence of global warming. The students were encouraged to formulate questions that reflected their curiosity. Then, they were prompted to consider the following: (i) what factors contribute to rising sea levels, (ii) which human activities may contribute to this phenomenon, and (iii) how their responses relate to relevant chemical concepts. During the *Investigating* stage, the students independently explored global warming phenomena using an AR application, which allowed them to visualize and analyze environmental processes more interactively and develop a deeper conceptual understanding. The intervention employed a marker-based augmented reality application named AR-Global Warming, which was specifically developed by the researchers for this study. The application operated offline on Android smartphones and was installed on the students' devices before the intervention. The AR application included several interactive features, such as three-dimensional molecular models, animations of greenhouse gas interactions, explanatory text, and embedded quizzes. The students could manipulate the molecular structures by rotating, zooming, and examining the molecules from different perspectives. These visual representations helped the students understand abstract microscopic processes that are difficult to observe through conventional instructional materials.

The intervention utilized a marker-based augmented reality application developed for chemistry learning and operated on Android smartphones. The students individually explored AR visualizations illustrating greenhouse gas emissions, atmospheric interactions, global temperature increases, and environmental consequences associated with climate change. Each AR session lasted approximately 35 minutes. After that, the students were presented with a second discourse on greenhouse gas emissions and asked how technology could be used to monitor and reduce such emissions, including examples of practical solutions. They subsequently completed the tasks provided in their worksheets. In the *Making* stage, the students worked collaboratively in small groups to design a campaign poster aimed at encouraging others to take action against global warming. This activity was novel to most students and prompted them to investigate the processes involved in creating digital content, such as blogs or visual media. Finally, in the *Synthesizing* stage, each group presented its poster to the class and was encouraged to demonstrate creativity in both the content and the delivery. Meanwhile, other students were expected to provide constructive feedback on each group's presentation.



Figure 1. Screenshot of augmented reality.



Figure 2. Students' activity using the AR app in the experimental group.

2.4.2. Treatment in the control group

The students in the control group studied the same topic using the same QIMS inquiry-based learning framework, but without the integration of AR technology. In the *Questioning* stage, the teacher stimulated the students' thinking by presenting a video related to global environmental issues. The students accessed learning content through educational videos from YouTube (<https://www.youtube.com/>) that covered the same concepts and learning objectives as their peers in the experimental group. Then, they were invited to respond to the issues raised and encouraged to pose their own questions. During the *Investigating* stage, the students identified key learning points by exploring information related to global warming. Relevant information was provided by the teacher, and the students were also permitted to conduct additional research using the Internet. The teacher facilitated discussion by allowing the students to ask questions and express their opinions on the topics presented. In the *Making* stage, the students worked in their groups to discuss the guiding questions and collaboratively produce a written piece using a digital platform. In the *Synthesizing* stage, the groups presented their work to the class. The teacher guided the students in summarizing and drawing conclusions from the material covered during the lesson.

2.5. Data analysis

Data were processed and analyzed using IBM SPSS, version 25.0, with the level of statistical significance set at $\alpha = 0.05$. Descriptive statistics, including means and standard deviations, were first computed to summarize students' performance on each dependent variable for both groups. Given the nature of the data, a parametric statistical analysis was employed, specifically an ANCOVA, to compare post-test mean scores between the experimental group (EG) and the control group (CG), while controlling for any pre-existing differences. In this model, the pre-test scores were

entered as a covariate to statistically adjust for baseline disparities between groups, thus ensuring that any observed post-test differences could be more confidently attributed to the instructional intervention rather than to initial variations in the students' prior knowledge. The independent variable was group (experimental vs. control), and the dependent variable was the post-test score. For all analyses, the statistical significance ($p < 0.05$), effect size (η^2), and descriptive statistics were reported. It should be noted that no participant attrition occurred during the study, and no missing data were identified. Assumptions of the ANCOVA were evaluated using residual analyses.

3. Results

3.1. Digital literacy

Table 1 shows that both groups had comparable levels of digital literacy at the pre-test, with mean scores of 25.50 ($SD = 3.64$) for the EG and 25.31 ($SD = 2.89$) for the CG. At the post-test, the EG achieved a higher mean score ($M = 42.56$, $SD = 4.19$) than the CG ($M = 33.22$, $SD = 3.64$), yielding a mean difference of 9.34 points. Correspondingly, the EG demonstrated a greater mean gain in digital literacy ($M = 17.06$, $SD = 6.32$) compared to the CG ($M = 7.92$, $SD = 4.50$), indicating more substantial improvement following the intervention. Given the possibility of pre-existing differences in digital literacy among participants, an ANCOVA was conducted to control for initial variations.

Table 1. Differences in digital literacy between EG and CG.

Group	Pre-test		Post-test		Gain	
	M	SD	M	SD	M	SD
EG	25.50	3.64	42.56	4.19	17.06	6.32
CG	25.31	2.89	33.22	3.64	7.92	4.50

Prior to performing the ANCOVA, its underlying assumptions were examined. The assumption of homogeneity of regression slopes was met, as indicated by the non-significant interaction between the educational group and the pre-test digital literacy scores, $F = 2.188$, $p = 0.144$. Additionally, Levene's test confirmed the homogeneity of variances, $F = 0.108$, $p = 0.744$. Furthermore, the Shapiro–Wilk test suggested that the data did not significantly deviate from a normal distribution ($p = 0.156$).

Table 2. ANCOVA results for digital literacy.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial η^2
Corrected Model	1593.033 ^a	2	796.517	52.140	<.001	.602
Intercept	2080.058	1	2080.058	136.161	<.001	.664
Pre-test	25.033	1	25.033	1.639	.205	.023
Group	1578.498	1	1578.498	103.329	<.001	.600
Error	1054.078	69	15.276			
Total	106008.000	72				
Corrected Total	2647.111	71				

a. R Squared = .602 (Adjusted R Squared = .590)

In the ANCOVA, the pre-test digital literacy scores served as the covariate, the teaching method served as the independent variable, and the post-test digital literacy scores served as the dependent variable. Table 2 presents the results of the ANCOVA. After controlling for the pre-test scores, the students who received AR-based instruction performed significantly better in digital literacy at the post-test compared with their counterparts in the non-AR group. The partial eta squared ($\eta^2 = 0.60$) indicated a strong effect of the instructional approach on the students' digital literacy.

3.2. Academic achievement

Table 3 indicates that prior to the intervention, the EG and CG exhibited similar levels of academic achievement, with mean pre-test scores of 6.75 ($SD = 2.13$) and 6.25 ($SD = 1.87$), respectively. Following the instructional treatment, both groups improved; however, the the post-test mean score of the EG ($M = 12.06$, $SD = 2.20$) exceeded that of the CG ($M = 8.75$, $SD = 1.86$) by 3.31 points. This difference corresponds to approximately 22% of the total score on the 15-item achievement test, indicating that students exposed to AR-enriched QIMS inquiry learning answered about three additional items correctly compared with their peers in the control group. As reflected in the gain scores, the students in the EG ($M = 5.31$, $SD = 1.45$) demonstrated greater academic progress compared to their counterparts in the CG ($M = 2.50$, $SD = 1.21$). Because these descriptive results could not rule out the influence of initial differences in academic achievement, an ANCOVA was conducted.

Table 3. Differences in academic achievement between the EG and CG.

Group	Pre-test		Post-test		Gain	
	M	SD	M	SD	M	SD
EG	6.75	2.13	12.06	2.20	5.31	1.45
CG	6.25	1.87	8.75	1.86	2.50	1.21

Prior to the ANCOVA, all relevant statistical assumptions were examined. The assumption of homogeneity of regression slopes was satisfied, as indicated by the non-significant interaction between the instructional group and the pre-test academic achievement scores, $F = 0.015$, $p = 0.902$. The Shapiro–Wilk test confirmed that the data were normally distributed ($p = 0.986$), and Levene's test indicated homogeneity of variances across groups, $F = 0.328$, $p = 0.568$.

Table 4. ANCOVA results for academic achievement.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial η^2
Corrected Model	374.528 ^a	2	187.264	114.559	<.001	.769
Intercept	167.208	1	167.208	102.289	<.001	.597
Pre-test	177.847	1	177.847	108.798	<.001	.612
Group	149.835	1	149.835	91.661	<.001	.571
Error	112.791	69	1.635			
Total	8279.000	72				
Corrected Total	487.319	71				

a. R Squared = .769 (Adjusted R Squared = .762)

In the ANCOVA, the pre-test academic achievement scores were treated as the covariate, the type of instruction served as the independent variable, and the post-test academic achievement scores were the dependent variable. Table 4 presents the ANCOVA results. After adjusting for the pre-test achievement, the students who participated in the AR-based learning environment ($M = 12.06$, $SD = 2.20$) demonstrated significantly higher academic achievement than those who learned through non-AR instruction ($M = 8.75$, $SD = 1.86$, $p < 0.001$). The partial eta squared value ($\eta^2 = 0.57$) suggested a large effect of the instructional method.

4. Discussion

This study aimed to examine the effect of AR-enriched QIMS inquiry learning on students' digital literacy. To address RQ1, an ANCOVA was conducted. The results revealed a significant difference between the experimental and control groups, indicating that the students who learned with AR demonstrated higher digital literacy after the treatment compared to those who did not use AR. This finding is consistent with a growing body of research showing that AR can positively influence students' digital literacy [35,55,63]. In particular, Nevrelova et al. [40] reported that students exposed to AR exhibited more effective digital literacy than those who were not. Similarly, Choolarb et al. [32] emphasized that AR-based learning environments can facilitate the development of students' digital literacy.

The higher digital literacy performance observed in the EG may be associated with the learning experiences provided through the AR-enriched environment. This interpretation aligns with Hsu et al. [55], who argued that AR has the potential to enhance digital literacy by immersing students in technology-mediated learning experiences. Through AR, the students were not only required to understand the academic content, but also to effectively navigate and utilize digital tools, thus strengthening their digital literacy skills. This is in line with Maas and Hughes [36], who noted that AR enables realistic simulations that help students comprehend complex or abstract concepts.

Additionally, the increase in the mean digital literacy scores in the EG compared to the CG further substantiates the effectiveness of AR-enriched QIMS inquiry learning. This result corroborates previous studies suggesting that AR can enhance digital literacy [55,63,64]. The improvement observed in the EG may be explained by the students' need to appropriately use and interact with AR technology, which, in turn, promoted the development of their digital competencies [65]. In this regard, Nevrelova et al. [40] highlighted that AR creates new technological learning experiences that can further strengthen digital literacy. Given these promising outcomes, it is imperative that teachers stay informed about technological advancements and develop the necessary pedagogical strategies to effectively integrate AR into classroom instruction [10].

Additionally, this study was conducted to investigate the effect of AR-enriched QIMS inquiry learning on students' academic achievement. To address RQ2, an ANCOVA was employed. The results indicated that, after the intervention, the students in the EG who learned with AR achieved significantly higher academic performance compared to those in the CG who did not receive the AR-based instruction. This finding is consistent with prior research demonstrating that AR can positively influence a student's academic achievement [47,53]. Similarly, Amores-Valencia et al. [8] suggested that AR can function as a viable alternative instructional approach that supports and enhances a student's academic performance. In addition, Ziden et al. [11] emphasized that AR not

only improves achievement but also facilitates more meaningful learning experiences. C  nara Olim et al. [13] highlighted that AR-based instruction increases a student's engagement in chemistry learning, thus leading to significant academic gains.

In the present study, the students in the EG demonstrated higher academic achievement on the global warming topic, likely because AR facilitated more active engagement in seeking, processing, and sharing information. This interpretation aligns with Cetintav and Yilmaz [39], who found that AR increases a student's engagement, which, in turn, positively affects their academic achievement. Similar patterns have been reported in other studies, particularly within STEM education contexts, where AR implementation has been associated with improved student performance [38]. A plausible explanation for these findings lies in the distinctive affordances of AR technology. By superimposing interactive 3D virtual objects onto real-world environments, AR enables students to better comprehend abstract, invisible, or complex scientific concepts such as atoms and molecules [47,54]. This enhanced visualization supports deeper conceptual understanding and memory retention. Furthermore, AR-based learning environments promote active, hands-on exploration and collaborative interaction, which align with constructivist learning principles and may contribute to improved academic outcomes [2]. Additionally, the integration of AR into instructional settings has been shown to shape a student's learning processes by influencing their cognitive load, which subsequently plays a significant role in enhancing their academic achievement [30].

5. Conclusions

Based on the findings of this study, it can be concluded that AR-enriched QIMS inquiry learning was associated with higher post-intervention digital literacy and academic achievement in chemistry learning about global warming. This conclusion is supported by the results of the ANCOVA analysis, which revealed significant differences between the experimental and control groups following the intervention. The students who participated in the AR-enriched QIMS learning environment reported higher levels of digital literacy and achievement following the intervention. Furthermore, the students in the EG demonstrated greater improvements in both digital literacy and academic achievement compared to those in the CG. This suggests that AR-enriched QIMS inquiry learning can be a promising teaching approach.

In summary, the findings suggest that AR-enriched QIMS inquiry learning not only enhances a student's academic performance but also supports a student's perceived digital literacy, which is a crucial competence in increasingly technology-driven learning environments. These results highlight the importance of fostering a student's ability to adapt to digital contexts, effectively access information, and meaningfully engage with technological tools. Consequently, this study provides valuable implications for teachers and educators to integrate AR into chemistry teaching practices to promote students' digital literacy and achievement. AR may be beneficial when used to support the learning of abstract, invisible, microscopic, or complex chemical phenomena that are difficult to visualize through conventional instructional approaches. Topics such as molecular structures, chemical bonding, and reaction mechanisms may particularly benefit from AR-enhanced visualization. However, the effectiveness of AR-enriched inquiry learning is likely to depend on the availability of adequate technological infrastructure, including compatible mobile devices, reliable internet access, and appropriate digital learning resources. In addition, teachers require sufficient professional development not only in the technical operation of AR applications but also in pedagogical strategies for integrating AR within inquiry-based learning environments.

6. Limitations and recommendations

This study has several limitations that provide directions for future research. The investigation focused on the use of AR-enriched QIMS inquiry learning to enhance tenth-grade students' digital literacy and academic achievement, specifically on the topic of global warming; therefore, future studies could extend the application of AR-assisted learning to other chemistry topics, particularly those that require strong 3D visualization, as well as to other disciplines to examine the broader applicability of this technology. In addition, this study employed a primarily quantitative approach to examine the effects of AR-enriched QIMS inquiry learning, which limits the depth of insight into the students' learning processes and experiences. To address this, future research could incorporate qualitative methods such as interviews, classroom observations, and think-aloud protocols, or adopt a mixed-methods design to allow for more comprehensive triangulation and interpretation of findings. Finally, as the intervention was solely conducted over four sessions, the results may not fully capture the longer-term development of the students' digital literacy; thus, future studies are recommended to employ longitudinal designs to better understand how digital literacy evolves over time through sustained exposure to AR-based learning environments. Additionally, future studies should incorporate delayed post-tests to evaluate whether improvements in digital literacy and academic achievement are sustained over time.

Author contributions

Irwanto Irwanto: Conceptualization, methodology, data analysis, writing manuscript, supervision. Rizkiyah Fajariyah: Conceptualization, data analysis, project administration, writing manuscript. Elsa Vera Nanda: Methodology, data analysis, writing manuscript, review and editing, supervision. All authors have read and approved the final version of the manuscript for publication.

Use of Generative-AI tools declaration

We used the AI tool ChatGPT for the purpose of proofreading. After using this AI tool, we reviewed and verified the final version of our manuscript.

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Conflict of interest

The authors declare that there is no conflict of interest.

Ethics declaration

The study was reviewed and approved by Jakarta State University, Indonesia, with the approval number: 8470/UNJ39.12/KM/2024. Participation was voluntary, and written informed consent was obtained from all individual participants included in this study. To ensure confidentiality, all responses were made anonymous, and no identifying data was disclosed.

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