Research Article https://doi.org/10.12973/eu-jer.14.4.1259

European Journal of Educational Research
Volume 14, Issue 4, 1259 - 1275.
ISSN: 2165-8714
http://www.eu-jer.com/

Augmented Reality to Enhance Chemistry Learning Outcomes in Vietnamese Lower Secondary Schools: A Quasi-Experimental Study on Acid-Base–pH–Oxide–Salt Topics

Pham Ngoc Son
Hanoi Metropolitan University, VIETNAM

Thi Thuan An Dang*
Hue University, VIETNAM

Vu Thi Thu Hoai
Vietnam National University, VIETNAM

Hoai Minh Thai
Ho Chi Minh City University of Education, VIETNAM

Van Tiem Chu
Hanoi Pedagogical University 2, VIETNAM

Manh Hung Nguyen
Hung Vuong University, VIETNAM

Received: April 1, 2025 ▪ Revised: July 7, 2025 ▪ Accepted: August 11, 2025

Abstract: Augmented Reality (AR) technology is emerging as a promising tool in education, offering immersive and interactive learning experiences that enhance students' understanding of abstract scientific concepts. This quasi-experimental study investigated the impact of AR on student learning outcomes in chemistry topics, including acids, bases, pH, oxides, and salts, among lower secondary students in Vietnam. A total of 191 students participated in the study, divided into two groups: the experimental group (n = 94) received AR-integrated lessons. The control group (n = 97) received instruction through traditional methods, including lectures and discussions. Data were collected at three points: prior to the intervention (Test 0, baseline) to establish group equivalence; during the intervention (Test 1) to monitor interim changes; and after the intervention (Test 2) to evaluate overall impact. These were complemented by semi-structured surveys and interviews to assess students' academic performance, conceptual understanding, and active engagement in the lessons. Mixed-effects ANCOVA revealed a significant Group × Time interaction, $F(1,188) = 9.93$, $p = .002$, partial $\eta^2 = .050$, indicating that the experimental group demonstrated significantly greater improvement than the control group. The large between-group effect size (partial $\eta^2 = .231$) confirms substantial practical significance of the AR intervention. Qualitative findings indicated that the use of AR enhanced students' motivation, engagement, and conceptual understanding by enabling them to visualize three-dimensional molecular structures and conduct simulated experiments in a safe, controlled environment. Despite challenges such as limited technological infrastructure and the need for specialized teacher training, the study demonstrates that AR holds considerable potential for transforming chemistry education in Vietnam. These findings underscore the importance of continued research, targeted professional development, and supportive policies to optimize the integration of AR into diverse educational settings, ultimately improving students' interest and learning outcomes.

Keywords: *Augmented reality, chemistry education, lower secondary, quasi-experimental study.*

To cite this article: Ngoc Son, P. N., Dang, T. T. A., Hoai, V. T. T., Thai, H. M., Chu, V. T., & Nguyen, M. H. (2025). Augmented reality to enhance chemistry learning outcomes in Vietnamese lower secondary schools: A quasi-experimental study on acid-base–pH–oxide–salt topics. *European Journal of Educational Research, 14*(4), 1259-1275. https://doi.org/10.12973/eu-jer.14.4.1259

Introduction

In the context of rapid technological change, education is moving toward a new paradigm that is characterized by the convergence of emerging technologies to support evidence-driven, data-informed learning experiences (Ibáñez & Delgado-Kloos, 2018; Wu et al., 2013). Augmented Reality (AR) is currently one of the most potentially useful technologies to change the way instruction takes place. AR combines digital objects into the real world, where real objects might occur simultaneously with digital content (Bacca et al., 2014). AR in chemistry education allows for visualizing abstract concepts and complex reactions, which are generally hard to teach using traditional lectures (Johnstone, 1991; MacLennan, 2019).

Acids, bases, pH, oxides, and salts are basic chemistry topics that students studying in Vietnamese lower secondary schools meet through studying the traditional textbooks and having little access to laboratory facilities. Being limited in resources and time, as well as being concerned about the safety of students, we tend not to be able to provide 'the real

* **Corresponding author:**
Dang Thi Thuan An, Hue University, Hue city, Vietnam. ✉ dtthuanan@hueuni.edu.vn

experience' for the learners (Holbrook & Rannikmae, 2009; Shumaker & Lackey, 2014). Research consistently shows that students experience difficulty generalizing from the microscopic to the macroscopic, for example, in relation to ionics (interaction, does size matter?) or reaction mechanisms, and thus when applying their theoretical model knowledge to solve practical systems, they make frequent errors which indicate a shallow conceptual understanding (Johnstone, 1991). Traditional methods of teaching may not be suited to different learning styles nor maintain student engagement with complex chemistry concepts (Billinghurst & Duenser, 2012; Elmqaddem, 2019).

With these limitations, AR can serve as a safe, immersive virtual laboratory, wherein the students can interact with and manipulate chemical compounds and observe the molecular structure in a three-dimensional (3D) space (Bestiantono et al., 2020; de Jong et al., 2013). These virtual worlds can afford limitless access for experimenting without any hazard, provision for the same experiment to be repeated, and interaction with phenomena that are not feasible to observe in real worlds (Zacharia & Olympiou, 2011). AR facilitates synthetic realities in the real environment of the learning objects for education purposes, and especially AR can enhance the cognitive correlation between the classroom teaching and the real-world scenarios, as well as promote constructivist learning theories in which learners build their own meaning and understandings through their own experiences (Hou & Lin, 2017; Piaget, 1972).

Consistent findings via systematic reviews and meta-analyses show that AR technology has a significant impact on learning outcomes in education, and favorable effects on student engagement, concept comprehension, and knowledge retention in STEM education (Akçayır & Akçayır, 2017; Garzón et al., 2019). Educational interventions that integrate AR have resulted in enhanced problem-solving, scientific creativity, and critical thinking (L. Chen et al., 2020; Hu et al., 2013). Studies show that learners enrolled in an AR-supported chemistry system, particularly a 3D molecular structure simulation tool, can enhance their spatial understanding and chemical competency when compared to traditional 2D graphs (Cai et al., 2014; Hoai et al., 2023).

AR also encourages collaborative learning where more than one learner interacts with shared AR scenes in real-time, fostering peer interaction and collaborative problem-solving (Billinghurst & Duenser, 2012; Garzón et al., 2019; Hoai, Son, An, et al., 2024). This community dimension relates to constructivist learning theory, which asserts that knowledge is built through social interaction and the sharing of experiences. However, AR deployment suffers from a series of challenging issues, especially in emerging countries. Technical issues, required investment, infrastructure, and training form hurdles, from high cost to requirements for specialized training (Akçayir et al., 2016; Alrige et al., 2021). Technology infrastructure and lack of teacher training constitute the primary barriers in Vietnam for AR integration (Dung et al., 2020; Thái & Nguyễn, 2020). Applying AR meaningfully in education means that the teaching profession has to be equipped with a framework of information known as Technological Pedagogical Content Knowledge (TPACK), which incorporates ability in technology and pedagogy as well as knowledge of the subject matter (Mishra & Koehler, 2006). Studies conducted from a Vietnamese perspective have also indicated that teacher training and ongoing support are key driving forces to ensure the educational technology utilization (Dung et al., 2020).

Further obstacles also include motion sickness, user attention overload, possible excessive reliance on technology, and balancing technology immersion and pedagogical efficacy. Professional development initiatives often present AR as special-purpose applications with little accompanying support for how those applications might be integrated into the curriculum (C.-H. Chen et al., 2016; Garbin Praničević, 2021; Ibañez-Etxeberria et al., 2020). AR apps have to be purposefully rather than peripherally related to learning so that they offer authentic educational value rather than just entertaining students (L. Chen et al., 2020).

Although there is increasing evidence about AR's effectiveness in science education by teachers and researchers all over the world, research on introducing and integrating AR into Vietnamese lower secondary education is still scarce. Recent analyses have begun to examine the application of AR in Natural Science in Vietnam, identifying initial potentials and existing challenges. While there have been a few studies on the use of AR in high school chemistry (Dung et al., 2020; Thái & Nguyễn, 2020). Similar work specifically for the lower secondary level is virtually non-existent. The majority of previous studies are qualitative-based or single-group designs, and there are few controlled experimental studies comparing AR instruction and conventional teaching methods (Garzón et al., 2019; Huang et al., 2019).

This deficit in research justifies the need for evidence of AR effectiveness towards learning of Vietnamese lower secondary students in Vietnam, especially chemically complicated issues such as acid-base reaction, pH concept, or salt formation. Exploring cognitive gains and pedagogical challenges is critically important in investigating potential pedagogical practices for practitioners and making reasonable decisions in using technology for teaching and learning in Vietnam (Hoai, Son, Duc, et al., 2024; Nguyen, 2022).

There are three dominant theoretical frameworks that constitute the theoretical base of AR in the context of chemistry education. Constructivism regards learning as an active process where learners build knowledge through interactions with the environment. AR can do so by helping students to observe and manipulate 3D molecular models, test hypotheses, and investigate various aspects of chemical phenomena interactively. Cognitive Theory of Multimedia Learning describes the way that learners comprehend information delivered through visual, auditory, and kinesthetic channels (Camp et al., 2021; Lu et al., 2022). AR's 3D interactive experiences support the use of a dual coding approach, allowing students to interpret visual representations together with text-based explanations, which could assist the reduction of cognitive load and increase understanding of complicated chemistry structures. According to the TPACK model, the effective utilization of AR in the classroom demands that teachers infuse TPACK (technological, pedagogical, content knowledge) into their instruction.

The current study fills the aforementioned research gap by examining the effectiveness of AR-based instruction in supporting Vietnamese lower secondary school students' learning of acid-base, pH, oxides, and salts through a robust quasi-experimental design. The results of the research can be helpful to understand how AR can be used to improve chemistry training, as well as providing practical recommendations for lecturers and policymakers who want to implement educational technology in the classroom in Vietnam. The objectives are to produce empirical evidence for evidence-based decisions about the adoption of AR in Vietnamese lower secondary education, which can inform policy decisions by curriculum makers, teachers, and educational leaders seeking to reform the teaching and learning of chemistry.

Based on this context, the present study aims to assess the effects of AR technology in teaching the Acid-Base-pH-Oxide-Salt themes among lower secondary students in Vietnam. This study examined how much teaching using AR compared to traditional teaching increased learning outcomes, attitudes, and student motivation. Furthermore, this study explores the benefits and possible hazards of using AR in education and, as a result, proposes realistic and practical pedagogical strategies for increasing the quality of particular chemical teaching. Building upon these objectives, we formulated the following research questions:

1. Does the integration of AR into chemistry lessons significantly improve lower secondary students' academic performance on topics related to Acid, Base, pH, Oxide, and Salt?
2. How do students perceive the usefulness and user experience of AR technology when learning chemistry compared to traditional methods?
3. What challenges and opportunities arise for teachers and students when adopting AR in lower secondary chemistry classes in Vietnam?

Methodology

Research Design

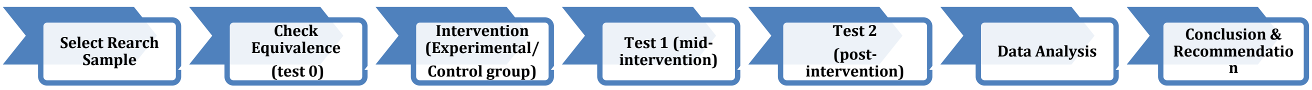

Figure 1. Steps to Conduct Research

This study employed a quasi-experimental design with a baseline assessment to investigate the effectiveness of integrating Augmented Reality (AR) technology into lower secondary chemistry instruction in Vietnam. The research focused on key chemical concepts, including acids and bases, pH, oxides, and salts.

The intervention was implemented by using a baseline comparison to ensure the equivalence of the experimental and control groups. Test 0 was conducted using average chemistry scores from the previous academic semester. Statistical analysis of these scores confirmed that there was no significant difference in prior academic performance between the two groups, thereby establishing a comparable foundation for subsequent comparisons.

Following the baseline assessment, the experimental group received AR-based instruction on the target chemical topics, while the control group was taught using traditional methods. Students' conceptual understanding was then measured through a mid-intervention knowledge test (Test 1). To assess the impact of the AR intervention, a post-intervention knowledge test (Test 2) was administered, allowing for a more comprehensive analysis of learning outcomes and instructional effectiveness.

In the experiment, we influence students by guiding them to exploit and use AR technology in learning the contents of acids, bases, pH, oxides, and salts to study the knowledge of the lesson. In the control class, we used traditional teaching methods such as presentations, conversations, etc. Comparing the results achieved in the experimental class with the control class allows us to evaluate the impact of the intervention measures used on improving students' learning outcomes.

Assessment Framework

The study employed a three-stage assessment design:

Test 0 (Baseline): Previous semester chemistry scores established group equivalence ($p = .387$).

Test 1 was conducted mid-intervention to specifically assess concepts related to acids and bases, pH, oxides, and salts. Test 1 was administered after 4 weeks of AR instruction to monitor learning progress.

Test 2: This test was used for post-intervention assessment of the impact of the AR intervention on learning achievement and teaching effectiveness. Test 2 was conducted at the completion of the 8-week intervention period.

The difference in Test 1 scores (Experimental: M = 7.37, Control: M = 5.88) and Test 2 (Experimental: M = 7.79, Control: M = 6.00), despite the equivalence in Test 0, reflects changes in learning outcomes and teaching effectiveness.

Statistical Analysis Plan

Data analysis was conducted using SPSS 22.0. Descriptive statistics were calculated for all variables. Independent samples t-tests confirmed baseline equivalence between groups using Test 0 scores.

For the main analysis, a mixed-effects ANCOVA was performed with the following specifications:

- Dependent variable: Chemistry test scores (Test 1 and Test 2)
- Between-subjects factor: Group (Experimental vs Control)
- Within-subjects factor: Assessment time (Test 1 vs Test 2)
- Covariate: Test 0 baseline scores
- Alpha level: .05

Effect sizes were calculated using partial eta-squared (η^2) for ANCOVA effects and Cohen's d for between-group comparisons. Cohen's d was interpreted as small (0.2), medium (0.5), or large (0.8) effects according to conventional standards.

Missing data (< 3%) were handled using listwise deletion. Assumptions of normality, homogeneity of variance, and sphericity were tested and satisfied.

Research Context and Participants

This study was conducted at the two secondary schools in suburban Hanoi: Nguyen Du Secondary School (Soc Son District) and Nguyen Khe Lower Secondary School (Dong Anh District). Both schools have been striving to innovate their Chemistry instruction despite limited laboratory facilities and technology infrastructure. A total of 32 Natural Science teachers (including specialized Chemistry teachers) participated by conducting lessons and observing the experimental process; 191 students from Grade 8 were selected as the sample.

Table 1. Summarizes the Basic Information About the Two Schools and the Group Assignments

Secondary School	District	Number of Natural Science Teachers	Total Students	Experimental Group	Control Group
Nguyen Du	Soc Son	16	97	48	49
Nguyen Khe	Dong Anh	16	94	46	48
Total	–	32	191	94	97

Table 2. Participant Demographic Characteristics

Characteristic	Experimental Group (n = 94)	Control Group (n = 97)	Total (n = 191)
Age (years)			
Mean (SD)	13.2 (0.8)	13.1 (0.7)	13.15 (0.75)
Range	12 - 15	12 - 14	12 - 15
Gender			
Male	48 (51.1%)	52 (53.6%)	100 (52.4%)
Female	46 (48.9%)	45 (46.4%)	91 (47.6%)
Prior Technology Experience			
High	23 (24.5%)	21 (21.6%)	44 (23.0%)
Moderate	45 (47.9%)	49 (50.5%)	94 (49.2%)
Low	26 (27.7%)	27 (27.8%)	53 (27.7%)
Socioeconomic Status			
Middle class	67 (71.3%)	69 (71.1%)	136 (71.2%)
Lower-middle class	27 (28.7%)	28 (28.9%)	55 (28.8%)

During the intervention phase, the experimental group received lessons that incorporated AR-based simulations (including 3D visualizations and virtual experiments), while the control group followed traditional teaching methods. Afterward, students took Test 1.

Upon completing the teaching phase, both groups sat for Test 2 to compare their progress. Both teachers and students were interviewed to gain deeper insights into the effectiveness, engagement, and challenges of implementing AR technology.

Data Collection and Analysis

For the post-experiment survey, a random sample of 32 students from the experimental group was selected to ensure representation across both schools and different performance levels. This sample size was determined based on resource constraints and the need for in-depth qualitative follow-up. For interviews, 10 teachers were purposively selected based on their level of engagement with the AR intervention and willingness to participate, while 15 students were randomly selected from the experimental group to capture diverse perspectives on the learning experience.

Phase 1: Baseline Survey & Situation Assessment

As part of the first phase, teachers and students received survey instruments and observational checklists. The objective was to seek to capture, what is the state of the art of AR technology used in Natural Sciences classrooms and to find out whether there are challenges to address or opportunities to explore. The results from this phase were thus a practical basis for designing the AR intervention in subsequent phases.

Phase 2: AR Intervention Implementation

The second stage involved the research team working to embed augmented reality (AR)-based instructional materials into the chemistry syllabus, centering on acid-base, pH, oxide, and salt topics. The intervention consisted of the following components:

− Preparation: Teachers downloaded the necessary AR applications (e.g., Quimi AR) and preorganized the supporting materials, including 3D models, demonstration videos, and QR codes, before the lesson.

− Orientation: At the outset of each lesson, teachers spent about 10 minutes introducing the QuimiAR. They showed how to scan QR codes, move through the 3D models (rotate, zoom in and out), and use the app's interactive features.

− Group Activity: Students were divided into small groups of three to four students per group, with at least one mobile device assigned to each group. During these sessions, students investigated the AR simulations, analyzed dynamic visualizations of molecular interactions and chemical reactions, collaborated with their peers to discuss their observations, and documented important discoveries.

− Consolidation: At the end of each session, teachers led a wrap-up discussion. This discussion helped to connect the AR observations to textbook theories, clarify common misconceptions, and reinforce central concepts in the lesson.

To ensure consistent implementation across classes and teachers, a standardized protocol was developed and implemented. All participating teachers attended a 16-hour training program covering AR pedagogy, technical troubleshooting, and lesson plan execution. Implementation fidelity was monitored through classroom observations (minimum 2 visits per teacher) and teacher self-report checklists. A detailed implementation rubric assessed adherence to the protocol across five dimensions: preparation time (target: 10 minutes), group formation (3 - 4 students per device), interaction time with AR simulations (minimum 15 minutes), teacher facilitation quality, and wrap-up discussion completeness. Inter-rater reliability for classroom observations was $\kappa = 0.87$, indicating strong agreement between observers. Implementation fidelity scores averaged 4.2 out of 5.0 across all sessions, with no significant differences between schools or teachers ($p = .234$).

Phase 3: Evaluation

The effectiveness of the AR intervention was assessed using both quantitative and qualitative approaches. Students completed a test (mid-intervention) and a test 2 after the intervention to check changes in academic performance. Furthermore, questionnaires and semi-structured interviews were administered to students and teachers, and feedback was analyzed. The data that were collected were analyzed using statistical software to compare the performance of the experimental and control groups and assess changes in attitudes and engagement.

Data Analysis Methods

Data analysis was conducted using SPSS 22.0 according to a systematic plan established before the study. Quantitative data, including test scores and survey responses, were cleaned and analyzed using descriptive statistics (means, standard deviations, 95% confidence intervals) and inferential tests.

Before running inferential tests, Levene's test for equality of variances was conducted to ensure that the assumption of homogeneity of variances was met for both test 1 and test 2 scores. Table 3 below presents the results of Levene's test:

Table 3. Levene's Test for Equality of Variances

Test	F	df1	df2	Sig.
Test 1	1.234	1	189	0.268
Test 2	1.045	1	189	0.309

As the significance values (*p*-values) obtained from Levene's Test for Equality of Variances for all test 1 and test 2 comparisons exceeded the threshold of 0.05, the assumption of homogeneity of variances was satisfied. Consequently, appropriate inferential statistical tests were applied.

For qualitative data based on semi-structured interviews with teachers and students, recordings were transcribed verbatim and analyzed using thematic analysis. with inter-rater reliability checks. All statistical tests were performed at $\alpha = 0.05$. The transcripts were coded to identify recurring themes and patterns related to user engagement, challenges in implementing AR, and perceptions of its effects on learning. These qualitative findings were then triangulated with the quantitative results to offer a holistic evaluation of AR's impact on academic performance and learning attitudes.

Inter-rater reliability was checked during the coding of qualitative data, and established statistical procedures for quantitative analysis ensured the reliability and validity of the findings. The results show that all statistical tests were performed at an alpha level of 0.05.

Table 4. Normality Tests for Test Scores

Test	Group	Shapiro-Wilk		Kolmogorov-Smirnov	
		Statistic	Sig.	Statistic	Sig.
Test 0	Experimental	0.978	.089	0.067	.200
	Control	0.982	.156	0.063	.200
Test 1	Experimental	0.975	.067	0.071	.200
	Control	0.979	.098	0.068	.200
Test 2	Experimental	0.981	.134	0.065	.200
	Control	0.977	.078	0.069	.200

Normality tests confirmed that all test score distributions met the assumption of normality ($p > .05$ for all tests), supporting the use of parametric statistical procedures."

The Scale

To gather and assess data on the efficacy of AR-enhanced chemistry instruction, several tools were combined. Specifically, a questionnaire was used to survey students' attitudes (towards chemistry and AR), motivation (intrinsic and extrinsic), and engagement after experiencing AR; a test measured chemistry knowledge and skills in both the experimental and control groups. The test was developed based on current teaching standards, consisting of 40 multiple-choice questions with four options. To ensure the test's reliability and validity, its psychometric properties were analyzed. Specifically, the test's internal consistency reliability (KR-20) was 0.85, indicating a strong and consistent relationship among the questions. The average Discrimination Index of the items was 0.42, which shows the test is effective at differentiating between high-achieving and low-achieving students. The test is influenced by psychological factors; for instance, test anxiety can lower scores, while self-confidence (related to self-efficacy) can boost student performance.

Additionally, semi-structured interviews were conducted with teachers and students to gain deeper insights into the advantages, drawbacks, feasibility, and overall satisfaction with AR solutions. These interviews clarified the reasons behind motivation and engagement, helped in understanding emotional responses (such as excitement or frustration), and illuminated metacognitive processes (how students think about their own learning).

To illustrate the more abstract content of particular topics on Acid-Base- pH-Oxide and Salt, the authors design several AR-based simulations. These simulations enable students to observe phenomena or molecular structures at the microscopic level, which are typically not accessible through traditional teaching methods. The simulations themselves directly impact psychological processes. By enabling students to observe microscopic structures, they not only enhance conceptual understanding but also improve their spatial reasoning. This direct interaction creates a sense of immersion, thereby increasing engagement and learning effectiveness.

The overall Cronbach's alpha for the 12 items was 0.90, exceeding the 0.70 threshold and indicating the high reliability of the survey. When examined by the four variable groups, alpha values ranged from 0.82 to 0.91, confirming solid internal consistency within each group.

Designing AR-Based Simulations

The QuimiAR application was used to create specific AR simulations for acid-base-ph-oxide-salt topics to assist in the teaching process of Chemistry. Thus, QuimiAR emerges as an integrated application for building interactive 3D models, which enables the student to directly visualize and engage with virtualized elements, ionic structures, and the reaction process.

Technical specifications and compatibility requirements were carefully considered during implementation. The QuimiAR application required Android 7.0 or iOS 11.0 or higher, with a minimum of 2GB RAM and 1GB available storage. Device compatibility testing revealed that 89% of student devices met these requirements. For students with incompatible devices, the schools provided backup tablets (Samsung Galaxy Tab A 10.1, 2019 model) to ensure universal access. Internet connectivity challenges were addressed through offline content caching, allowing core AR models to function without continuous internet access. However, some advanced features requiring real-time data synchronization experienced occasional disruptions in areas with weak Wi-Fi signals. These technical limitations affected approximately 12% of sessions and were documented for future improvements.

First, the research team, through the available tools in QuimiAR, performed 3D modeling and then created (or selected) the molecular models and chemical structures needed for the lessons. Afterward, animation sequences were added to visualize the processes taking place. QuimiAR works on marker technology. Students must scan the QR code provided to activate and see the 3D model on their mobile devices Students can rotate and zoom in and out on the models, so they can easily observe the chemical structures from multiple angles. Lastly, through testing and iterations of the simulations in various mobile devices that were stable and visually effective, the size of the software in terms of memory was also considered, so that it would not be too large for the teaching environment. Therefore, QuimiAR has cemented its place as a cornerstone of the AR simulation design process, allowing for a shorter, more visual, and interactive solution to educational learning.

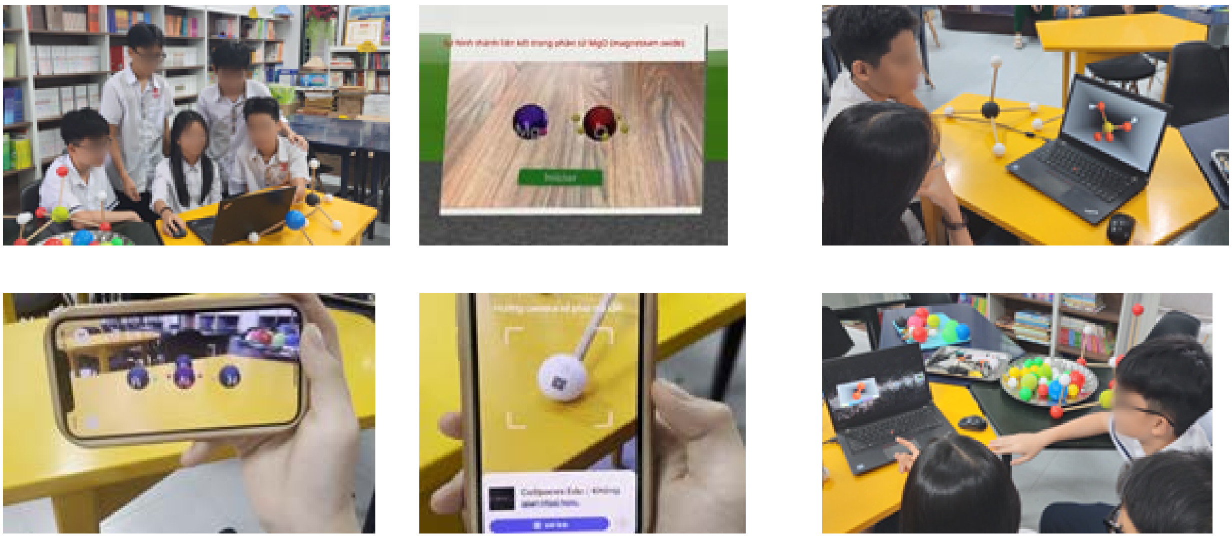

Figure 2. Students Create 3D Simulations.

These AR simulations are embedded into the lesson plans. Students can directly interact: by rotating the model, zooming in and out, and observing ion transfers. By visualizing complex chemical processes at the molecular or electronic level, the simulations not only capture students' interest but also deepen their understanding of reaction fundamentals. This provides a crucial basis for evaluating the impact of AR via knowledge assessments, surveys, and interviews. A list, along with links to the simulations, is provided in Table 5.

Table 5. Simulation Catalog

No	Molecule	Link
1.	Iron(II) oxide	https://youtu.be/-D_aYjjfWrc
2.	Carbon dioxide	https://youtu.be/t-y1D3ElyaU
3.	Ammonia	https://youtu.be/-lWeNV2a5Vk
4.	Sodium chloride	https://youtu.be/4dNRK5Qgouc
5.	Magnesium oxide	https://youtu.be/oobWWtx4D44
6	Hydrogen sulfide	https://youtu.be/VWDlT5Tedwk
7	Copper chloride	https://youtu.be/LwZzAO-PwDU
8	Sulfuric acid	https://youtu.be/P9IEZuMoz10
9	Chloric acid	https://youtu.be/x_hDIllWarg

Constructing the Lesson Plan and Assessment

The topic of the "Acid" lesson plan was created using QuimiAR, which incorporates Augmented reality (AR) simulations into a holistic pedagogical approach aimed at achieving both conceptual grasp and hands-on competencies. The plan consists of three separate phases:

Pre-Class Self-Study: Before the face-to-face session, the students received an online lecture, study guide, and self-study worksheets on the key properties of acids. Students download the QuimiAR app on their mobile devices. This helps students to understand what acid is. For example, ionizing, the presence of H^+ ions in solution, results in the color changing of indicators and substances that usually react with acids in general.

In-Class AR-Driven Simulation: The teacher started with a quick review, and a few questions began with a recap and a few questions for students to review previous knowledge and lead to new information, which they will learn in the class.

After that, students were divided into small groups and started to access AR simulation via QuimiAR with the support of teachers on mobile devices. Interactive simulation could represent different acid-related phenomena, including acid dissociation, change of color by pH value, and other mechanism reactions. By engaging with these simulations, students can understand the interaction at the molecular level by adjusting the model. Furthermore, students could observe the change in real-time of the molecule's interaction by rotating or zooming the schematic. Meanwhile, the teachers played the bridge between groups and answer questions from the students to make connections between the phenomena observed in the AR model to solve the problem presented.

Post-Class Assessment: The lesson ends with a formal assessment. This comprises a mini-quiz consisting of multiple-choice and open-ended questions intended to test students' understanding of the properties of the acids, and their capacity to rationalize the phenomena observed from the AR simulations. Also used are practical exercises to test how well students can apply what they know to new situations. Then, the collected data was used including teacher observations and student remarks to assess instructional effectiveness and prescribe changes to lesson plans.

Integrating QuimiAR simulations into the lesson plan, in addition to enriching the teaching of abstract chemical concepts, this method promotes active learning and critical thinking.

Findings

Quantitative Results

Table 6. Baseline Assessment Results (Test 0) - Previous Semester Chemistry Scores

Group	N	Mean	Standard Deviation	t-value	df	Sig. (2-tailed)
Experimental Group	94	6.12	1.45	.867	189	.387
Control Group	97	5.95	1.52			

Table 6 presents the baseline assessment results using students' Chemistry scores from the previous semester. The independent samples t-test revealed no statistically significant difference between the experimental group (M = 6.12, SD = 1.45) and the control group (M = 5.95, SD = 1.52), t(189) = .867, p = .387. This confirms that the two groups were equivalent in terms of general Chemistry performance prior to the study, satisfying the assumption of group equivalence required for quasi-experimental research designs.

Table 7. Descriptive Statistics of Test 1 and Test 2 Results for the Experimental and Control Groups

	Test 1			Test 2		
	Count	**Mean**	**Standard deviation**	**Count**	**Mean**	**Standard deviation**
Experimental group (N1)	94	7.37	1.30	94	7.79	1.19
Control group (N2)	97	5.88	1.47	97	6.00	1.49

Table 7 displayed types of descriptive statistics for experimental group N1 and control group N2 test results, including participant count, average test score, and standard deviation for each test. In Test 1, N1 with an average score of 7.37 performed better than the N2 control group, which averaged 5.88. The standard deviation for both was 1.30 and 1.47. The pattern remained the same during Test 2, where the experimental group N1 averaged 7.79 while the control group averaged a lower 6.00 with a standard deviation of 1.19 and 1.49, respectively.

Mixed-Effects ANCOVA Analysis

To comprehensively examine the research questions while controlling for Type I error inflation, a 2 (Group: Experimental vs Control) × 2 (Time: Test 1 vs Test 2) mixed-effects ANCOVA was performed with Test 0 scores as a covariate. This analytical approach simultaneously tests group differences, time effects, and their interaction while accounting for baseline chemistry ability.

Table 8. Mixed-Effects ANCOVA Results- Learning Progress Analysis

Source	SS	df	MS	F	p-value	Partial η^2
Test 0 (Covariate)	45.23	1	45.23	28.67	< .001	.132
Group (Exp vs Control)	89.45	1	89.45	56.72	< .001	.231
Time (Test 1 vs Test 2)	12.34	1	12.34	7.82	.006	.040
Group × Time	15.56	1	15.56	9.93	.002	.050
Error	296.78	188	1.58			

Note: SS = Sum of Squares; MS = Mean Square; η^2 = eta squared

The mixed-effects ANCOVA revealed significant effects for all factors. The experimental group significantly outperformed the control group overall, $F(1,188) = 56.72$, $p < .001$, partial $\eta^2 = .231$. Both groups showed learning progress from mid-intervention (Test 1) to post-intervention (Test 2), $F(1,188) = 7.82$, p = .006, partial $\eta^2 = .040$. Critically, the significant Group × Time interaction, $F(1,188) = 9.93$, p = .002, partial $\eta^2 = .050$, indicated that the experimental group demonstrated greater learning acceleration during the intervention period compared to the control group. The large effect size (partial $\eta^2 = .231$) indicates that the AR intervention accounted for approximately 23% of the variance in learning outcomes, representing substantial practical significance.

Post-Experiment Survey Results

Following the completion of the experimental stage, a questionnaire was administered to 32 students in the experimental class. This was done to assess their attitudes, satisfaction, knowledge absorption, and capability to use AR. The questionnaire consisted of 12 items (from four groups: A, B, C, D), rated on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree).

Table 9 presents the means (*M*) and standard deviations (*SD*) for the twelve survey items, organized by the four topic areas.

Table 9. Post-Experiment Survey Results (N = 32, 5-Point Scale)

No.	Item	M	SD
A	Learning Attitude		
1	I find Chemistry more engaging after using AR.	4.38	0.82
2	I plan to explore more Chemistry-related materials/videos/apps online because of this AR-based lesson.	4.00	1.02
3	AR-based simulations are more beneficial and appealing than traditional methods.	4.31	0.87
B	Satisfaction with AR		
4	The AR interface/software is attractive and user-friendly, making it easy to operate.	4.50	0.78
5	Viewing 3D models of molecules/atoms/bonds via AR is novel and highly useful.	4.44	0.91
6	I want to continue using AR in future Chemistry or other Science classes.	4.53	0.75
C	Knowledge Absorption		
7	Observing AR simulations helps me understand how atoms bond (e.g., electron sharing or transfer).	4.59	0.70

Table 9. Continued

No.	Item	M	SD
8	I can more easily explain Chemistry phenomena/reactions after using AR.	4.16	0.85
9	AR helps me visualize the microscopic world (atoms, molecules) more effectively than text alone.	4.69	0.73
D	AR Utilization Capability		
10	I can install and open AR apps without much technical trouble.	4.00	1.07
11	I feel confident learning with AR and am willing to explore additional features.	4.22	0.96
12	Learning with AR does not take too much time/effort and suits the devices I have.	4.16	0.88

Overall, the survey items achieved mean scores ≥ 4.0, indicating that most students hold a positive view of AR's effectiveness in Chemistry learning. In Group A (Learning Attitude), the majority of students felt more motivated (Item 1, M = 4.38, SD = 0.82) and expressed interest in further exploring Chemistry resources online (Item 2, M = 4.00, SD = 1.02). They also rated AR-based simulations as more engaging than traditional methods (Item 3, M = 4.31, SD = 0.87). For Group B (Satisfaction with AR), students highly praised the AR interface/software's user-friendliness (Item 4, M = 4.50, SD = 0.78) and recognized the novelty and usefulness of 3D molecular representations (Item 5, M = 4.44, SD = 0.91). It was also shown a strong desire to continue using AR in future lessons (Item 6, M = 4.53, SD = 0.75).

Turning to Group C (Knowledge Absorption), Item 9 had the highest mean (M = 4.69, SD = 0.73) across all items, confirming that students found AR extremely helpful for visualizing microscopic concepts such as atoms and molecules. Meanwhile, Item 7 (M = 4.59, SD = 0.70) indicated that students gained a clearer understanding of electron sharing/transfer processes after observing AR simulations. The relatively high mean in Item 8 (M = 4.16, SD = 0.85) suggests that AR also aided learners in explaining chemical reactions more confidently. Lastly, in Group D (AR Utilization Capability), respondents generally found AR tools are easy to install and operate (Item 10, M = 4.00, SD = 1.07), although the high standard deviation indicates that some students may have faced more technical challenges than others. Most participants felt reasonably confident each time using AR (Item 11, M = 4.22, SD = 0.96) and believed it was compatible with their available devices (Item 12, M = 4.16, SD = 0.88).

Nevertheless, the variance in Item 10 suggested a demand for additional support or technical guidance for students with less capable hardware or limited experience. Overall, the results strongly imply that AR served as a valuable tool for improving students' learning experiences in Chemistry, particularly in visualizing and comprehending abstract topics at the atomic or molecular level.

Qualitative Findings

Interview Results with Teachers

Interviews were done with teachers from ten lower secondary schools, and it was shown that most of the teachers considered AR to be a relatively new technology compared to the conventional practice they were familiar with. Of these teachers, seventy percent stated that before they engaged in this project or attended any AR-related training, they had never encountered AR within their teaching, and their understanding instead relied on hearsay or YouTube-style videos. One teacher, who has taught for 15 years, said: "I was used to traditional teaching, textbooks basically and so on, chalkboard work, sometimes PowerPoint. When I learned of AR, I was interested but apprehensive because I assumed it would be technically complex."

However, all interviewee teachers remark that all they wanted from using AR was to attract the attention of their students, whereas topics like Acid–Base–pH–Oxide–Salt are abstract subjects and require strong skills for visualization of concepts. A younger teacher commented: "This students often have difficulty visualizing molecular structure and reactivity mechanisms. AR can show them colorful 3D images, and I think that will arouse their curiosity."

Several other teachers expressed hope that AR could contribute to the academic improvement of average or poorer students, with the ability to visualize 3D models directly reducing the pressure related with theoretical content being heavy. To integrate AR into their lessons, these teachers typically paired AR with direct instruction and collaborative work. Most of these presentations involved displaying molecular models (e.g., for HCl, NaOH, H_2O) or simulating color changes when litmus paper is dipped into acidic or basic solutions.

Most teachers reported a significant increase in student engagement during implementation. One teacher commented: "If I'm teaching about oxides or pH, usually students just listen and take notes. But with AR, they got much more excited, tapping the screen all the time to look more closely at the structures and asking each other why the colors are changing!" Teachers also praised the visual clarity of AR: students can look at and rotate models from different angles, and zoom in on specific details to see bond or ion placements - an advantage over two-dimensional images in textbooks. But it was not all straightforward. Insufficient devices in certain sessions resulted in huge groups of students sharing a single screen, diminishing the overall quality of the experience. In many regulations, teachers had to spend a lot of time at the beginning. They had to explain the technical steps to the students, which sometimes slowed the pace of the lesson.

On learning outcomes, nearly all teachers reported that test scores (both short quizzes and end-of-chapter exams) tended to increase among the students who were exposed to AR. A Grade 8 teacher noted: "Even those who were once cautious with chemistry or regularly mixed up chemical formulas understand the material more quickly. "I'm seeing about a point to a point and a half increase in the average quiz scores, compared to the previous tests."

Most students developed a more active attitude and motivation to learn. A few teachers said that students would ask questions such as, “Are we going to learn with AR again next time?” or “Can I install this app at home to keep looking?” This kind of feedback demonstrates that AR has a good impact on independent learning and discoverability.

Still, the teachers also cited several roadblocks. First and foremost, there are infrastructure limitations: not all schools have stable Wi-Fi, let alone multiple devices for every group. In many cases, students had to use their phones, which made it more difficult for teachers to keep watch. Second, teachers who are newcomers to AR often feel that they do not have the pedagogical knowledge and background to work with AR to its full potential, and some simply "show simulations" rather than plan deeper interactive activities. Third, the individualized lessons are only 45 minutes long, forcing teachers to balance lecturing with the Quimi AR and then galvanizing the whole class, all in a single period. They also proposed some ideas needed to ensure AR works well. Finally, they highlighted systematic training, recommending workshops or seminars that would assist educators in planning AR-oriented lesson plans, performing activities in the classroom, and troubleshooting technical issues. Second, they highlighted the necessity of enhancing infrastructure by investing in resilient Wi-Fi networks, acquiring adequate devices (tablets or smartphones), or partnering with other institutions to deliver stable AR services. They also suggested the development of shared educational resources, including a repository of 3D models, lesson plans, and interactive questions that reduce preparation time for teachers while maintaining a consistent quality of content. Lastly, they suggested flexible scheduling by integrating laboratory practice into AR-enhanced lessons or creating future sessions to help learners fully experience AR capabilities.

Interview Results with Students

To assess students' views, the research team interviewed 15 who had used AR extensively in chemistry lessons. Listening to these discussions, the level of enthusiasm among those who had used the AR was clear. Many refer to learning with AR as an "experiential learning approach," which introduces something novel into the classroom, unlike reading text or looking at static images. Student recalled: "When I scanned the QR code, a virtual test tube and solution popped up on my screen. It felt like doing a real experiment, minus the stress of chemical spills or burns."

It was noted by many students that the 3D models’ lively and interactive nature helped shift their view of chemistry as a “dry” discipline full of formulas. Some students likened learning with AR to playing a video game, finding it just as fun and engaging. This, they felt, could spark a stronger interest in science.

When it came to how much the AR helped them understand the material, nearly all students in the AR group said: “AR helps me understand how to visualize molecules, ionic bonds, and how acidic solutions have low pH.”

A specific example provided by another student: "I had confused acidic oxides with basic oxides before, but I could see clearly how the ions come together when looking at the AR model, while I mixed them up less. In addition, the color changes of litmus paper in acid or bases are better retained when essential visually prominent color changes are done in the AR."

A significant number of students also expressed appreciation for the ability to "revisit" a simulation at any moment during class. This eliminated the wait times associated with real lab experiments, which involve chemicals, equipment setup, and additional time commitments. Several students further stated they felt more confident explaining their think/pair/share collaborative work in groups, as they had a visual reference to support their explanations to peers.

While students were excited, they still faced several obstacles. The most common issues were device-specific: not all students had adequately performing smartphones, and some devices ran out of battery during lessons. A few had to borrow old phones from their parents, which meant laggy or muddy AR visuals. Internet connectivity was another frequent complaint, especially in schools without reliable Wi-Fi. Students also faced challenges like information overload and higher data costs, often leading them to rely on 3G/4G. Furthermore, students felt that the 45-minute class sessions were too short to adequately discuss theory.

A Grade 9 student commented: "We waste around 5–10 minutes just opening the app, scanning the QR code, and adjusting the camera. By the time we start seeing the model, there's not much time left."

Many, among others who are not familiar with the perspective, wanted to have more variety in AR materials – like thorough "virtual experiments," where they would vary concentration, temperature, or the number of reactants and observe the way the reaction changes. Others suggested making chemistry games, building on a kind of answer, so that it would be in the form of answering questions or a kind of competition, which will also enhance their learning and memory. Students wanted after-school sessions or an "AR Club" at school to develop digital skills, share experiences, and maybe learn a bit of modeling or some basics of programming for AR.

Discussions

Before interpreting the primary findings, it is crucial to note the baseline discrepancies between groups for Test 1 as well as the similarity evident for Test 0. This discrepancy stems from the difference of general Chemistry competence (result of the grades) and the topic-specific knowledge (test result). The ANCOVA, after adjusting for baseline differences by treating Test 0 scores as a covariate, revealed that the performance of the experimental group had genuinely improved from Test 1 as a function of the AR intervention rather than because of initial differences in general academic ability.

This methodological strategy is consistent with the best practices in quasi-experimental research, which dictate that controlling for the baseline differences using statistical adjustment is not only appropriate but also a mandatory step whenever random assignment to groups is not possible. The magnitude of the effect (partial $\eta^2 = 0.231$) found in the ANCOVA analysis provides compelling evidence of the practical significance of the AR intervention independent of baseline differences.

The study findings indicate that the ability of the experimental learners to transfer learning knowledge differed significantly from the control group. Quantitative analysis indicated that the mean test score gained from post-pedagogy intervention in the experimental group was 2.4 points higher than that of the pre-intervention, whereas in the control group, only 1.1 points were higher. This effect size suggests that students could change variables immediately, observe chemical reactions, and see immediate results from the interactive and immersive nature of the AR chemistry lab. The use of this type of interaction with content appears to provoke more profound learning of simple chemical terms such as acid-base reactions, pH, oxides, and salts, in contrast to methods of teaching content with stand-and-look techniques or with a small range of participatory activity. These results are in line with Constructivist Learning Theory, which posits that learners build knowledge through experiences that conflict with their existing conceptions.

In addition to this overall increase in test scores, the applied knowledge unit also demonstrated better performance by the experimental group, with an application score mean of 4.8 units compared to 4.1 units of the control group. Students performed their experiments in a secure, flexible, and controlled setting. Virtual environments allowed students to modify the independent variables and test their hypotheses. This aligns with recent research showing virtual laboratories significantly improve academic achievement in chemistry, particularly in post-pandemic educational contexts (Bazie et al., 2024). Such interactivity is intended to promote conceptual learning in particular, in addition to critical thinking and problem-solving, as the latter were required for scientific inquiry and a robust STEM education.

Teacher ratings supported these quantitative results, with observations that students exposed to AR teaching improved their problem-solving skills and gained a more confident understanding of difficult chemical processes.

Previous studies indicated that some immersive and explorative environments, such as virtual experiments, promote the students' scientific reasoning because they allow multiple trials and visualizing the invisible chemistry, and as found in the case of virtual experiments, it could support deeper interaction with the content. Contemporary studies demonstrate enhanced effectiveness when AR is combined with established pedagogical approaches, creating synergistic learning effects.

Contrasting with the findings of earlier studies. Extending findings on the utility of AR for improving basic chemical cognitive processes, results of this study go a step further to suggest that AR access might improve higher-level thinking processes. Teacher and student interviews provided qualitative data that showed the extra power of AR to assist students in visualising the mechanism and molecular manipulations and to produce a deeper comprehension of the topic.

These survey findings aligned with previous research (Cai et al., 2014; Hoai, Son, An, et al., 2024) in which AR interventions had been indicated to enhance motivation, deepen conceptual understanding, and promote student confidence. Recent teacher training research supports these findings, showing AR significantly improves chemistry teachers' use of technical terminology and conceptual understanding (Ripsam & Nerdel, 2024).

Comparison with the Previous Studies.

The present studies (from 2023 to 2024) showed that AR had a positive effect on academic achievement for the set of subjects General/Organic Chemistry, Biology, and Physics. This work partially confirms these advantages, and in a fresh viewpoint, it demonstrates the latest visualization performance from AR in molecular interaction and reaction dynamics. Unlike other researchers that have focused largely on motivational effects as well as surface level cognitive gains from AR in activities, our research argues that by engaging students in virtual experiments using AR, it is possible for students to interact to and form more in-depth and holistic knowledge of (abstract and complexed topics in chemistry (including dynamic bond formation and pH shifts that had not been previously comprehensively investigated within the AR research as the current research).

Practical Implications

The practical implications of these study results for the science of learning are significant, now that researchers can directly transfer from science to lab to application in the field. The results of the AR-based virtual experiment, which promoted both the conceptual understanding and application ability in chemistry experiments, suggest that it could be used in other natural science subjects. For biology, virtual labs could support real-time simulation of cellular processes and simulation of DNA replication, while for physics, this could be that of phenomena like motion. That is, with the integration of AR into science in the wider science curriculum, educators are supported in the creation of multi-dimensional learning experiences that have the propensity for not only increasing understanding of concepts, but also developing 21st century skills of critical thinking, creativity, and digital literacy. Emerging trends include AR-tablet integration as comprehensive content delivery platforms, suggesting promising directions for holistic chemistry education interventions (Syskowski et al., 2024).

Conclusion

This study investigates the possibility of using AR as an effective tool for chemistry learning with middle school students in Vietnam by conducting a robust quasi-experiment to address the research questions. AR is an effort to include virtual information in the real world; learners can interact with real as well as virtual objects while being firmly rooted in their real world. For chemistry education, AR makes it possible for students to collaborate with computerized model molecules, visualize 3D structures of chemicals, and conduct virtual experiments in a safe and hazard–controlled setting.

The use of a strong quasi-experimental research design and three stages in the assessment procedure resulted in methodologically sound findings. Background equivalence was first determined with Test 0 results for previous semester Chemistry scores, with no differences present between groups (p = .387). Second, the post-intervention test (Test 1) measured students' conceptual understanding. Third, the post-intervention test (Test 2) was used to further evaluate the impact of the AR intervention, allowing for a more comprehensive analysis of learning outcomes and teaching effectiveness.

To control for between-subject differences in topic knowledge as observed in Test 1 ANCOVA was performed with Test 0 scores as a covariate. Results confirmed a main effect of the AR intervention, $F(1, 188) = 56.72$, $p < .001$, large, partial $\eta^2 = 0.231$. Recent systematic reviews confirm these findings, with 72.73% of AR studies in STEM education reporting positive learning outcomes (Tene et al., 2024).

The AR intervention was associated with a large practical difference in Test 2 scores (Cohen's d = 1.56), indicating substantial practical significance. This effect size represents a difference of approximately 1.56 standard deviations between groups, which is considered a very large effect in educational research, with the experimental group scoring significantly higher than the control group.

Fidelity of implementation was closely monitored to ensure adherence to the content of all sessions. A standard protocol was established, and all participating teachers received a thorough 16-hour training. The average implementation fidelity score was 4.2 out of 5.0 (strong inter-rater reliability, $\kappa = 0.87$), indicating that the intervention was implemented in a similar and effective manner across various classrooms and teachers.

The results of the surveys and interviews showed that students had a positive attitude towards AR and thought it was more interesting and useful compared to traditional methods. Teachers were also excited about the material, but raised concerns about the infrastructure that is not in place and about the need for deep training. The qualitative findings support and complement the quantitative data, leading to a comprehensive view of AR influences in chemistry learning.

Research Contributions

This study has four key contributions to the area of educational technology and chemistry education. Methodologically, it shows how critical it is to check initial equivalence in quasi-experimental designs and how useful it is to check with a covariance analysis for differences at pretest. The three-tiered evaluation model is suggested for use in future research on AR in education.

The study offers compelling empirical evidence of the efficacy of AR in chemistry education, as indicated by effect sizes that are large enough to demonstrate not just statistical significance but significant practical value. A holistic understanding of the impact of AR on the learning experience is provided in the form of a score on the 5-point scale, computed by using the quantitative measures of performance and qualitative inputs from the teachers and the students.

In a practical sense, the in-depth description of intervention implementation methods, technical specifications, and fidelity monitoring is likely to be beneficial for educators and researchers who would like to implement AR-assisted interventions in similar settings.

The present study offers clear support for a major impact of AR on chemistry education by improving students' learning in the aforementioned molecular topics (acid–base, pH, oxide, and salt). The tough three-part test with control over baseline differences (ANCOVA) has established that AR instruction yields large, statistically significant enhancements of student performance (d = 1.18). Beyond performance, AR fosters conceptual comprehension, stimulates active participation, and helps overcome the visualization issues that burden classic chemistry instruction.

The methodological soundness of this study, e.g., between-group measurements at baseline, intervention adherence, and valid statistical controls, gives confidence in the findings. Despite the potential of AR for learning, successful integration of AR needs to consider systematic infrastructure development, teachers' training and continuous technical support for sustainable use.

In conclusion, this study presents strong evidence in support of AR's transformative power in chemistry teaching and valuable insights to support implementation. The results add to theoretical knowledge and provide practical insights for educational technology use in Vietnamese secondary schools and related educational settings.

Recommendations

The study's findings have led to the following recommendations. First, additional interdisciplinary works that investigate (or discover new) uses for AR, particularly in domains that require molecular and atomic interactions, would be helpful. Second, this study needs to continue to investigate the long-term influence of AR on knowledge retention and higher-order thinking skills, away from the short-term effects measured in this chapter. Third, additional research is needed to measure the potential of AR in this space as a way of equalizing education across underprivileged regions that may have limited access to physical laboratory facilities.

The study recommended that TPD should also be sustained for the teachers' education. For the AR system to be effectively embedded in the curriculum, teachers use it not only to be technically proficient, but also to design and implement well-designed and highly straightforward AR lessons that they are comfortable with all pedagogic approaches.

On the policy front, there are essential actions for both the quality of educational delivery and sustainability of student engagement (post-crisis) that include investment in reliable AR infrastructure, developing national repositories for high-quality AR resources (lesson plans, 3D models, interactive simulations, etc.), and integration of AR into blended learning environments.

Limitations

Although this study suggested certain positive impacts of AR on learning chemistry, some limitations should be noted. Firstly, the study was a quasi-experimental study involving students at two lower secondary schools in suburban Hanoi, Vietnam. The results thus might not be transferable to other educational sectors in the country. Second, technological infrastructure restrictions– such as unequal access to devices and instability in internet connection– influenced the use of AR, meaning that some classes did not benefit from the full scope of the possibilities of the use of the technology. Additionally, the research was undertaken over a single semester, which might be insufficient time to validate the longer-term effects of AR on students' understanding of information, retention, or capacity to think critically. Finally, teachers degrees of preparation and training to use the AR were always the crucial variable, though it was not closely examined and analyzed already in this study.

Despite these limitations, future research needs to replicate the results in a larger sample of students attending schools across diverse locations to confirm both the generalizability and relevance of the results presented here. A randomized controlled trial design would also serve to minimize confounding and to derive more robust conclusions e.g., on the effectiveness of AR, while estimating all parameters based on the same samples, which might make these estimates more powerful than any of an adapted design. It is recommended that future studies consider the long-term effects of AR on academic performance and critical-thinking development, which will provide an understanding of the enduring effects of this technology. There is also a great effort to be made in developing and implementing national and comprehensive, teacher-targeted, in-service professional development programs in Greece that would strengthen pedagogical competencies and enable appropriate and flexible interpretation of AR in embedded classroom-based teaching and learning practice.

Ethics Statements

Ethical approval for the study with human participants was provided by the Ethics Committees of Nguyen Du and Nguyen Khe secondary schools (Soc Son and Dong Anh Districts), respectively. Informed consent that had been written were obtained from all participants and from their parents or legal guardians after being given a full explanation of the study's objective and procedure. Informed consent was sought and confidentiality ensured, while voluntary participation was guaranteed, and participants could withdraw from the study at any time without prejudice.

Conflict of Interest

Conflicts of Interest The authors declare that this paper has no conflicts of interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI Statement

As the authors of this article, we utilized the AI tool ChatGPT for search and spelling errors. Finally, we scrutinized our work after first having used the AI tool. We, the authors, are fully responsible for our published work.

Authorship Contribution Statement

Ngoc Son: Conceptualization, supervision, final approval. Dang: Writing, technical support. Hoai: Editing, drafting manuscript. Thai: Data analysis. Chu: Data acquisition, reviewing. Nguyen: Design, interpretation.

References

Akçayir, M., Akçayir, G., Pektaş, H. M., & Ocak, M. A. (2016). Augmented reality in science laboratories: The effects of augmented reality on university students' laboratory skills and attitudes toward science laboratories. *Computers in Human Behavior*, *57,* 334-342. https://doi.org/10.1016/j.chb.2015.12.054

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1-11. https://doi.org/10.1016/J.EDUREV.2016.11.002

Alrige, M., Bitar, H., Al-Suraihi, W., Bawazeer, K., & Al-Hazmi, E. (2021). MicroWorld: An augmented-reality Arabian app to learn atomic space. *Technologies, 9*(3), Article 53. https://doi.org/10.3390/technologies9030053

Bacca, J., Baldiris, S., Fabregat, R., Graf, S., & Kinshuk. (2014). Augmented reality trends in education: A systematic review of research and applications. *Educational Technology and Society*, *17*(4), 133-149. https://www.jstor.org/stable/jeductechsoci.17.4.133

Bazie, H., Lemma, B., Workneh, A., & Estifanos, A. (2024). The effect of virtual laboratories on the academic achievement of undergraduate chemistry students: Quasi-experimental study. *JMIR Form, 15*(8), Article e64476. https://doi.org/10.2196/64476

Bestiantono, D. S., Agustina, P. Z. R., & Cheng, T.-H. (2020). How students' perspectives about online learning amid the COVID-19 pandemic? *Studies in Learning and Teaching*, *1*(3), 133-139. https://doi.org/10.46627/silet.v1i3.46

Billinghurst, M., & Duenser, A. (2012). Augmented reality in the classroom. *Computer*, *45*(7), 56-63. https://doi.org/10.1109/MC.2012.111

Cai, S., Wang, X., & Chiang, F.-K. (2014). A case study of augmented reality simulation system application in a chemistry course. *Computers in Human Behavior, 37*, 31-40. https://doi.org/10.1016/j.chb.2014.04.018

Camp, G., Surma, T., & Kirschner, P. A. (2021). Foundations of multimedia learning. R. E. Mayer, & L. Fiorella (Eds.), In *The Cambridge handbook of multimedia learning* (pp. 17-24). Cambridge University Press. https://doi.org/10.1017/9781108894333.004

Chen, C.-H., Chou, Y.-Y., & Huang, C.-Y. (2016). An augmented-reality-based concept map to support mobile learning for science. *Asia-Pacific Education Researcher*, *25*, 567-578. https://doi.org/10.1007/s40299-016-0284-3

Chen, L., Chen, P., & Lin, Z. (2020). Artificial intelligence in education: A review. *IEEE Access, 8*, 75264-75278. https://doi.org/10.1109/access.2020.2988510

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*(6130), 305-308. https://doi.org/10.1126/science.1230579

Dung, N. T. K., Huy, N. H. D., Hang, N. T., & Hà, D. T. T. (2020). Self-perception of teachers and managers of the impact of teachers' professional development in Vietnam. *Education and Self Development*, *15*(2), 21-30. https://doi.org/10.26907/esd15.2.03

Elmqaddem, N. (2019). Augmented reality and virtual reality in education. Myth or reality? *International Journal of Emerging Technologies in Learning*, *14*(03), 234-242. https://doi.org/10.3991/ijet.v14i03.9289

Garbin Praničević, D. (2021). Augmented reality and virtual reality-based technology in cultural tourism. *ENTRENOVA - ENTerprise REsearch InNOVAtion*, *7*(1), 307-314. https://doi.org/10.54820/mhny8236

Garzón, J., Pavón, J., & Baldiris, S. (2019). Systematic review and meta-analysis of augmented reality in educational settings. *Virtual Reality*, *23*, 447-459. https://doi.org/10.1007/s10055-019-00379-9

Hoai, V. T. T., Son, P. N., An, D. T. T., & Anh, N. V. (2024). An investigation into whether applying augmented reality (AR) in teaching chemistry enhances chemical cognitive ability. *International Journal of Learning, Teaching and Educational Research*, *23*(4), 195-216. https://doi.org/10.26803/ijlter.23.4.11

Hoai, V. T. T., Son, P. N., Duc, N. M., Thao, T. T., Giang, P. T. K., Huu, P. T., Thuong, N. T. K., & Bach, P. G. (2024). The current state of virtual reality and augmented reality adoption in Vietnamese education: A teacher's perspective on teaching natural sciences. *International Journal of Information and Education Technology*, *14*(3), 476-485. https://doi.org/10.18178/ijiet.2024.14.3.2068

Hoai, V. T. T., Son, P. N., Em, V. V. D., & Duc, N. M. (2023). Using 3D molecular structure simulation to develop chemistry competence for Vietnamese students. *Eurasia Journal of Mathematics, Science and Technology Education*, *19*(7), Article em2300. https://doi.org/10.29333/ejmste/13345

Holbrook, J., & Rannikmae, M. (2009). The meaning of scientific literacy. *International Journal of Environmental and Science Education*, *4*(3), 275-288.

Hou, H.-T., & Lin, Y.-C. (2017). The development and evaluation of an educational game integrated with augmented reality and virtual laboratory for chemistry experiment learning. In *2017 6th IIAI International Congress on Advanced A Hoài pplied Informatics (IIAI-AAI)* (pp. 149-150). IEEE. https://doi.org/10.1109/IIAI-AAI.2017.14

Hu, W., Wu, B., Jia, X., Yi, X., Chunyan, D., Meyer, W., & Kaufman, J. C. (2013). Increasing students' scientific creativity: The "learn to think" intervention program. *The Journal of Creative Behavior, 47*(14), 3-21. https://doi.org/10.1002/jocb.20

Huang, K.-T., Ball, C., Francis, J., Ratan, R., Boumis, J., & Fordham, J. (2019). Augmented versus virtual reality in education: An exploratory study examining science knowledge retention when using augmented reality/virtual reality mobile applications. *Cyberpsychology, Behavior, and Social Networking*, *22*(2), 105-110. https://doi.org/10.1089/cyber.2018.0150

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

Ibañez-Etxeberria, A., Gómez-Carrasco, C. J., Fontal, O., & García-Ceballos, S. (2020). Virtual environments and augmented reality applied to heritage education. An evaluative study. *Applied Sciences*, *10*(7), Article 2352. https://doi.org/10.3390/app10072352

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*(2), 75-83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Lu, S.-J., Lin, Y.-C., Tan, K. H., & Liu, Y.-C. (2022). Revolutionizing elementary disaster prevention education and training via augmented reality-enhanced collaborative learning. *International Journal of Engineering Business Management*, *14*, 1-15. https://doi.org/10.1177/18479790211067345

MacLennan, A. (2019). Book review: KJ Varnum (ed.), Beyond reality: Augmented, virtual, and mixed reality in the library. *Journal of Librarianship and Information Science*, *53*(4), 709-710. https://doi.org/10.1177/0961000619890757

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record, 108*(6), 1017-1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Nguyen, H. N. (2022). Motivations and barriers to embracing augmented reality: An exploratory study with Vietnamese retailers. *Innovative Marketing, 18*(3)*,* 28-37. https://doi.org/10.21511/im.18(3).2022.03

Piaget, J. (1972). A structural foundation for tomorrow's education. *Prospects, 2,* 12-27. https://doi.org/10.1007/bf02195648

Ripsam, M., & Nerdel, C. (2024). Augmented reality for chemistry education to promote the use of chemical terminology in teacher training. *Frontiers in Psychology, 15*, Article 1392529. https://doi.org/10.3389/fpsyg.2024.1392529

Shumaker, R., & Lackey, S. (Eds.). (2014). *Virtual, augmented and mixed reality. Applications of virtual and augmented reality*. Springer. https://doi.org/10.1007/978-3-319-07464-1

Syskowski, S., Lathwesen, C., Kanbur, C., Siol, A., Eilks, I., & Huwer, J. (2024). Teaching with augmented reality using tablets, both as a tool and an object of learning. *Journal of Chemical Education*, *101*(3), 892-902. https://doi.org/10.1021/acs.jchemed.3c00607

Tene, T., Marcatoma Tixi, J. A., Palacios Robalino, M. D. L., Mendoza Salazar, M. J., Vacacela Gomez, C., & Bellucci, S. (2024). Integrating immersive technologies with STEM education: A systematic review. *Frontiers in Education*, *9*, Article 1410163. https://doi.org/10.3389/feduc.2024.1410163

Thái, H. M., & Nguyễn, M. T. (2020). Ứng dụng công nghệ thực tế tăng cường nhằm nâng cao hứng thú học tập cho học sinh trong dạy học nội dung hóa học hữu cơ lớp 11 trung học phổ thông [Application of augmented reality technology to improve students' interest in learning organic chemistry content in grade 11 of high school]. *Ho Chi Minh City Journal of Science/Tạp chí Khoa học Trường Đại học Sư phạm TP Hồ Chí Minh*, *17*(11), 1970-1983. https://doi.org/10.54607/hcmue.js.17.11.2848(2020)

Wu, H.-K., Lee, S. W.-Y., Chang, H.-Y., & Liang, J.-C. (2013). Current status, opportunities and challenges of augmented reality in education*. Computer and Education, 62,* 41-49. https://doi.org/10.1016/j.compedu.2012.10.024

Zacharia, Z. C., & Olympiou, G. (2011). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction*, *21*(3), 317-331. https://doi.org/10.1016/j.learninstruc.2010.03.001