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DEVELOPING AUGMENTED REALITY CLASSROOM USING TPACK MODEL FOR TEACHING GENERAL CHEMISTRY IN HIGH SCHOOLS

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Abstract. In the digital transformation era, the integration of Information Technology in education is pivotal. Augmented Reality (AR), with its capacity to visualize abstract concepts, is increasingly recognized as a valuable tool in Chemistry education. The abstract nature of general Chemistry content, like the visualization of atoms and molecules, poses significant comprehension challenges for high school students. This study aims to investigate the effectiveness of AR in enhancing the understanding of general Chemistry among high school students using the Technological Pedagogical Content Knowledge (TPACK) model. The research data included 90 high school chemistry teachers from high schools in four northern provinces, collected through classroom observations and surveys using a 5-point Likert scale; the data were analyzed using both descriptive and inferential statistics. The findings indicate significant improvements in students' understanding of Chemistry when taught using AR-integrated lessons designed with the TPACK model. Students demonstrated enhanced engagement, better conceptual grasp, and increased satisfaction with the learning process. AR technology, when integrated with the TPACK framework, substantially enhances the learning of general Chemistry in high schools. This study supports the broader application of AR in educational settings to improve the effectiveness of teaching and learning processes.

Keywords: augmented reality, TPACK model, chemistry education, general chemistry, high school.

1. Introduction

The application of Information Technology in education has become an undeniable trend in the current era of digital transformation [1]. This is particularly important because relying solely on available textbooks may lead to the omission of significant content [2]. The application of Augmented Reality (AR) technology, with its numerous advantages, has proven its value, especially in the field of Chemistry Education [3].

For topics covered in the general Chemistry curriculum of the 2018 Education program, a majority of the content is abstract in nature. Many of the objects and phenomena described within the general Chemistry curriculum are not visible to the naked eye, making it challenging for students to visualize and comprehend during the learning process [4]. Concepts such as atoms, molecules, electron orbitals, and chemical bonds remain abstract when students rely solely on textbook images. This presents a major difficulty when approaching the general Chemistry curriculum and is a reason why many students are hesitant to engage in and study Chemistry. Therefore, the application of Information Technology following the TPACK model can make Chemistry more accessible and vivid, thereby enhancing the interest and active participation of high school students in the subject [5].

In this context, the emergence of AR partly addresses the aforementioned challenges due to its outstanding advantages. AR supplements real-world environments by incorporating additional details to enhance students' learning experiences [6]. The 3D virtual environment stimulates a more visual and dynamic approach to learning Chemistry. AR utilizes interactive features that allow students to manipulate objects by zooming in and out, rotating objects, and programming objects to conduct experiments following predefined procedures. As a result, AR is widely adopted in various domains of life. In education, AR is often applied during the teaching process to facilitate students' exploration of knowledge, enhance spatial imagination, improve concentration, and provide a visual representation of abstract concepts. AR-based learning products create an extremely engaging learning environment [7]. However, AR and virtual reality products are not yet widely prevalent in Vietnam.

Therefore, it is highly necessary to conduct research on the application of AR in Chemistry education. In this study, the research team has designed AR-integrated lessons for the general Chemistry curriculum following the TPACK model, aiming to provide students with an exciting learning environment and enhance their enthusiasm for learning [8]. These findings serve as a basis for proposing measures to develop students' qualities and competencies in accordance with the new General Education program [7].

2. Content

2.1. Research methods

**** Research design***

This scientific study investigates the use of augmented reality technology, interactions, and the teaching of general chemistry in high school through the Technological Pedagogical Content Knowledge (TPACK) model. Research objectives of the study include investigation of the effect of the AR technology integration on students' general chemistry understanding, the impact of the TPACK model on the effective integration of AR in chemistry instruction, and the physical and mental experiences during the learning of chemistry using the AR. The data were collected through classroom observation, surveys, and interviews. Quantitative data were described and inferred using descriptive and inferential statistics, while qualitative data were broken down into thematic analyses. Ethical issues will be taken into account: informed consent as well as confidentiality and privacy of the individuals. The limitations of the study include the context-specific manner and the potential challenges the availability of AR technology may pose. The research design intends to add to the grasp of AR and the TPACK model on teaching and learning general chemistry in high school, leading to the enrichment of the practices in the field and the shaping of the curriculum as well.

**** Participants***

The research timeline of the study is from October 2023 to April 2024. The current scientific exploration studies 90 high school teachers. The survey was conducted in Ha Noi, Nghe An, Ha Nam, and Thai Nguyen, which were representative educational sites in Vietnam. Teachers were selected strictly based on their knowledge of chemistry, ensuring that they could share beneficial experiences with the combination of augmented reality and the TPACK model. Teachers and students were active members engaged in better understanding how learning is affected by the application of AR technology and how it, in turn, affects instructional strategies and outcomes. A questionnaire was used to gather quantitative information about participants' characteristics, prior involvement with AR, their comfort level with educational technology, and their perceptions of the impact of AR in improving their comprehension of chemistry concepts in general. The participation of teachers from various locations enhanced the appreciation of this approach and the identification of potential challenges that may arise when using AR and the TPACK model in high school.

**** Data collection instruments and data analysis***

The data were collected through the online survey with a set of criteria. The sentence items were formulated using five-point Likert scale closed-ended questions ranging from 'Strongly Disagree’ to 'Strongly Agree’. The questionnaire was run for teachers and a total of 90 samples were collected. Descriptive analysis of all quantitative data was performed using the Statistical Package for the Social Sciences (SPSS) software program (version 27.0). Descriptive statistical analysis was conducted to calculate Cronbach's alpha (CA), Mean (M), Standard Deviations (SD), Exploratory factor analysis (EFA), and ANOVA for each item, assessing their respective levels.

2.2. Augmented reality in education

Augmented reality is the integration of digital information with the user's environment in Real Time. Unlike virtual reality, which creates an artificial environment, AR users experience a real-world environment with generated perceptual information overlaid on top of it [9]. Augmented reality is used to either visually change natural environments in some way or to provide additional information to users. The primary benefit of AR is that it manages to blend digital and three-dimensional (3D) components with an individual's perception of the real world [10]. AR has a variety of uses, from helping in decision-making to entertainment [11].

AR delivers visual elements, sound, and other sensory information to the user through a device like a smartphone or glasses [12]. This information is overlaid onto the device to create an interwoven experience where digital information alters the user's perception of the real world. The overlaid information can be added to an environment or mask part of the natural environment.

Recent studies show that augmented reality is becoming more and more popular, benefiting various industries and it has been proven to have huge opportunities in the field of education. In 2013, Di Serio, Ibáñez, and Kloos conducted a comparative study and they found that the level of concentration and satisfaction of students in learning environments with augmented reality applications was higher than in learning with slides [13].

The AR experience is thriving as a significant trend, and it is estimated that by 2023 there will be 2.4 billion augmented reality mobile users worldwide [14]. However, there were only 200 million users in 2015. It is an excellent influx in numbers that can't be ignored. However, it is about the staggering number that is looming around the usage of augmented reality in education and eLearning applications. Many people are only aware of augmented reality being used in mobile games like Pokémon Go which went viral in 2016 all over the globe and social media platforms like Snapchat. However, education is another significant space where this technology can blow up the candles.

Another aspect of the AR experience is that it includes 25% digital reality and 75% existing reality. It means it doesn't replace the complete environment with the virtual; rather, it integrates virtual objects into the real world.

With AR, classroom education can be extraordinary and more interactive, as AR can enable teachers to show virtual examples of concepts and add gaming elements to provide textbook material support. This will enable students to learn faster and memorize information.

2.3. TPACK model

TPACK stands for "Technological pedagogical and content knowledge". The TPACK model is a theoretical framework that emphasizes the integration of technology, teaching, and content knowledge in educational environments. It is used to guide the effective integration of technology into teaching and learning methods. This framework recognizes that effective teaching with technology requires an understanding of the interaction between these three elements: technology (T), pedagogy (P), and content (C). The TPACK framework combines and rearranges the three types of knowledge - TK, PK, and CK - in various ways. (TPK) focuses on the connections and interactions between technological tools and pedagogical practices, (PCK) focuses on the connections between pedagogical practices and specific learning objectives, and (TCK) focuses on the relationships and intersections between technologies and learning objectives [15]. These interrelated areas form the TPACK framework, which recognizes the interplay among all three areas and acknowledges that educators operate within this intricate space.

With TPACK, teachers not only possess subject matter knowledge in Chemistry but also understand how to teach and use technology in the process of knowledge transmission. The TPACK model allows teachers to effectively utilize technology to convey Chemistry knowledge to students. By integrating subject matter knowledge in Chemistry, pedagogical knowledge, and technological knowledge, teachers can design and implement creative and interactive learning activities. Technology enhances student engagement and understanding while providing opportunities for them to apply Chemistry knowledge in practical contexts.

In this paper, we have included the TPACK model as the main framework to introduce AR into teaching with three fundamental elements: content, pedagogy, and technology, as well as the interconnections and interactions among them. Teaching with technology is difficult to do well. The TPACK framework suggests that content, pedagogy, technology, and teaching/learning contexts have roles to play individually and together. We believe that it is the foundation to effectively apply technology to teaching. Teaching successfully with technology requires continually creating, maintaining, and re-establishing a dynamic equilibrium among them. These core elements will be briefly summarized in the following section:

Content Knowledge

Teachers need to understand and master knowledge of chemical structures, chemical formulas, chemical reactions, etc. They must know how to design AR products to visualize chemical bonds, experiments, and more. This specialized knowledge is necessary to explain and guide students in using the products correctly.

Pedagogical Knowledge

Teachers need to have knowledge of appropriate teaching methods to use software in teaching Chemistry. They can design activities such as visual lectures, practice drawing chemical bonds, and solve exercises related to the lesson. Teaching knowledge helps teachers create an interactive and engaging learning environment for students so that they can absorb knowledge most effectively.

Technological Knowledge

Teachers need to know how to use and exploit the features of Cospaces Edu software. This technological knowledge helps teachers take full advantage of the potential of Cospaces Edu software and create rich and diverse learning activities.

2.4. Designing and using augmented reality technology applying the TPACK model to students in teaching chemistry

2.4.1. Design principles

To apply AR in teaching chemistry effectively, when designing products using augmented reality, we must research based on proposed theories and practical knowledge. When designing an AR product, it is necessary to ensure the following goals: knowledge, skills, attitudes and capacity development orientation. When designing products using AR, you need to ensure the following principles:

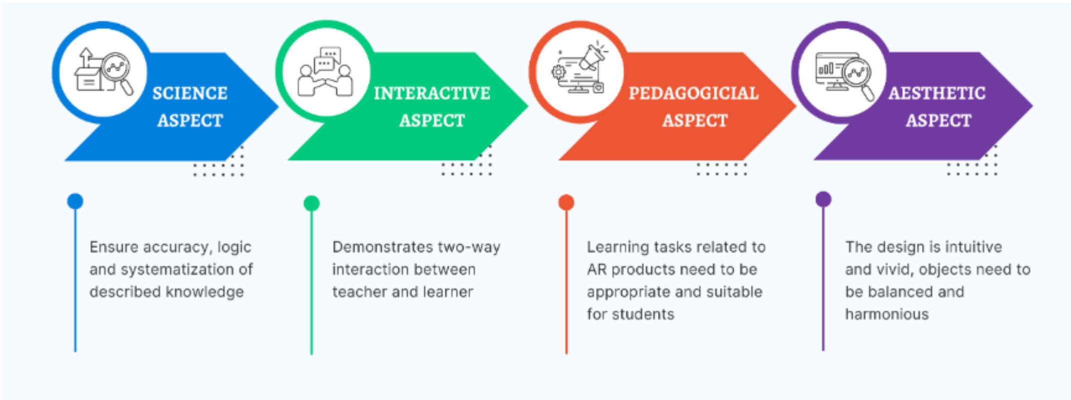

Figure 1. AR design principles in education (Source: own author)

2.4.2. Design process

Figure 2. AR product design process in teaching chemistry (Source: own author)

Step 1: Determine the target

This is the most important step in the process, guiding the steps that follow. In this step, teachers need to identify the requirements and goals to be achieved for the product. Analyze the content and nature of things and phenomena.

Step 2: Create an outline

Based on the set goals, teachers plan the content, form, and organization of teaching activities using AR products, through which teachers can choose appropriate design tools and find resources to implement teaching ideas.

Step 3: Create the content

Based on the scenario and the resources found, the teacher builds detailed content for the AR product. Content includes quotes, information, images, models, questions, order of appearance, and how to set up effects between parts of content.

Step 4: Artistic design

The teacher uses the selected design tool, inserts the built content into the AR product, and adjusts the objects in the product in terms of color, size, layout, and font style to harmonize. spectacular. Then set effects for objects according to the proposed ideas.

Step 5: Evaluation

Teachers re-examine the product to find inappropriate points in the technical design process, content creation, and sometimes ideas and goals. Teachers find explanations and conclusions if a product defect is discovered.

2.4.3. Designing augmented reality products using CoSpaces Edu application

CoSpaces Edu is a 3D graphics application for education, running on web browsers, iOS, Android, and Windows operating systems. CoSpaces Edu application allows users to design and experience content with many different modes such as gyroscope, virtual reality, augmented reality, etc.

This application was developed specifically for education so it is suitable for teachers and students. Experiencing AR through the CoSpaces Edu application can be done easily with a smartphone with an internet connection and the application installed. After reviewing the features and usage of the CoSpaces Edu application, we decided to choose the CoSpaces Edu application to design AR products.

We researched the application of AR to design model 3D, games, etc., applications in teaching Chemistry. The research team has designed the following products.

Table 1. List of AR products designed

No	Name of products	QR - Code	Link to products
1	Ionic bond formation		https://edu.cospaces.io/YFX-WZQ
2	Covalent bond formation		https://edu.cospaces.io/RVK-MLG
3	Periodic Table		https://edu.cospaces.io/YWM-JLE
4	Noble gas's atomic structure		https://edu.cospaces.io/YUE-KRC
5	Electrochemical Battery		https://edu.cospaces.io/PHQ-PTM
6	Laboratory AR		https://edu.cospaces.io/UCQ-KUN

Designing lessons using AR in the general basic chemistry content has helped increase learning efficiency and make the learning process more interesting. AR makes lessons more attractive, bringing a new learning experience instead of reading books and doing tests, thereby making self-study more effective. Besides, AR can interact with learners using sight and touch, thus making learners attracted and focused [20 – 21]. This helps learners easily visualize and understand difficult concepts even though they are studying by themselves without getting bored.

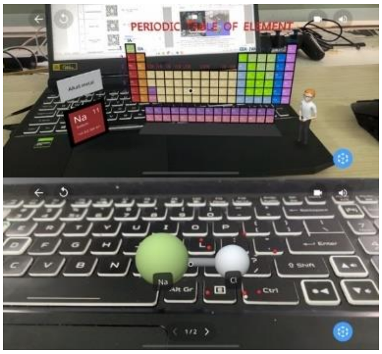

Figure 3. Image of some AR-Designed products

2.5. Results

Table 2 provides a comprehensive look at the study participants, which is essential for understanding the survey conditions. The table shows the demographics of the 90 study participants, including gender, age, seniority, degree, and workplace.

Female participants outnumber male participants by 68 (75.6%) to 22 (24.4%). Gender distribution is important for contextualizing survey responses because it affects AR perception and adoption in education. The majority of participants (34.4%) are 22–30 years old, followed by 41–50 years old (31.1%). The survey's diverse age range ensures a broad perspective on AR technology expertise and opinions. A large percentage (54.4%) of participants have over a decade of experience, indicating that experienced educators contributed to the findings. This may require a deeper understanding and informed evaluation of augmented reality in education.

Most participants have Bachelor's degrees (76.7%), while a smaller percentage have Master’s (17.8%). A large percentage of survey respondents have a strong educational background. Their AR technology opinions and feedback are more credible. The majority (81.1%) of their workplaces are public, which is likely typical of the educational sector. AR technology adoption and use in these settings may be affected.

Table 2. Survey items and Cronbach's alpha

Items	**Factor and description**	**Cronbach's Alpha**
Factor A. Quality educational content when applying AR in teaching		
A1	Content with AR applications suitable for students and educational programs.	0.939
A2	Difficult and abstract knowledge will be described more accurately and scientifically when presented through AR.	0.934
A3	The level of attractiveness and interaction of content when applying AR in lessons, including visual and sound effects.	0.930
A4	The ability of AR content to provide deeper knowledge than traditional methods.	0.939
A5	Learning content is more diverse and richer when provided with knowledge and skills through AR applications.	0.933
A6	Student feedback on the clarity and understandability of learning content when applying AR.	0.936
A7	The support of AR content helps showcase the different learning styles of students.	0.929

Factor B. Impact of AR on learning outcomes		
B1	Enhance problem solving and critical thinking related to chemistry using AR.	0.941
B2	The degree to which students apply knowledge learned through AR into practice.	0.946
B3	Students' awareness and learning outcomes are better after applying AR.	0.947
B4	Students' confidence in practicing when experiencing virtual experiments through AR before practicing in a real environment.	0.942
B5	Students' ability to remember basic concepts in chemistry is longer after participating in an AR class.	0.939
B6	Students' participation and interaction are more active in the learning process with AR content	0.939
Factor C. Student interaction and cooperation when applying AR in teaching		
C1	The level of interaction of students with each other and with the lesson is better through the AR application.	0.921
C2	Student participation and interaction in group activities are better when using AR.	0.903
C3	The frequency and quality of interaction between students and teachers is more effective in an AR learning environment	0.893
C4	Students feel more motivated and supported by friends and teachers in an AR learning environment	0.889
Factor D. Student satisfaction and learning attitude when using AR		
D1	Students feel satisfied with their experience using AR in learning.	0.927
D2	Students are more interested in learning when learning through AR compared to traditional methods.	0.934
D3	Students want to continue using AR in subsequent lessons in Chemistry.	0.931
D4	Students feel comfortable and have no difficulty applying AR in learning.	0.941
Factor E. Students' problem-solving skills when applying AR classrooms		
E1	Students apply learned knowledge to solve specific problems after experiencing learning through AR.	0.942
E2	Students are creative and unique in solving problems in the AR learning environment.	0.924
E3	Students work in groups more effectively in the process of learning AR applications.	0.903
E4	Students are more confident when solving complex chemistry problems and learning tasks through AR applications.	0.910
Factor F. The development of teachers' TPACK skills when applying AR		
F1	Teachers understand and apply the TPACK model better in teaching with AR applications.	0.912
F2	Teachers Integrate AR technology into better teaching and learning activities.	0.914
F3	The quality and effectiveness of lectures when teachers apply TPACK are better than traditional lessons (No application of AR in teaching).	0.927
F4	Teachers develop better expertise by incorporating TPACK and AR into teaching.	0.925

Table 3 analyses survey items on several factors that affect educational AR implementation. The table lists six criteria, including AR instructional content quality and teacher TPACK development. Each factor has survey items and Cronbach's alpha values, which indicate item reliability.

The Cronbach's alpha coefficients for all factors exceed 0.89, indicating high internal consistency and reliability of survey responses across many questions within each component. Factor A, which evaluates AR-based educational content, has alpha values from 0.929 to 0.939. AR-provided educational information was consistently rated higher in quality and appeal.

Factor B, which examines how augmented reality affects educational achievement, also has strong alpha values (0.939 to 0.947), indicating that AR improves problem-solving, information application, and learning retention in chemistry.

Factors C and D show how AR affects student interaction, cooperation, contentment, and learning attitude. The alpha values show that participants agree that AR improves these traits.

Factor E develops students' problem-solving skills in AR classrooms. Items E1 to E4 reliably assess how AR improves creativity, group collaboration, and confidence in solving difficult chemical problems.

Factor F uses AR to assess teachers' TPACK skills, focusing on technological, pedagogical, and content knowledge. Responses were consistent, with alpha values ranging from 0.912 to 0.927, indicating that augmented reality improves teachers' teaching skills.

Table 3. Descriptive statistics

	N	*Mean*	*Std. Deviation*	*Variance*	*Skewness*		*Kurtosis*	
	Statistic	*Statistic*	*Statistic*	*Statistic*	*Statistic*	*Std. Error*	*Statistic*	*Std. Error*
Factor A. Quality educational content when applying AR in teaching								
A1	90	4.00	0.835	0.697	-0.949	0.254	1.404	0.503
A2	90	4.01	0.855	0.730	-1.016	0.254	1.932	0.503
A3	90	4.14	0.894	0.799	-1.353	0.254	2.404	0.503
A4	90	4.00	0.793	0.629	-0.829	0.254	1.511	0.503
A5	90	4.12	0.885	0.783	-1.240	0.254	2.180	0.503
A6	90	4.00	0.848	0.719	-0.905	0.254	1.173	0.503
A7	90	4.01	0.930	0.865	-1.051	0.254	1.269	0.503
Factor B. Impact of AR on learning outcomes								
B1	90	3.93	0.832	0.692	-0.951	0.254	2.006	0.503
B2	90	3.94	0.879	0.772	-1.008	0.254	1.623	0.503
B3	90	3.99	0.906	0.820	-0.999	0.254	1.365	0.503
B4	90	4.01	0.942	0.888	-1.012	0.254	1.081	0.503
B5	90	4.01	0.906	0.820	-1.043	0.254	1.470	0.503
B6	90	4.16	0.886	0.785	-1.305	0.254	2.343	0.503

Factor C. Student interaction and cooperation when applying AR in teaching								
C1	90	4.04	0.763	0.582	-0.696	0.254	0.589	0.503
C2	90	4.07	0.859	0.737	-0.566	0.254	-0.437	0.503
C3	90	3.97	0.841	0.707	-0.865	0.254	1.146	0.503
C4	90	4.04	0.873	0.762	-0.916	0.254	0.966	0.503
Factor D. Student satisfaction and learning attitude when using AR								
D1	90	4.00	0.861	0.742	-1.188	0.254	2.273	0.503
D2	90	4.08	0.915	0.837	-1.148	0.254	1.637	0.503
D3	90	4.04	0.860	0.740	-1.170	0.254	2.274	0.503
D4	90	4.02	0.899	0.808	-1.088	0.254	1.639	0.503
Factor E. Students' problem-solving skills when applying AR classrooms								
E1	90	4.01	0.841	0.708	-0.832	0.254	1.044	0.503
E2	90	4.13	0.837	0.701	-1.315	0.254	2.988	0.503
E3	90	4.07	0.897	0.804	-1.184	0.254	1.909	0.503
E4	90	4.11	0.917	0.841	-1.118	0.254	1.510	0.503
Factor F. The development of teachers' TPACK skills when applying AR								
F1	90	3.98	0.807	0.651	-0.878	0.254	1.495	0.503
F2	90	4.11	0.841	0.707	-0.911	0.254	1.139	0.503
F3	90	4.09	0.895	0.801	-0.851	0.254	0.558	0.503
F4	90	4.09	0.830	0.689	-1.255	0.254	2.910	0.503

Table 4 provides a detailed statistical analysis of how augmented reality affects Chemistry instruction. Each of the six factors in the table is assessed with multiple items. It gives the mean, standard deviation, variance, skewness, and kurtosis for each item and the number of responses (N=90).

All items had average ratings of 3.93 to 4.16, indicating that respondents generally liked using augmented reality in Chemistry. Factor B (AR's impact on learning outcomes) and Factor E (Students' problem-solving skills when using AR in classrooms) have means above 4.0. This suggests that AR improves learning and problem-solving. The standard deviation values (0.763–0.942) show little variation in responses. The responses were not widely distributed and clustered around the average, supporting the positive assessment of AR's influence. The skewness values for all items are negative, showing a distribution with a longer tail on the left side. This implies that most responses were high-end. Kurtosis values, though diverse, often show a sharp peak, indicating that the responses were positive and well aligned.

Table 4's statistical data strongly suggest that AR technology is well-received and useful in improving high school chemistry teaching. The consistency in responses across several parameters shows that augmented reality can improve educational content, learning outcomes, student participation and happiness, and problem-solving skills. AR also helps instructors develop TPACK. These data are crucial to the results section, showing how AR affects modern educational models.

Table 4. **ANOVA**

Dependent Variable: Workplace

ANOVA[a]					
Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	20.981	29	0.723	1.980	.013[b]
Residual	21.919	60	0.365		
Total	42.900	89			

(Analysis: Sig < 0.05 suitable impact factor...)

Model summary					
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.699[a]	0.489	0.242	0.604	2.032

(Analysis: 1.5 < Durbin-Watson value < 2.5 suitable impact factors...)

The ANOVA analysis in Table 4 examines how several factors affect the 'Workplace' variable. This variable shows how diverse employment contexts affect education AR technology adoption.

Table 5 shows a significant F-value (F = 1.980) with a significance (Sig.) level of 0.013, below the widely accepted 0.05. This suggests that the workplace affects the dependent variable because there are statistically significant differences between groups. This finding is crucial to understanding the potential differences in augmented reality implementation and efficacy in Chemistry instruction across educational settings. The R-squared value of 0.489 indicates that the model's independent variables explain 48.9% of the dependent variable's variability. This percentage is high, but it also suggests that factors not considered in this model account for more than 50% of variation. The corrected R-square value, which accounts for model predictors, is 0.242. The value is significantly lower than the R-squared, suggesting that some predictors may not be contributing to the model or that there may be too many predictors in the data. The Durbin-Watson statistic, used to detect autocorrelation in regression analysis residuals, has a value of 2.032. Assuming no residual autocorrelation and an appropriate regression model, the result is within the acceptable range of 1.5 to 2.5.

The ANOVA results from Table 4 show that the workplace setting significantly affects the variables under investigation in an augmented reality classroom using the Technological Pedagogical Content Knowledge (TPACK) model for teaching Chemistry. The model also suggests that other factors affect augmented reality's effectiveness in education. These findings emphasize the importance of considering the workplace when using AR technologies in high school Chemistry instruction.

3. Conclusions

This research proved the effectiveness of augmented reality, integrated with the Technological Pedagogical Content Knowledge (TPACK) framework in enhancing the teaching and learning of general chemistry in high schools. It instilled the students with the visualization of the abstract concept of the chemicals and, most importantly, kept them on their toes, as students, which increased their understanding and retention of the subject matter.

The findings indicate that the use of AR in chemistry education leads to a deeper comprehension of complex topics such as atomic structures, molecular interactions, and chemical reactions. The AR application can overlay digital information in the real world. In other words, it allows students to view and interact with the 3D model of chemical structures, effectively bridging the gap between theoretical knowledge and visual representation.

AR technology deployment is technologically sound, pedagogically robust, and content-specific thanks to the TPACK framework. TPACK-equipped teachers can implement AR solutions that meet educational goals, improving teaching strategies and student outcomes. Positive student and teacher feedback on the AR-enhanced lessons shows the value of combining technology with pedagogical strategy and content knowledge.

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