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FACTORS INFLUENCING TEACHERS' ADOPTION OF AUGMENTED REALITY IN HIGH SCHOOL CHEMISTRY EDUCATION

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Abstract

The integration of Augmented Reality technology into education holds significant potential for enhancing teaching and learning practices, particularly in complex subjects like Chemistry. Despite these benefits, its adoption among high school chemistry teachers remains low, necessitating an exploration of influencing factors. This study aims to investigate the determinants of AR adoption by high school chemistry teachers through a comprehensive analysis of individual, contextual, and technological factors. A mixed-methods approach was employed, combining quantitative data collection through surveys and qualitative insights from interviews. The findings reveal that technological proficiency, pedagogical compatibility, resource availability, training and support, and institutional encouragement are critical drivers of AR adoption. Furthermore, perceived efficacy significantly influences teachers' willingness to integrate AR in their teaching practices. These results underscore the importance of tailored interventions, including targeted training programs and resource allocation, to support teachers in leveraging AR technology effectively. This study contributes to the growing body of literature on educational technology adoption and provides actionable insights for policymakers and educators seeking to enhance the implementation of AR in science education.

Keywords – Augmented reality, Chemistry education, Teacher adoption, High schools, Educational technology.

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1. Introduction

Augmented Reality (AR) technology has emerged as a transformative technology in recent years, driving innovative ways to improve teaching and learning dynamic. AR allows a blend of digital objects with the real-world environment, serving to make abstract and complex concepts more tangible and interactive. AR offers unique opportunities within Chemistry education to visualize molecular structures, simulate chemical reactions, and promote inquiry-based learning, which collectively address long-standing challenges in engaging students with abstract scientific concepts (Zheng & Waller, 2017).

AR's usage in high school chemistry settings is low despite its power. The discrepancy can be due to many reasons—from the unavailability of resources, to inadequate teacher-training and the lack of institutional support. It is essential to comprehend these elements in order to develop strategies that encourage the acceptance and optimal use of AR technology in the field of education (Huang, Ball, Francis, Ratan, Boumis & Fordham, 2019). This study will review the greatest difficulties in the widespread implementation of AR in Chemicalogy education, which is the high school teacher reluctance to embrace this technology. ALl aforementioned technological and pedagogical advantages of AR are well explored so far, but factors that affect teachers' AR adoption have been investigated only in few studies. It is imperative to fill this gap to create practical mechanisms that enable AR adoption, leading to improved educational outcomes in the field of Chemistry.

Existing literature has demonstrated a number of predictors of educational technology adoption including teachers' technological expertise, teaching philosophy and interests, resource availability, and institutional support. Studies by Chen and Arici show is how AR can deepen the understanding from students towards the complex subjects by allowing them to engage in immersive learning experiences (Arici, Yildirim, Caliklar & Yilmaz, 2019; Chen, Chen & Lin, 2020). Nonetheless, hurdles such as teachers' opposition to change, unfamiliarity with AR tools, and infrastructure limitations have received consistent reports. Our findings indicate that more controlled and elaborate explorations of the relationship between users, factions, and the technology itself are warranted.

This study aims to bridge the knowledge gap by examining the determinants of high school chemistry teachers' intention to adopt AR through the identification and analysis of the main predictors. More specifically, the study looks at:

1. Individual factors such as technological proficiency and perceived efficacy of AR in teaching.
2. Contextual factors including pedagogical compatibility, institutional support, and resource availability.
3. Technological factors like the usability and accessibility of AR tools.

In addressing these aims, this study looks to furnish evidence-based findings for the design of targeted interventions and professional development programs by educators, policy makers, and technology developers. Expand your knowledge of technology adoption in education by taking a closer look at AR in a secondary school context. This study represents a small step toward informing practices that will help schools and teachers address some of the barriers that currently inhibit more widespread adoption so that high school Chemistry teachers can use AR to support the full potential of student learning outcomes.

2. Literature Review

AR technology in education has demonstrated significant potential due to its ability to integrate virtual content into real-world environments, thereby promoting interactivity and immersion. AR helps students grasp abstract concepts in science, particularly chemistry, by simulating molecular structures or reaction mechanisms using 3D models (Hoai, Son, Em & Duc, 2023; Wu, Lee, Chang & Liang, 2013). The development of mobile, graphics, and programming technologies has allowed ever more diverse AR applications, ranging from simple text overlays to interactive 3D content that fosters constructivist learning (Rana, Sharma, Sarkar & Choudhary, 2021; Turner, 2022; Yoon, 2023). Owing to its intuitive nature, AR encourages students to explore independently, receive immediate feedback, and stay engaged (Ibáñez & Delgado-Kloos, 2018). Research has also noted AR's positive effects on student interest, motivation, and learning outcomes (Centorrino, Condemi, di Paola & Ferrigno, 2021; Dunleavy & Dede, 2014).

In the chemistry learning environment, AR enhances the observation of microscopic phenomena, assisting students in understanding molecular shapes, reaction steps, and interaction mechanisms. This leads to improved critical thinking and problem-solving skills (Bacca, Baldiris, Fabregat, Graf & Kinshuk, 2014; Martins, Tomczyk, Amato, Eliseo, Oyelere, Akyar et al., 2020). Theoretically, the Technology Acceptance Model (TAM) (Davis, 1989) indicates that "perceived usefulness" and "perceived ease of use" determine users' acceptance of technology; this has been extended within AR contexts by emphasizing AR's practicality in teaching (Arici et al., 2019; Koçak, Yilmaz, Kucuk & Göktaş, 2019). Moreover, the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh, Morris, Davis & Davis, 2003) highlights the role of social influence and supportive conditions in schools, including continuous training and robust technical infrastructure, to enhance teacher confidence (Wang & Chen, 2019). Teachers' belief in their own capabilities—aligned with Bandura's and Schunk's perspectives—is also a critical factor influencing AR adoption (Bandura, Freeman & Lightsey, 1999; Schunk, 1995).

Various studies point to three main groups of factors affecting AR adoption: individual competence, school environment, and technological characteristics (Hwang, 2014; Tang, Chen, Law, Wu, Lau, Guan et al., 2021). When teachers have strong digital skills, they encounter fewer technical barriers and are more inclined to experiment with AR (Kaufmann, Schmalstieg & Wagner, 2000). At the same time, successful AR-based teaching depends on policy support and adequate resources from schools, such as providing devices, training, and professional development opportunities (Dunleavy & Dede, 2014; Tsai, Lin, Chang, Chang & Lee, 2020). Nevertheless, many obstacles persist, including limited funding, inconsistent infrastructure, and teachers' reluctance toward technology (Hew & Brush, 2007; Short, Clarke, Carnelli, Uttley & Smith, 2018). Even so, AR is highly valued for enhancing instructional quality—particularly at the secondary level—through creating active learning environments (Clark-Louque & Latunde, 2019). A comprehensive approach involving long-term investments, professional training, and interdisciplinary collaboration will help leverage AR's enduring effectiveness while opening new research avenues on its sustainability and scalability in education.

Technological Proficiency (TP). The effective integration of AR technologies in educational environments, especially in the teaching of challenging topics like Chemistry, hinges on teachers' technological expertise. Research has highlighted the need for instructors to possess the skills to effectively utilize both hardware and software components of AR technologies (Phan, Aguilera & Tracz, 2021). This proficiency encompasses not only fundamental operational skills but also a deeper understanding of how AR can be manipulated to enhance learning outcomes (Marrahi-Gomez & Belda-Medina, 2023). Teachers' confidence in using technology in their classrooms and their openness to embracing new tools are directly linked to their technological competence (Torrato, Prudente & Aguja, 2020). Research indicates that higher levels of technological proficiency are strongly correlated with a greater likelihood of AR adoption, as they reduce perceived complexity and improve the usability of AR applications in educational settings (Ronaghi, Ronaghi & Boskabadi, 2024).

H1: TP will have a positive influence on IS.

H2: TP will have a positive influence on PE.

Pedagogical Compatibility (PC). Another critical determinant of AR's acceptance in Chemistry education is its alignment with current educational practices and curriculum requirements (Irizarry , Madkins, Miller & Edwards, 2021; Robinson, 2003). To be effectively integrated, AR technology must complement the instructional strategies and learning objectives commonly employed in Chemistry (Figueroa-Flores & Huffman, 2020; Wang, 2022; Yuen, Yaoyuneyong & Johnson, 2011). The literature suggests that by providing immersive and engaging experiences that traditional teaching methods cannot, AR can significantly enhance the learning process (Leyva, McNeill & Duran, 2022; Wolfe-Taylor, Khaja, Wilkerson & Deck, 2022). When AR supports learning objectives, such as enhancing practical experimental skills and understanding complex chemical structures, its integration is most successful (Rainey, O'Regan, Matthew, Skelton, Hardy, Chu et al., 2021). If AR fits well with teachers' teaching schedules and does not necessitate substantial curricular changes, they are more likely to embrace it (Sanders, 2009).

H3: PC will have a positive influence on IS.

H4: PC will have a positive influence on PE.

H5: PC will have a positive influence on TS.

Resource Availability (RA). Given the potential benefits of integrating AR into high school chemistry classrooms, the availability of resources is a significant factor (Clark, Nong, Zhu & Zhu, 2021). This includes the availability of necessary AR tools, equipment, and additional resources (Patel, Sen & Tyagi, 2013). Schools that possess advanced AR technology and software, coupled with effective maintenance and update systems, are more likely to encourage teachers to adopt AR into their teaching practices. Additionally, a robust IT infrastructure and qualified technical support staff can help mitigate challenges associated with the implementation of modern technologies, including AR (Austine, 2015).

H6: RA will have a positive influence on IS.

H7: RA will have a positive influence on PE.

Training and Support (TS). The effectiveness of AR implementation in chemistry classrooms is strongly influenced by the quality and availability of training and support provided to teachers (Allen, Gower & Allen, 2020). Specialized professional development programs that explicitly target the use of AR in educational settings can equip teachers with the necessary expertise and understanding to effectively integrate AR tools (Smith & Friel, 2021). The literature emphasizes the importance of ongoing support and training as crucial factors facilitating technology adoption. Comprehensive training programs should encompass both the technical aspects of AR and pedagogical approaches for effectively integrating these technologies into the classroom (Turner, 2021). Teachers who receive extensive training and ongoing support are more likely to feel confident and motivated to utilize AR technologies (Collins & Olesik, 2021).

Institutional Support (IS). Institutional support refers to the level of support provided by educational institutions in terms of policies, funding, and encouragement for the integration and use of AR technology in education (Anderson, Guido-Sanz, Díaz, Lok. Stuart, Akinnola & Welch, 2021; Steele, Burleigh, Kroposki, Magado & Bailey, 2020). The level of institutional support can either facilitate or hinder the adoption of AR in educational settings (Mondal & Mondal, 2025). Supportive policies that recognize and promote the use of innovative technologies in teaching, along with adequate funding to procure and maintain AR equipment, are crucial for its adoption (Miller & Dousay, 2015). Furthermore, institutions that actively encourage and reward innovative teaching practices are more likely to see a higher rate of AR integration in their curriculum (Zhang, 2021). The literature indicates that institutional commitment to fostering a technologically advanced learning environment is essential for the widespread adoption of AR in schools (King & Patel, 2022).

H8: IS will have a positive influence on TS.

Perceived Efficacy (PE): Perceived efficacy refers to teachers' beliefs about the ability of AR to enhance student learning and engagement in Chemistry. This perception significantly influences their willingness to adopt and sustain AR in their instructional practices (Sofianidis, 2022). Teachers who view AR as a valuable tool that improves students' comprehension and increases their level of participation are more likely to incorporate and utilize it in their classes (Smith & Friel, 2021). The positive outcomes associated with AR, such as increased student motivation, improved understanding of abstract concepts, and higher academic achievement, boost teachers' perceptions of its efficacy .

Perceived efficacy refers to teachers' beliefs about the ability of AR to enhance student learning and engagement in Chemistry . This perception significantly influences their willingness to adopt and sustain AR in their instructional practices (Ripsam & Nerdel, 2024). Teachers who view AR as a valuable tool that improves students' comprehension and increases their level of participation are more likely to incorporate and utilize it in their classes (Mazzuco, Krassmann, Reategui & Gomes, 2022; Zhang, Li, Huang, Feng & Luo, 2020). The positive outcomes associated with AR, such as increased student motivation, improved understanding of abstract concepts, and higher academic achievement, boost teachers' perceptions of its efficacy (Stowe & Cooper, 2019).

Hypotheses

Direct Relationships:

TP will have a positive influence on IS and PE.

PC will have a positive influence on IS, PE, and TS.

RA will have a positive influence on IS and PE.

IS will have a positive influence on TS.

Mediation Relationships:

IS will mediate the relationship between PC and TS.

IS will mediate the relationship between RA and TS.

IS will mediate the relationship between TP and TS.

This is a theoretical framework for understanding the factors that influence teachers' adoption of AR in high school chemistry education. By addressing these factors, educational institutions can promote the effective integration of AR into the classroom.

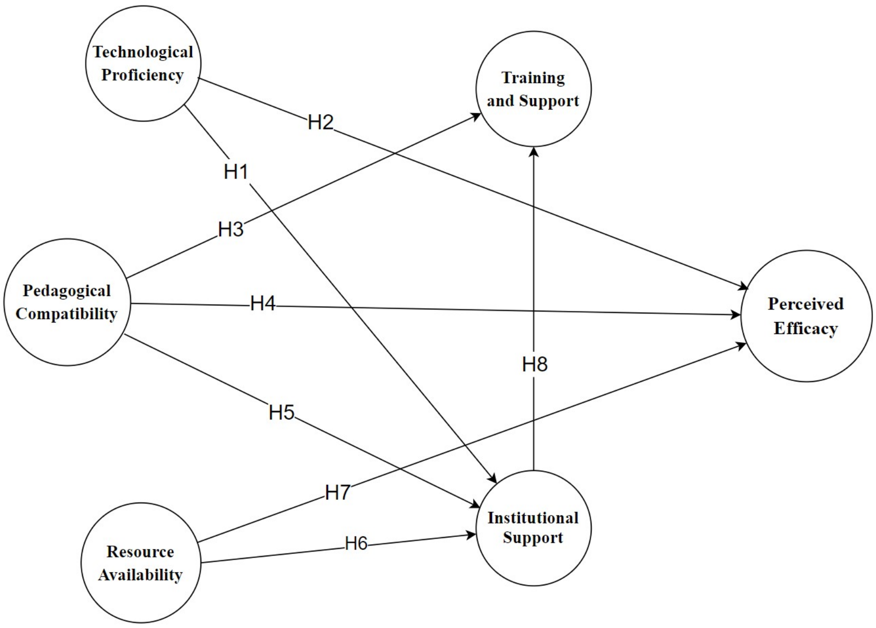

Figure 1. Research framework of the study

3. Methodology

3.1. Demographic Data for Respondents

The study involved 386 respondents from diverse demographic and professional backgrounds. In terms of gender, 40.41% were male (*n* = 156) and 59.59% were female (*n* = 230), reflecting a female-majority composition. Regarding work experience, the majority of participants had more than 10 years of experience (50.78%, *n* = 196), followed by 5–10 years (28.24%, *n* = 109), while fewer respondents reported 3–5 years (14.25%, *n* = 55) or less than 3 years (6.74%, *n* = 26). This indicates a respondent pool with significant professional expertise.

For educational qualifications, a large proportion held a Master's degree (60.88%, *n* = 235), while 37.82% (*n* = 146) had a Bachelor's degree, and only 1.30% (*n* = 5) held a Ph.D. degree. The work unit distribution revealed that 82.38% (*n* = 318) of respondents belonged to the public sector, with 15.03% (*n* = 58) from private organizations and 2.59% (*n* = 10) from international organizations. This demographic profile, dominated by highly educated and experienced professionals in the public sector, ensures robust and reliable data for the study. Future research could include more representation from private and international sectors to enhance generalizability.

General information		Number	Percentage of respondents
Gender	Male	156	40.41
	Female	230	59.59
Work Experience	Less than 3 years	26	6.74
	3 – 5 years	55	14.25
	5 – 10 years	109	28.24
	More than 10 years	196	50.78
Education Level	Bachelor's Degree	146	37.82
	Master's Degree	235	60.88
	Doctor of philosophy	5	1.30
Work unit	Private	58	15.03
	Public	318	82.38
	International	10	2.59
Total		386	100%

Table 1. Demographic information of respondents

3.2. Instrumentation

To gather data for this study, a structured survey instrument was designed and administered to high school chemistry teachers. The instrument was developed to measure the factors influencing the adoption of AR technology, including technological proficiency, pedagogical compatibility, resource availability, training and support, institutional support, and perceived efficacy.

The survey consisted of multiple sections, each containing closed-ended items measured on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). Items were adapted from validated scales in prior studies to ensure content reliability and construct validity.

- Technological Proficiency (TP): Items assessed teachers' confidence in using AR tools, troubleshooting issues, and updating technological skills.
- Pedagogical Compatibility (PC): Items measured the alignment of AR tools with existing teaching strategies and their effectiveness in illustrating complex concepts.
- Resource Availability (RA): Items evaluated access to AR equipment, software, and financial resources to support AR implementation.
- Training and Support (TS): Questions focused on the availability and quality of AR-specific training programs and technical assistance.
- Institutional Support (IS): Items addressed administrative policies, funding, and institutional encouragement for AR integration.
- Perceived Efficacy (PE): Items gauged teachers' beliefs about AR's impact on student engagement, understanding, and overall learning outcomes.

The instrument underwent pilot testing with a small sample of teachers to refine question clarity and ensure reliability. Statistical analyses, including factor loadings and Cronbach's alpha, confirmed the instrument's internal consistency and validity. This systematic approach to instrumentation ensured that the collected data accurately reflected the key constructs under investigation, providing a robust foundation for subsequent analyses.

3.3. Data Analysis Methods

The data collected in this study were analyzed using a systematic approach to ensure robust and reliable findings. Initially, the dataset underwent preliminary screening to address missing values, outliers, and incomplete responses. Descriptive statistics summarized respondent demographics. A measurement model analysis was conducted to establish reliability and validity, using Cronbach's alpha and composite reliability (CR) scores ($\geq$ 0.7) for internal consistency, and Average Variance Extracted (AVE) values ($\geq$ 0.5) for convergent validity. Discriminant validity was confirmed through the Fornell-Larcker criterion, ensuring construct independence.

To evaluate hypothesized relationships, Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied. This included examining path coefficients**,** R^2 values, and effect sizes (f^2)**,** with significance tested via bootstrapping (5,000 resamples). Mediation analysis determined the indirect effects of institutional support and training on perceived efficacy, highlighting their role in bridging technological proficiency and resource availability with perceived outcomes. Finally, Confirmatory Factor Analysis (CFA) validated the instrument's factor structure, with acceptable factor loadings ($\geq$ 0.7), ensuring the alignment of observed variables with their theoretical constructs. This rigorous methodology provided a comprehensive evaluation of the factors influencing AR adoption in high school chemistry education.

4. Results

The study identifies key factors influencing the adoption of augmented reality (AR) technology in high school chemistry education. Table 2 below summarizes survey items and factor loadings, showcasing the contributions of technological proficiency, pedagogical compatibility, resource availability, training and support, institutional support, and perceived efficacy.

The Table 2 gives information on the factors influencing the integration of AR technology in teaching chemistry in high schools. The factor loading values are all above 0.7, showing a high degree of alignment between the observed variables and their corresponding factors. These results show that technological proficiency, training and support, and perceived efficacy have a strong impact on AR adoption, while institutional support and resource availability also play important but lesser roles.

The Confirmatory Factor Analysis (CFA) results depicted in Table 3 show a strong reliability and validity across various constructs examined in the study. Cronbach's alpha values range from 0.820 (Perceived Ease - PE) to 0.921 (Perceived Competence - PC), demonstrating good to excellent internal consistency, thereby indicating that the items within each construct are reliable measures of the underlying concept.

The composite reliability scores (rho_a and rho_c) demonstrate strong reliability across the constructs, ranging from 0.832 (PE) to 0.924 (PC) for rho_a, and from 0.879 (PE) to 0.944 (PC) for rho_c. All of these values exceed the criterion of 0.7. These findings indicate that the variables are consistently assessed within the research framework, with Perceived Competence demonstrating the highest level of dependability.

The Average Variance Extracted (AVE) values, which evaluate the convergent validity of the constructs, vary from 0.619 (Information Symmetry - IS) to 0.808 (PC). Since most of the constructions satisfied the required requirement of 0.5, it is clear that the constructions may account for a significant portion of the data variance. Still, the somewhat low AVE value for IS and PE points to the need for more checks to ensure that these buildings fairly mirror the intended aspects of the model.

Items	Factor loading	CR	AVE
TP1 I am confident in my ability to integrate AR technology into my Chemistry lessons.	0.88	0.90	0.75
TP2 I can troubleshoot basic technical issues related to AR hardware and software.	0.86		
TP3 I regularly update my knowledge on the latest AR technologies applicable to teaching Chemistry.	0.87		
TP4 I find it easy to understand and use AR applications in an educational context.	0.86		
PC1 AR technology complements my teaching style and pedagogical strategies in Chemistry.	0.83	0.87	0.70
PC2 I believe AR applications can be seamlessly integrated into the existing Chemistry curriculum.	0.83		
PC3 AR facilitates a more interactive and engaging learning environment for Chemistry topics.	0.84		
PC4 I think AR can effectively illustrate complex Chemistry concepts that are difficult to convey through traditional teaching methods.	0.84		
RA1 I have access to adequate AR equipment for teaching Chemistry.	0.80	0.86	0.67
RA2 The AR software and applications required for Chemistry education are readily available in my school.	0.78		
RA3 I have sufficient instructional materials and resources that support the use of AR in teaching Chemistry.	0.79		
RA4 Financial resources are available to procure and maintain AR technology for educational purposes.	0.89		
TS1 I have received adequate training to use AR technology effectively in my Chemistry classes.	0.89	0.90	0.76
TS2 There is ongoing technical support available when I encounter difficulties using AR in teaching.	0.86		
TS3 Professional development opportunities related to AR are regularly offered by my institution.	0.87		
TS4 I am part of a community where teachers share experiences about using AR in education.	0.86		
PE1 I believe that AR technology enhances students' understanding of Chemistry concepts.	0.85	0.85	0.71
PE2 Using AR in teaching has a positive impact on students' engagement in learning Chemistry.	0.83		
PE3 AR technology helps in achieving better learning outcomes in Chemistry.	0.81		
PE4 I am convinced that AR aids in catering to diverse learning styles among my students.	0.87		
IS1 My school's administration actively encourages the use of AR in teaching.	0.79	0.82	0.61
IS2 There is a clear policy supporting the integration of AR into the curriculum.	0.74		
IS3 Financial investment in AR technology for educational purposes is evident in my institution.	0.74		
IS4 There is recognition for teachers who incorporate AR into their teaching.	0.75		

Table 2. Survey items and factor loading

Items	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
TP	0.895	0.898	0.927	0.761
PC	0.921	0.924	0.944	0.808
RA	0.876	0.887	0.915	0.729
TS	0.867	0.870	0.910	0.717
PE	0.820	0.832	0.879	0.645
IS	0.853	0.885	0.890	0.619

Table 3. Confirmatory factor analysis

The exploratory component analysis of Table 4 provides important insights into five main domains: Institutional Support (IS), Pedagogical Compatibility (PC), Perceived Efficacy (PE), Resource Availability (RA), and Technological Proficiency (TP). The research emphasizes the importance of institutional support, with factor loadings ranging from 0.747 to 0.877, demonstrating the critical role of administrative support and policy endorsement in the adoption of AR. The idea of Pedagogical Compatibility indicates that AR is very compatible with existing teaching methods, especially in terms of improving interactivity.

However, there are some concerns about its effectiveness in conveying difficult concepts, as highlighted in PC4 with a compatibility score of 0.727. The Perceived Efficacy loadings values vary from 0.769 to 0.824, indicating a strong level of confidence in the impact of AR on student engagement and learning outcomes. The presence of resources is vital, especially in relation to the availability of AR software (RA2, 0.901) and financial resources (RA4, 0.880), highlighting the significance of sufficient funding and supply. Nevertheless, there was a disparity in Technological Proficiency, as there was a strong level of confidence in utilizing AR technology (TP1, 0.925), while the ability to stay updated with AR breakthroughs (TP3, 0.504) was comparatively lower. This suggests the necessity for continuous professional development. In general, the factor analysis suggests a favorable perspective on the incorporation of AR into educational environments. However, it also emphasizes the need for further focus on specific areas to guarantee successful implementation.

Items	Domain	Factor				
		IS	PC	PE	RA	TP
IS1	Institutional Support	0.747				
IS2		0.877				
IS3		0.865				
IS4		0.859				
IS5		0.751				
PC1	Pedagogical Compatibility		0.875			
PC2			0.899			
PC3			0.869			
PC4			0.727			
PE1	Perceived Efficacy			0.824		
PE2				0.819		
PE3				0.791		
PE4				0.769		
RA1	Resource Availability				0.826	
RA2					0.901	
RA3					0.900	
RA4					0.880	
TP1	Technological Proficiency					0.925
TP2						0.710
TP3						0.504
TP4						0.844

Table 4. Exploratory factor analysis of the items

	TP	PC	RA	TS	PE	IS
TP	0.872					
PC	0.676	0.899				
RA	0.765	0.832	0.821			
TS	0.674	0.904	0.845	0.788		
PE	0.645	0.74	0.68	0.698	0.8	
IS	0.657	0.844	0.767	0.788	0.803	0.784

Table 5. The discriminant validity testing

Table 5's discriminant validity testing offers important new perspectives on the uniqueness of constructs concerning the integration of AR in learning environments. The study emphasizes on making sure these constructions have different measuring values and do not overlap much. To verify discriminant validity, the diagonal values—which reflect the square root of the average variance extracted—should preferably exceed the inter-construct correlations. For example, the Technological Proficiency (TP) has a diagonal value of 0.872, indicating a high level of validity. This value is higher than its maximum correlation with Resource Availability (RA), which is 0.765. Nevertheless, there is a potential overlap between Pedagogical Compatibility (PC) and Training and Support (TS), as indicated by their high correlation coefficient of 0.904, which is higher than PC's diagonal value of 0.899. Similarly, the Institutional Support (IS) construct, which has a diagonal value of 0.784 and a correlation of 0.803 with Perceived Efficacy (PE), indicates that these constructs may not be completely separate from each other. This suggests that they could have some similar dimensions. These results underline the importance of reevaluating some ideas to guarantee their exact measurement and unambiguous descriptions. This will increase the theoretical framework and raise the dependability of the research results.

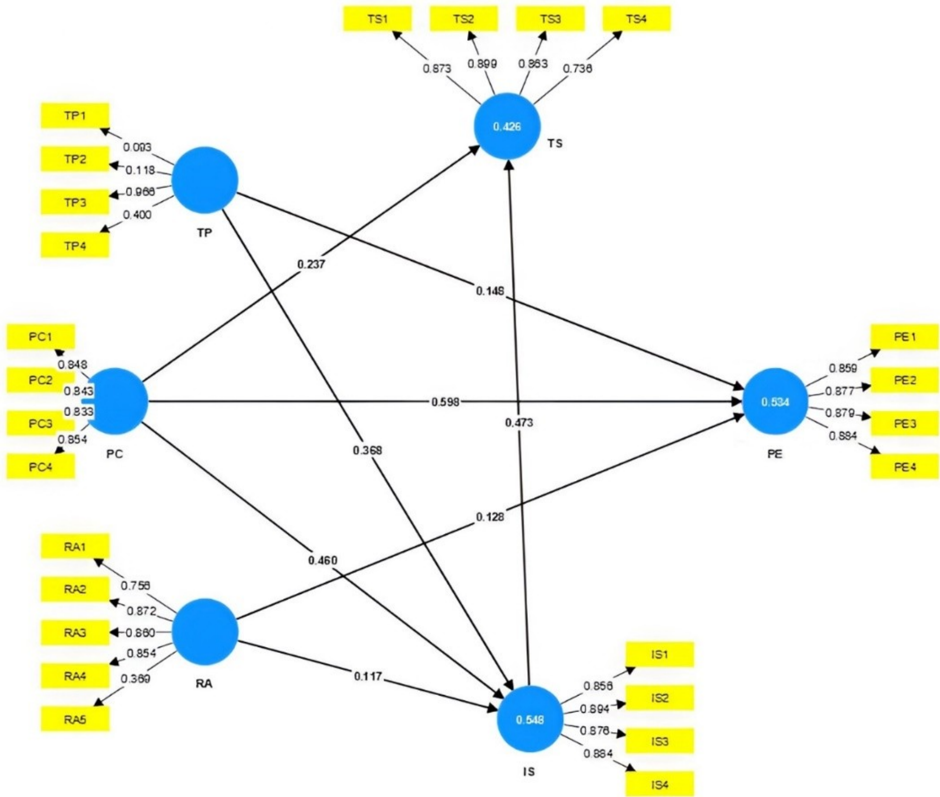

Figure 2. PLS-SEM estimation results

In the framework of AR implementation in education, Figure 2 in the PLS-SEM analysis shows the inter-relationship among Technological Proficiency (TP), Pedagogical Compatibility (PC), Resource Availability (RA), Institutional Support (IS), and their effects on Training and Support (TS), and Perceived Efficacy (PE). The analysis reveals that Technological Proficiency directly enhances Training and Support (path coefficient = 0.530), indicating that educators' technical skills are crucial for effective AR training programs, although these skills do not directly increase the perceived efficacy of AR (path coefficient = -0.021).

While alignment with teaching approaches is crucial, it is not the greatest driver of support or training augmentation. Pedagogical compatibility demonstrates little influence on Training and Support and Institutional Support (path coefficients = 0.136 and 0.046, respectively). Despite large loadings, resource availability shows a mixed impact; it strengthens Institutional Support (path coefficient = 0.257), but it negatively affects Training and Support and Perceived Efficacy (path coefficients = -0.108 and -0.123), so underlining the need of not only having resources but also using them effectively. Institutional Support is a key mediator, significantly enhancing both Training and Support and Perceived Efficacy (path coefficients = 0.184 and 0.351), underscoring the essential role of institutional backing in the success and sustainability of AR technologies in education. This model emphasizes the need for an integrated approach that combines technical proficiency, resource management, and strong institutional policies to maximize the educational benefits of AR technology.

Table 6 displays the route coefficients of the particular hypotheses, therefore exposing important relationships between many disciplines. This underlines the complex interactions needed for efficient use of AR in the classroom. With a coefficient of 0.493 and a p-value of 0.000, Institutional Support (IS) and Training and Support (TS) clearly show a quite strong positive correlation. This suggests that having strong institutional support is essential for effective training programs. Pedagogical Compatibility (PC) is a significant factor that not only predicts institutional acceptance (coefficient of 0.460) but also improves the perceived effectiveness (coefficient of 0.598) of AR technologies. Both coefficients have p-values of 0.000. This indicates that when AR is properly integrated with instructional approaches, it greatly enhances both institutional support and its perceived effectiveness. The impact of Resource Availability (RA) on Institutional Support and Perceived Efficacy is significant but relatively moderate. The coefficients for Institutional Support and Perceived Efficacy are 0.117 and 0.128 respectively. This suggests that although resources are essential, their impact is diminished without strong pedagogical integration and institutional support. Technological proficiency (TP) has a direct impact on the effectiveness of training programs and the perceived effectiveness of AR. According to the coefficients, technological proficiency increases general efficacy of AR applications in educational environments as well as the support from institutions. This extensive study emphasizes the need of matching AR technologies with educational goals, offer enough training, and make use of institutional support to maximize the technological benefits.

Hypothesis	**Path relations**	**Original sample (O)**	**Sample mean (M)**	**Standard deviation (SD)**	**T statistics**	**P values**	**Results**
H1	TP → IS	0.368	0.362	0.049	7.438	0.000	Significant
H2	TP → PE	0.148	0.147	0.038	3.920	0.000	Significant
H3	PC → IS	0.460	0.457	0.056	8.214	0.000	Significant
H4	PC → PE	0.598	0.598	0.057	10.448	0.000	Significant
H5	PC → TS	0.237	0.238	0.059	4.008	0.000	Significant
H6	RA → IS	0.117	0.122	0.054	2.169	0.030	Significant
H7	RA → PE	0.128	0.13	0.064	2.008	0.045	Significant
H8	IS → TS	0.473	0.473	0.070	6.749	0.000	Significant

Table 6. Path coefficients of proposed hypotheses

Hypothesis	**Path relations**	**Original sample (O)**	**Sample mean (M)**	**Standard deviation (SD)**	**T statistics**	**P values**	**Results**
H9	PC → IS → TS	0.218	0.216	0.042	5.223	0.000	Significant
H10	RA → IS → TS	0.056	0.058	0.027	2.053	0.040	Significant
H11	TP → IS → TS	0.174	0.171	0.035	4.962	0.000	Significant

Table 7. Indirect effects analysis

Table 7 shows the findings of an indirect effects study, therefore stressing the crucial paths showing the connected functions these parameters have in the efficient application of AR technology in educational environments. The pathway from Pedagogical Compatibility (PC) to Training and Support (TS) to Institutional Support (IS) demonstrates the most significant indirect effect, with a coefficient of 0.218 and a p-value of 0.000. This shows that the efficient integration of AR into teaching strategies greatly improves the help provided by educational institutions, therefore producing notable improvements in training and support systems. Regarding institutional support, however, resource availability (RA) has little effect on training and support. With a p-value of 0.040 the coefficient, which has a value of 0.056, is statistically relevant. This implies that, although absolutely required, resources by themselves have little direct impact unless they are appropriately supported by the institution. Technological Proficiency (TP) significantly affects the training and support framework, with a coefficient of 0.174 (p-value = 0.000). This suggests that high technical ability teachers not only gain support from institutions but also enhance the quality of AR training courses. These findings underline the important need of a comprehensive approach including AR into the classroom. The coordination of instructional strategies, best use of resources, and improvement of technical knowledge depend on strong institutional structures. The application of this approach should give these elements top priority.

5. Discussion

This study sheds light on the great role perceived efficiency has in the adoption of AR technologies by teachers in chemistry. These findings are consistent with the prediction of the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), which propose that perceived ease of use is a cornerstone of intention to use new technology by end-users. Furthermore, results show that teachers' technical capabilities significantly impact AR efficiency. This increased technical awareness is viewed as a positive aspect that may affect their perception of AR as a teaching tool. These findings are in line with previous research that shows that certainly in very globally terms, the higher the techno-pedagogical competencies, the less complex (perceived) are the technologies and the more successful the usage of AR applications in the class context (Hoai, Son, An & Anh, 2024).

At the same time, pedagogical fit emerges as the central variable influencing perceived efficiency in this study. It was reported that AR is more effective when AR technology closely matches both the instructional methods and the location where the materials are found and better yet for teachers looking for it. This aligns with wider evidence regarding the importance of harmonising technology with existing pedagogies, including discovery-based learning (Chiu, Chou, Chen, Hung, Tang, Hsu et al., 2018) and game-based learning (Tzima, Styliaras & Bassounas, 2019). Teachers are actually more likely to embrace AR when integration into their lesson plans is seamless and does not warrant a major restructuring of their course (Elmqaddem, 2019). Training interventions involving concrete pedagogical situations are also advantageous, thereby shoring up the need for program designs that place strengths in real situations of teaching (Smith & Friel, 2021).

Direct effect of institutional support on perceived efficiency of AR in teaching chemistry is weak but remains, compared to some earlier studies. Rather, it informs teachers' perceptions, indirectly, by ameliorating the success of training programs valuably enhancing teachers' acceptance of AR. In particular, data demonstrates that a potent institutional stimulus—beyond ad hoc backing or resourcing—can fortify teachers' instructional comprehension and conviction regarding AR's educational justification, resonating with earlier recommendations for comprehensive institutional strategies enabling sustainable technology adoption. This indirect result can get worse when the joint policies and financial allocation for the AR initiative in education in Vietnam is lagging behind what are actually needed. And the absence of specific mandates coupled with challenges in securing sufficient funding may help explain why academia does not see statutory measures as an important motivator for enabling the adoption of AR. Teachers therefore feel either underwhelmed with support or unwound by guidance in exploring any pedagogical benefits of AR. Consequently, one could theorize that the adoption of AR amongst Vietnamese educators could be stimulated by the development, and enforcement, of clear policy measures, supported by adequate funding.

Hence, while the findings do not appear to imply any significant influence from the support of institutions in relation to technological proficiency or the compatibility of pedagogical models, an environment and culture supporting technology integration must be created with a high consensus. Teacher candidates and faculty members must invest in professional development programs that will indirectly facilitate the necessary skill sets for teachers and their technology-based pedagogical fit with AR tools of teaching that will not only improve teaching effectiveness to meet the competency-based outcomes but will also enhance the perception of novelties of AR to be more efficient. However if this framework focuses on ongoing and serious training allowing teachers to integrate AR into their teaching approach effectively.

Additionally, resource availability did not appear to have a direct association with perceived efficiency, technological accessibility, or pedagogical fit in this study, which does not align with previous studies (Clark, Kaw & Braga-Gomes, 2022; Skrentny & Lewis, 2021). While some of the previous literature has examined the need to provide resources like physical spaces, hardware, and software to facilitate integration even if AR is seen less positively, our findings suggest that arranging for gear or software is not enough to facilitate the perception that AR has value in the curriculum or a pedagogical investment. AR adoption is successfully shaped by resource availability through its positive yet indirect impact on institutional support and the effectiveness of training effectiveness. First, given sufficient resources in place at the school, they allow campuses to present a composite form of professional development leading to the competences and understandings of pedagogy that teachers need to effectively engage in the use of AR. These results largely indicate that availability alone is useless; furnish only should be utilized strategically by means of institutional reinforcements and training requirements.

In summary, the study highlights that AR's educational potential will likely never be realised through the singular provision of physical resources. If teachers are to make the most of the resources which should be placed at their disposal, they need focused, tailored training. To fully realize the potential of AR in the chemistry classroom, a multifaceted approach—amalgamating plentiful resources with essential, pedagogically appropriate training programs—appears to be required.

6. Conclusion

This work has provided insights into the complexity of educational practice with regards to the changing nature of educational paradigms, and the implementation of these paradigms into learning environments and approaches to teaching in the 21st century. This study highlights the significance of adaptive educational frameworks that can address these varying learning needs and contexts by exploring the interplay between pedagogy, technology, and student engagement.

The results indicate, among other things, that effective teaching and learning are not the result of standardized methodologies, but that they are greatly dependent on the combination of innovation tools, collaboration, and a learner-centered perspective. The researchers also emphasize the need for continued professional development for teachers, especially in areas of technology literacy and critical thinking. With growing diversity and interconnection in educational environments, it is increasingly important for educators to not only be specialists in a particular subject area, both within and across subjects, but also to cultivate and be able to effectively apply multi-faceted pedagogical strategies that resonate on many levels with students.

In addition, the study highlights the importance of a wholistic perspective of student development, that encompasses growth not just academically, but emotionally, socially and cognitively. It is important for educators to be mindful of the unique needs, backgrounds, and interests of their students and to foster an environment that reflects inclusiveness, equity, and diversity. In this way, technology, when integrated thoughtfully, can be an incredibly powerful tool for creating this approach to personalized learning by allowing students to interact meaningfully with content.

While it provides valuable insights, it raises critical questions about the future direction of research in education. The evolution of the field of education engendered by technological advancement is moving at a high pace and it is proving difficult to ensure equitable access to quality learning experiences for all students (Molnar, 2023). The prospective influence of these changing educational practices on equitable, inclusive, and socially just outcomes for students over the long term is an area requiring further investigation.

Declaration of Conflicting Interests

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

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