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A SYSTEMATIC REVIEW ON THE INTEGRATION OF MOBILE APPLICATIONS IN CHEMISTRY EDUCATION: TRENDS AND EFFECTIVENESS

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Abstract

Chemistry education is often perceived as difficult by students due to the abstract and complex nature of its concepts, especially in linking macroscopic phenomena to submicroscopic levels. This study aims to identify the trends and effectiveness of the integration of mobile applications in chemistry education and their impact on student motivation and understanding. The method used is a Systematic Literature Review (SLR) with the PRISMA protocol. From an initial search of 193 articles on Google Scholar and Scopus from 2020 to 2026, 13 articles that met the inclusion criteria were selected for further analysis. The results show that the use of technologies such as Augmented reality (AR), Virtual laboratories, Simulations, and Game-based learning significantly enhances student engagement and facilitates 3D molecular structure visualization. However, technical challenges such as device limitations, smartphone sensor accuracy, and the still-limited coverage of topics remain major barriers. This study concludes that mobile applications are an effective complement to traditional teaching methods in creating a more inclusive and interactive learning environment.

Keywords: *Mobile Applications; Chemistry Education; Augmented Reality; Virtual Laboratories; Game-Based learning*

INTRODUCTION

Chemistry education is an integral part of the curriculum in many educational institutions worldwide. While an in-depth understanding of chemistry concepts is crucial, many students struggle with understanding chemistry material, especially when it comes to teaching abstract and complex concepts such as molecular structure, reaction mechanisms, and basic principles (Moju & Taylor, 2025). Many students find it difficult to understand chemical phenomena directly through text or 2D images, which sometimes fail to provide a clear representation of the processes occurring at the molecular level. Students are unable to visualize and connect particle structures/ processes with macroscopic phenomena (Rahmawati et al., 2021). The understanding of chemistry students regarding the structure-property relationship in higher education is complex and poorly integrated, thus requiring step-by-step teaching to improve their predictions of material behavior (Cooper et al., 2013). This is in line with research by Keiner & Graulich (2020) that in organic chemistry courses, students do not always connect the macroscopic and submicroscopic levels in their explanations. Students showed a diverse use of mechanistic features and struggled to link chemical representation levels in their explanations.

Address these challenges, the use of technology, particularly mobile applications in chemistry education, has become an effective solution to enhance students' learning experiences. With mobile applications, students can engage in virtual experiments, interact with 3D molecular simulations, and leverage augmented reality (AR) technology, enabling a better understanding of chemistry concepts that are difficult to explain with conventional methods (Aw et al., 2020). Applications such as Virtua Chem Sim, which provides virtual experiment simulations such as acid-base titration and litmus paper tests, offer students the opportunity to conduct chemistry experiments virtually. This is especially important in areas with limited physical laboratory facilities (Aslam et al., 2025). Game-based learning approaches in chemistry education have also gained significant attention in recent years.

Game-based learning in chemistry education increases motivation, engagement, and participation, as well as improves attitude, regular attendance, and grades (Chans & Portuguez Castro, 2021). Game applications such as Green Tycoon and Time Bomb Game have proven effective in increasing student motivation and involvement. By applying game elements such as challenges and rewards, these applications allow students to learn chemistry principles interactively and engagingly. The use of these educational games also provides immediate feedback, helping students improve their understanding of topics such as green chemistry and organic structure theory. The application of game technology in chemistry education allows students to explore concepts often perceived as difficult and enhance their cognitive skills in a more engaging and non-monotonous way (Lees et al., 2020; Da Silva Júnior et al., 2020). However, despite the numerous mobile applications developed in chemistry education, several challenges remain.

A major challenge related to the effectiveness and accessibility of these applications, especially in diverse educational contexts, is the limited scope of many mobile applications, which focus on simulations or only one aspect of chemistry learning, while other aspects such as measuring learning outcomes, the impact on motivation, and improving students' cognitive skills remain underexplored. For instance, the use of augmented reality in chemistry education enhances the understanding of complex concepts, with molecular structure being the most commonly used topic. However, challenges such as difficulty of use, distractions, and technical issues persist (Mazzuco et al., 2022). Moreover, mobile devices for chemistry education promote knowledge construction, visualization, self-regulation, and intellectual discourse, but the quality of learning resources poses challenges for cognitive capacity (Lok & Hamzah, 2021). Therefore, systematic research evaluating trends and the effectiveness of mobile application integration in chemistry education is crucial to provide a clearer picture of the potential and challenges faced by this technology in chemistry education (Wang et al., 2026; Aslam et al., 2025).

This research is essential due to the rapid development of technology and how it can be effectively integrated into chemistry education. As mobile applications continue to develop, there are opportunities to create a more inclusive learning environment accessible to more students. This research aims to identify which mobile applications are most effective in enhancing students' understanding of complex chemistry concepts and their impact on motivation and student engagement in learning. Therefore, a systematic review of mobile applications in chemistry education can significantly contribute to improving the chemistry curriculum and strengthening the understanding of how technology can enhance the quality of chemistry education globally. Based on the background outlined above, the research problem formulation is: What is the trend of mobile application integration in chemistry education, and how effective is its use in increasing student motivation and understanding?

METHODOLOGY

This study uses a Systematic Literature Review (SLR) design to identify Integration of Mobile Applications in Chemistry Education:

Trends and Effectiveness. The SLR approach, utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), is employed to identify, screening, eligibility, data extraction, analyze, and synthesize. The PRISMA approach was selected because it provides a systematic and transparent framework for the literature review process, ensuring that the results obtained are more valid and replicable (Page et al., 2021).

1. Identification of Studies

In the first stage, a literature search was conducted to identify relevant articles on mobile applications in chemistry education. The search was conducted on Google Scholar and Scopus using the keywords "Mobile Applications in Chemistry Education." From this search, 193 articles relevant to the topic were found, published between 2020 and 2026.

2. Screening (Title & Abstract Review)

After identifying relevant articles, the next step was to screen based on the title and abstract of the articles. Articles that did not focus on mobile applications in chemistry education, or did not discuss the use of AR, virtual labs, simulations, or game-based learning in the context of chemistry, were excluded. Articles that did not meet the inclusion criteria or were not relevant to the topic of chemistry education were filtered out, reducing the number of articles to approximately 50.

3. Eligibility (Full Text Review)

In this stage, the remaining 50 articles were further analyzed based on their full text. This screening process was carried out to ensure that the articles met more in-depth inclusion and exclusion criteria.

a. Inclusion Criteria:
   1) Articles that discuss mobile applications for chemistry education.
   2) Applications using AR, virtual labs, simulations, or game-based learning in the context of chemistry education.
   3) Articles published between 2020 and 2026.

b. Exclusion Criteria:
   1) Articles that do not focus on mobile applications in chemistry education.
   2) Articles that do not discuss the use of AR, virtual labs, simulations, or game-based learning for chemistry.
   3) Articles that do not provide experimental data or findings relevant to the topic.
   4) After the full-text screening, only 13 articles met the inclusion criteria and were included in this review.

4. Data Extraction

After selecting the relevant articles, data was extracted from the 13 selected articles. The extracted data included: the title of the article, authors, and year of publication. The key findings, especially those related to the effectiveness of mobile applications in chemistry education, were also extracted. The limitations found in the studies regarding mobile applications in chemistry education were recorded.

5. Synthesis & Analysis

The extracted data was then synthesized and analyzed to draw broader conclusions. In this stage, the main findings from the selected articles were grouped according to the type of mobile applications used, such as AR, virtual labs, simulations, and game-based learning, and the chemistry topics taught, such as organic chemistry, analytical chemistry, and polymer chemistry. Qualitative synthesis: Identifying common patterns and themes from the various relevant articles.

6. Results & Discussion

After the data was synthesized, the results and discussion from the 13 selected articles were explained. This discussion covers: Student engagement in learning through the use of mobile applications, improved understanding of complex chemistry concepts that are difficult to comprehend using traditional methods, the limitations encountered when using mobile applications in the context of chemistry education, such as device limitations, application complexity, and the limited scope of topics covered. The results of the analysis were visualized in a PRISMA flow diagram (Figure 1).

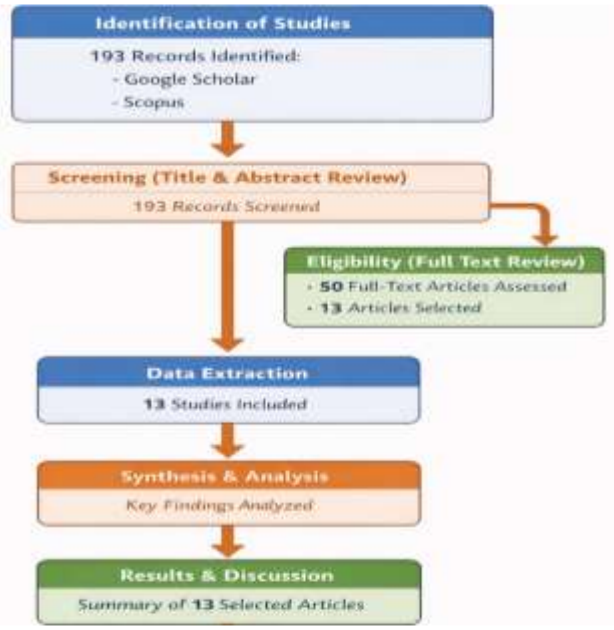

Figure 1. Prisma Flow Diagram Mobile Applications in Chemistry Education

RESULT AND DISCUSSION

This research began by searching and selecting articles from national and international journals through specific databases. The article search was conducted using keywords relevant to the research topic. Initially, 193 articles with similar themes were found, but after selection, only 13 were deemed most relevant to the research needs and the details shown in table 1.

The use of mobile applications in chemistry education has been growing and opens up many opportunities to enhance students' understanding of concepts that are often difficult to grasp. This technology offers an engaging, safe, and flexible learning alternative, which can address several limitations found in traditional learning. In this article, we discuss various types of mobile applications used in chemistry education, focusing on Augmented Reality (AR), Virtual Labs, Simulation-based Learning, and Game-based Learning. Each type of application has its advantages and limitations, which must be understood to optimize its use in chemistry teaching.

Table 1. Metadata of articles about mobile applications in chemistry education

Category	Mobile Learning App	Chemistry Topic/ Subject	Findings	Limitations	Authors	Journal Name
AR Application	BiochemAR	Macromolecular Structure and Function	The app allows students to visualize and interact with 3D molecular structures, improving spatial learning.	Limited user interactivity and requires basic AR hardware.	(Sung et al., 2020)	Journal of Chemical Education (Q2)
AR Application	Image Visualization with AR	Chemistry education for future teachers	Marker-based AR helps visualize molecular structures in 3D, aiding in chemistry teaching for future educators.	Does not address real-world implementation challenges in classrooms.	(Midak et al., 2021)	Journal of Physics: Conf. Series

AR Application	3D Molecular Structures Visualization	Chemistry, 3D Visualization	AR app allows students to view complex molecules in 3D, enhancing understanding of molecular geometry and interactions.	Limited to simpler molecules and not as advanced as other tools.	(Eriksen et al., 2020)	Journal of Chemical Education (Q2)
AR Application	Markerless AR Tool	Chemistry education	A markerless AR tool developed to improve spatial understanding of chemical structures.	Some tracking limitations in complex environments.	(Abdinejad et al., 2021)	Journal of Chemical Education (Q2)
AR Application	NuPOV	Organic Chemistry (Nucleophilic Addition)	NuPOV allows interaction with 3D models of nucleophilic addition reactions, enhancing spatial understanding.	Focus on a single reaction type, limiting broader application.	(Aw et al., 2020)	Journal of Chemical Education (Q2)
Game-based Learning	Green Tycoon	Green Chemistry, Biorefining	A mobile game teaching green chemistryprinciples and biorefining through interactive simulations.	Limited scalability for larger classes and mobile-dependent.	(Lees et al., 2020)	Journal of Chemical Education (Q2)
Game-based Learning	Time Bomb Game	Organic Chemistry, Structural Theory	Game where students disarm a bomb by answering questions about organic compounds' structural theory.	Focus on abstract concepts may not appeal to all students.	(Da Silva Júnior et al., 2020)	Journal of Chemical Education (Q2)
Game-based Learning	Gamifying Organic Chemistry Laboratory	Organic Chemistry Laboratory	Gamified organic chemistry lab course with points, levels, and rankings to enhance motivation and learning.	Limited to one subject area and may not appeal to all students.	(da Silva Júnior et al., 2025)	Journal of Chemical Education (Q2)
Simulation-based Learning	Virtua Chem Sim	Acid-Base Titration, Litmus Paper Test	Virtual lab for practicing acid-base titrations and litmus paper tests, enhancing foundational knowledge.	Limited to high school-level chemistry and basic experiments.	(Aslam et al., 2025)	Journal of Chemical Education (Q2)
Simulation-based Learning	Virtual Lab Simulators	Polymer Science Education	Virtual experiment simulators for polymer science education, enhancing students' learning in polymer concepts.	Limited to polymer science topics and specific virtual simulations.	(Wang et al., 2026)	Journal of Chemical Education (Q2)
Simulation-based	Universal Design for Learning	Laboratory Safety Education	UDL framework enhances virtual lab design, improving accessibility and	Some challenges with content	(Girmay et al., n.d.)	Journal of Chemical Education (Q2)

Learnin g	(UDL) Virtual Lab		study attention for chemistry students.	overload and accessibility.		
Simulati on-based Learnin g	Lab4Chemist ry (Smartphone App)	Chemical Equilibrium, Acid-Base Titration	The app uses smartphone camera sensors for colorimetric analysis of acid-base titrations and chemical equilibrium using everyday materials like red cabbage. Students can monitor changes in color as indicators for pH and equilibrium shifts.	Limited accuracy with highly concentrated or extremely low pH solutions, and subjective interpretation of color changes.	(Wu et al., 2024)	Journal of Chemical Education (Q2)
Simulati on-based Learnin g	Smart pH Reader, Smart Paper Reader, Smart Indicator Reader	pH Determinatio n, Acid-Base Titration	The app allows students to perform pH determinations and acid-base titrations using smartphone cameras for image analysis. The app can replace traditional pH meters, with results matching conventional measurements.	Accuracy can be affected by ambient lighting and the limitations of pH paper calibration.	(Li et al., 2023)	Journal of Chemical Education (Q2)

Augmented Reality (AR)

AR applications in chemistry education provide students the opportunity to directly interact with 3D models of molecules or chemical reactions that are difficult to understand using only two-dimensional images. AR technology integrates real-world elements with virtual objects, enabling students to view and manipulate molecules in three-dimensional space. Applications such as BiochemAR Sung et al., (2020) assist students in understanding macromolecular structures and protein functions by allowing them to view and manipulate protein models in 3D, something not possible in traditional learning contexts. AR applications also help students visualize complex molecules in 3D, improving their understanding of molecular geometry and interactions (Eriksen et al., 2020). This facilitates the understanding of the relationship between structure and function in biochemistry, a topic often considered difficult. Moreover, Lab4Chemistry (Wu et al., 2024) provides a deeper learning experience in chemical equilibrium and acid-base titration, replacing physical laboratory tools with smartphones and allowing students to perform experiments at home using simple materials such as red cabbage and acetic acid. This application simplifies the learning process and helps students understand complex chemistry experiments. However, its limitations include reliance on smartphone cameras, which may not be as accurate as traditional laboratory equipment.

AR applications offer more accessible and interactive visualizations, but there are some limitations to consider. The use of AR technology requires devices such as smartphones or tablets with adequate AR capabilities, which could pose a barrier for students without access to such devices (Mazzuco et al., 2022). Additionally, these applications tend to be more complex for students who are new to AR technology, making learning challenging for beginners who are not accustomed to interacting with 3D models.

Virtual Labs

Virtual laboratories are an effective solution when access to physical laboratory facilities is limited. Applications such as Virtua Chem Sim Aslam et al., (2025) provide students the opportunity to conduct experiments such as acid-base titrations and litmus tests virtually, without the need for hazardous chemicals or expensive equipment. The use of this application has proven to enhance students' understanding of chemical procedures and build confidence in performing chemical experiments in physical laboratories after practicing in a virtual environment. Additionally, simulation applications like OVESET (Wang et al., 2026) help students understand polymerization concepts and polymer kinetics, although they are limited to polymer science topics. Such applications allow students to perform experiments that they would typically be unable to access due to limitations in resources or time.

Virtual labs offer a flexible and safe alternative, but they cannot fully replace the hands-on experience in a physical laboratory, especially in practical skills such as manipulating tools and observing experiments in real-time. Many studies emphasize that virtual labs should be positioned as a complement or temporary alternative, rather than a complete replacement for physical labs (Reyes et al., 2024). The learning experience gained from virtual labs also heavily depends on the topics being simulated, and this application may not cover all chemistry topics taught in the curriculum. Some newer VR projects explicitly state that the range of experiments should be expanded to include more chemistry subjects (Jiang et al., 2024).

Simulation-based Learning

Simulation-based Learning is an approach that uses simulation applications to allow students to practice chemistry experiments interactively, with immediate feedback helping them understand difficult concepts. Applications like OVESET Wang et al., (2026) provide an interactive experience in chemistry polymer experiments, such as polymerization and molecular weight distribution, which are very helpful in developing students' understanding of the theories taught in class. By using this application, students can access experimental simulations independently and receive real-time feedback on their experiment results. Similarly, applications like Virtua Chem Sim (Aslam et al., 2025) offer simulations of acid-base titration and volumetric analysis, where students can learn without the risks or limitations of physical resources, with faster and more accessible results. The main advantage of simulation-based learning is its ability to provide virtual experiments that allow students to learn in a safer and more affordable environment. However, the main limitation of these simulations is that they cannot fully replace the physical laboratory experience, which involves handling tools and chemicals, and is still important for mastering practical skills.

Game Based Learning

Game based learning uses elements of games to increase student engagement and motivation in learning chemistry. Applications like Green Tycoon Lees et al., (2020) teach biorefining and green chemistry principles through a simulation game where students learn to manage a chemical plant. In this game, students play the role of a plant manager, learning about sustainability in chemistry and gaining insights into green chemistry processes.

Feedback from students shows that this game is engaging and beneficial, helping them understand green chemistry principles. Furthermore, the Time Bomb Game (Da Silva Júnior et al., 2020) incorporates game elements to help students understand organic compound structures. In this game, students must answer questions about organic compound structure theory to stop a time bomb, increasing their engagement in chemistry learning.

Game based learning has proven effective in improving students' motivation to learn, making it more enjoyable and interactive (Byusa et al., 2022). However, these applications have limitations in terms of coverage, as they are more suitable for specific topics like green chemistry and organic compounds. This game may not be suitable for more complex or technical chemistry topics that require a deeper approach to learning.

IMPLICATION

Implications for readers: This research helps students and educators choose effective types of mobile applications to increase motivation and understanding of chemistry concepts and provides guidance on combining technology with traditional learning to make the learning experience more interactive and flexible.

Implications for researchers: The results of this study open up opportunities for further studies related to the effectiveness of mobile applications, the development of technology-based teaching methods, and the evaluation of long-term impacts on students' conceptual and practical skills.

CONCLUSION

Based on the systematic review findings, it can be concluded that the integration of various types of mobile applications including Augmented reality (AR), virtual laboratories, simulations, and game-based learning has proven to be an effective tool for improving students' understanding of complex and abstract chemistry concepts. The trend of using AR technology and 3D simulations significantly helped students visualize molecular structures and reaction mechanisms that are difficult to understand through conventional methods. Moreover, the application of game-based learning and virtual labs has had a positive and tangible impact on increasing motivation, engagement, and active participation in the learning process. However, the effectiveness of this technology still faces challenges related to hardware limitations, sensor accuracy on smartphones, and the limited scope of topics covered in the curriculum. Future research should focus on expanding the range of chemistry topics covered in the development of these applications and exploring the integration of this technology more widely in the curriculum. Long-term studies on the effectiveness of mobile applications on students' cognitive learning outcomes and practical skills in real-life settings should also be conducted.

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