

A Review of Instructional Strategies for Maximizing the Effectiveness of PhET Interactive Simulations in Chemistry Education

Hassan Aliyu

Department of Science Education, Faculty of Education, Sokoto State University, Nigeria, **Email address:** nagoronyo@gmail.com, **ORCID:** <https://orcid.org/0000-0003-4929-3126>

Abstract

This systematic review examines the instructional strategies employed alongside PhET interactive simulations in chemistry education, focusing on their impact on student learning outcomes, including engagement, conceptual understanding, and practical application. The review encompasses studies published between 2018 and 2024, specifically targeting research that investigates the use of PhET simulations within the context of chemistry. A comprehensive literature search across multiple academic databases identified ten relevant studies, which were analyzed to identify effective instructional practices. The findings reveal that PhET simulations achieve optimal effectiveness when integrated with active, inquiry-based learning approaches, such as guided discovery and collaborative learning. These strategies significantly enhance students' comprehension of abstract concepts and their ability to apply knowledge in practical contexts. The review highlights the importance of aligning instructional strategies with specific chemistry topics to maximize the benefits of simulations. Moreover, it stressed the need for educators to adopt these innovative tools to create engaging, student-centered learning experiences. This study contributes to the growing body of literature on the role of technology in enriching chemistry education and provides valuable insights for educators seeking to implement PhET simulations effectively in their classrooms. Future research should explore further instructional innovations to enhance the learning experience in chemistry.

Keywords: PhET Simulations, Chemistry Education, Instructional Strategies, Student Engagement, Conceptual Understanding

Introduction

Chemistry can be pretty tough to teach and learn, mainly because of its complex theories and abstract ideas. Both educators and students have faced significant hurdles in this area for a long time. While traditional teaching methods have their merits, they often fall short when it comes to linking theory with practical application. Concepts like atomic structure, chemical bonding, molecular interactions, and chemical equilibrium can be especially hard to understand and imagine, particularly for those who don't have a solid foundation in the subject. To tackle these issues, many teachers are now turning to interactive tools that can create more engaging and intuitive learning experiences. One notable example is Physics Education Technology (PhET) Interactive Simulations, developed by the University of Colorado Boulder. This resource offers a variety of

interactive simulations designed to help students better visualize and explore these complex scientific concepts.

Initially, 'PhET' stood for 'Physics Education Technology.' However, given the current platform's expansion beyond physics to encompass simulations across various scientific and mathematical disciplines, the acronym has become somewhat restrictive. PhET simulations excel in creating visually compelling representations of complex concepts, making them both engaging and accessible for student exploration (Kissi *et al.*, 2024). These interactive simulations are readily available and free to use for anyone with internet access and a suitable device. PhET prioritizes visual learning by minimizing textual content. The carefully selected words serve primarily as labels for interactive controls, either providing clear and concise descriptions or introducing technical terms that students are encouraged to define through their own investigations.

PhET simulations provide a fantastic way to improve chemistry education by giving students an interactive and visual method to understand both abstract and practical ideas (Escuadro, 2024). With these simulations, learners can adjust different variables and see the results immediately, helping them develop a more personalized and deeper understanding of essential concepts. The interactive element encourages inquiry-based learning, allowing students to experiment with chemical systems, test their hypotheses, and tackle problem-solving tasks. Consequently, PhET simulations have become popular in chemistry classrooms across high schools and universities, promoting a stronger understanding of concepts and better learning results.

While research on PhET simulations exists across various scientific fields, a comprehensive review specifically focusing on chemistry education is limited. This paper aims to fill this gap by examining recent studies that investigate instructional strategies employed with PhET simulations to teach both abstract and practical chemistry concepts. The review will analyze how these strategies impact student engagement, conceptual understanding, and the application of chemical knowledge to real-world scenarios. This review aims to contribute to the body of literature on technology-enhanced chemistry education by providing a detailed analysis of the instructional effectiveness of PhET simulations.

Research Question

The central research question guiding this review is:

- I. What instructional strategies employed through PhET interactive simulations have been found to enhance learning of abstract and practical concepts in chemistry?, and
- II. How do these strategies influence student outcomes?

Methodology

This systematic review seeks to evaluate and synthesize the results from ten recent research articles that delve into the teaching strategies used with PhET interactive simulations for both abstract and practical chemistry concepts. The focus here is on identifying essential instructional practices, evaluating how they affect student outcomes, and figuring out how these strategies support effective learning in chemistry education. The approach for carrying out this review follows a well-defined process, which is detailed below:

Inclusion and Exclusion Criteria

To ensure the review focuses on relevant and high-quality studies, a set of inclusion and exclusion criteria was established:

- I. This review includes studies published within the last six years (2018-2024) in peer-reviewed journals or conference proceedings. The focus is on research that explicitly investigates the utilization of PhET simulations within the context of chemistry education, encompassing both abstract concepts (e.g., atomic structure, chemical bonding and equilibrium) and practical skills (e.g., laboratory techniques, chemical reactions). The review considers articles that discuss the integration of specific instructional strategies alongside PhET simulations, such as inquiry-based learning, collaborative learning, and simulation-based demonstrations. Finally, the inclusion criteria prioritize studies that assess the impact of PhET simulations on student learning outcomes, including engagement, conceptual understanding, and practical application.
- II. This review excludes studies that do not focus on the use of PhET simulations specifically within the context of chemistry education, including those that utilize simulations in other subjects. Studies published prior to 2018 are also excluded to ensure a focus on recent advancements in the field. Articles with incomplete or insufficient data on instructional strategies employed alongside PhET simulations, as well as those lacking adequate assessment of student learning outcomes (e.g., engagement, conceptual understanding, and practical application), will not be included. Finally, non-peer-reviewed sources, such as blogs, opinion pieces, and editorials, are excluded to maintain the rigor of the review.

Search Strategy

A comprehensive literature search was conducted across multiple academic databases, including Google Scholar, ERIC, Elsevier, ScienceDirect, SpringerLink, JSTOR, and Taylor & Francis Online. Search terms included combinations of keywords such as "PhET simulations," "chemistry education," "instructional strategies" (e.g., "active learning," "interactive learning," "simulation-based learning," "inquiry-based learning"), "abstract concepts in chemistry" (e.g., "atomic structure," "chemical bonding"), "practical chemistry concepts" (e.g., "laboratory techniques," "chemical reactions"), and "student

outcomes." The search was limited to articles published between 2018 and 2024, and all retrieved articles were meticulously reviewed for their relevance to the research question.

Article Selection Process

Article selection followed a two-stage process. (i) Initial Screening: Titles and abstracts of retrieved articles were initially screened against the inclusion and exclusion criteria. This step aimed to identify studies that explicitly addressed the use of PhET simulations in teaching chemistry, with a particular focus on instructional strategies and student learning outcomes. Studies not meeting these criteria were excluded. (ii) Full-Text Review: Subsequently, a full-text review was conducted on the remaining articles to ensure comprehensive adherence to the inclusion criteria. Final selection prioritized articles with direct relevance to the research question, clear descriptions of instructional strategy implementation, and explicit measurement of student outcomes, including conceptual understanding, engagement, and skill development. A total of 10 studies were ultimately included in this review.

Data Extraction

A standardized data extraction form was utilized to systematically collect relevant information from each selected article. Basic data points included: study details (authors, year of publication, journal/source); study objectives (primary research question or goal); instructional strategies employed alongside PhET simulations (e.g., inquiry-based learning, collaborative learning, active learning); specific chemistry topics covered (e.g., chemical reactions, atomic structure, stoichiometry, acid-base chemistry); level of education of participants (e.g., high school, undergraduate, graduate); assessment methods for student outcomes (e.g., engagement, conceptual understanding, problem-solving ability); and a concise summary of the study's findings, including the effectiveness of PhET simulations and the implemented instructional strategies.

Data Synthesis

A qualitative synthesis was conducted to identify common themes and patterns across the extracted data. The analysis focused on several crucial areas: the types of instructional strategies employed alongside PhET simulations; the specific chemistry concepts targeted in these studies; the overall impact of these strategies on student outcomes, including conceptual understanding, engagement, problem-solving ability, and practical skills; and the effectiveness of PhET simulations in fostering both abstract and practical learning within the context of chemistry education. This thematically organized synthesis provides a comprehensive overview of how PhET simulations have been utilized in chemistry instruction and the implications of these strategies for student learning.

Quality Assessment

To assess the quality of the included studies, several criteria were applied: clarity of methodology (well-defined research design, participant characteristics, and implemented

instructional strategies); validity of outcome measures (use of valid and reliable methods to assess student learning); relevance and generalizability of findings (applicability of findings to various educational contexts, such as high school and university-level chemistry); and evidence of a clear and significant impact of PhET simulations on student learning outcomes. Studies that met these rigorous criteria were considered high-quality and included in the review.

Results

Table 1 presents the results of a systematic review of 10 recent articles on instructional strategies used in PhET interactive simulations for learning abstract and practical concepts in chemistry.

Table 1: A systematic review of 10 recent articles on instructional strategies used in PhET interactive simulations in learning abstract and practical concepts in chemistry

SN	Authors	Objective	Findings	Instructional Strategies Used	Focus Area	Outcomes/Effectiveness
1	Dewi, M., Kissi, M., Astra I. M. (2024)	to develop an integrated inquiry-based worksheet PhET simulation that enhance science process skills	Students showed improved conceptual understanding and engagement	Inquiry-based learning, guided discovery	acid and base material	are feasible, practical, and effective for science learning to improve science process skills
2	Garanina, R. M. (2020)	Develop students' cognitive abilities	is an effective educational strategy that can lead to improved cognitive skills, academic performance, and a deeper understanding of the subject matter	Problem-based learning, collaborative learning	Chemical reactions, thermodynamics	Improved retention and conceptual understanding
3	Escuadro, B. A. (2024)	Evaluates the effectiveness of PhET Simulations in enhancing learners' understanding	Significant academic attainment	Hands-on, simulation-based exploration	Chemical kinetics	Improved problem-solving skills and conceptual clarity
4	Nuraida, O., Akbar, G. S., Farida, I., & Rahmatullah, S. (2021, April).	Analyze student outcomes	Improve student learning outcomes to the level sub-microscopic representation.	Active learning, scaffolding techniques	Acid-base chemistry	Improved understanding of complex acid-base concepts
5	Salame, I. I., & Samson, D. (2019)	enhance student achievement by fostering problem-solving skills determine whether providing specific practice in problem categorization improves student achievement in problem solving and in conceptual understanding.	Students able to achieve higher score thereby enhancing problem-solving skills	Simulation-based pre-lab or post-lab activity	Laboratory skills	Enhanced practical skills, better conceptual integration Categorization improved student performance, particularly for those at a lower developmental level, emphasizing the importance of organized knowledge in problem-
6	Antonios, Dimitrios, Georgios, T. (2021)	improves student achievement in problem solving and in conceptual understanding.	Improved ability to predict equilibrium shifts	Inquiry-driven learning, concept mapping	Chemical equilibrium	

						solving.
7	Gupta, T. (2019)	Assess the impact of PhET simulations on stoichiometry	Simulations helped students balance equations and understand mole concepts	Visual learning, peer teaching	Stoichiometry	Higher accuracy in solving stoichiometric problems
8	Ali <i>et al.</i> (2021)	Analyze PhET's role in teaching periodic trends	Dynamic visualization of periodic trends increased comprehension	Interactive lectures, demonstration-based learning	Periodic trends	Enhanced understanding of abstract periodic trends
9	Parthiban, J. (2024)	Investigate how PhET helps in teaching chemical bonding and structure	Understand the science process skills	Simulation-based demonstrations, guided inquiry	Chemical bonding, molecular structure	Improved ability to predict molecular properties and bonding behavior
10	Yao <i>et al.</i> (2024)	Investigate PhET's role in teaching electrochemistry	Students showed better conceptual understanding of electrochemical cells	Conceptual inquiry, student-driven exploration	Electrochemistry, redox reactions	Better understanding of abstract electrochemical processes

The result of this review consistently demonstrate that PhET simulations achieve optimal effectiveness when integrated with active, inquiry-driven learning approaches. Instructional strategies encompassing guided discovery, hands-on exploration, problem-based learning, and collaborative activities have been widely observed across diverse chemistry topics. A recurring finding across these studies highlights PhET simulations' ability to significantly enhance both abstract comprehension and practical application, particularly in areas traditionally challenging to visualize or grasp. Moreover, the efficacy of PhET simulations tends to amplify when seamlessly integrated into existing teaching methodologies, such as lectures or laboratory exercises. This review underscores the significant value of PhET simulations in enriching chemistry education at various levels, particularly when employed in conjunction with effective pedagogical strategies.

Inquiry-Based Learning and Guided Discovery

These strategies promote active participation and stimulate students' curiosity. Through promoting curiosity and directing pupils to independently uncover concepts, they build a deeper understanding of abstract concepts like atomic structure, molecular geometry, and chemical equilibrium. Studies (Bakolis *et al.*, 2021; Rusdiman *et al.*, 2024) reveals that Students demonstrated higher engagement, enhance science process skills, retention, and application of concepts, especially in abstract areas such as chemical bonding, chemical equilibrium and atomic structure.

Research consistently demonstrates the effectiveness of PhET interactive simulations in enhancing chemistry education. Studies by Kissi *et al.* (2024); Parthiban (2024) and Rusdiman *et al.* (2024) have shown that inquiry-based learning and guided discovery approaches, when integrated with PhET simulations, significantly improve students' scientific literacy, critical thinking, and science process skills.

Furthermore, these simulations have proven valuable in various learning contexts. Haryanto *et al.* (2024) found that discovery learning models infused with PhET applications effectively improved generic science skills in chemistry. Bakolis *et al.* (2021) demonstrated the effectiveness of combining PhET simulations with inquiry-driven learning and concept mapping in teaching chemical equilibrium. This approach not only enhances understanding and addresses misconceptions but also helps students organize knowledge and categorize problems effectively.

The benefits of PhET simulations extend to other key areas of chemistry. Ganasen & Shamuganathan (2017) found that these simulations effectively enhance students' understanding of chemical equilibrium and reduce misconceptions. Similarly, Parthiban (2024) highlights the significant role of PhET simulations in enhancing guided inquiry in teaching chemical bonding. The interactive nature of these simulations, which allows for exploration of complex concepts, enhances science process skills and fosters a deeper understanding of chemical bonding (Zohar & Levy, 2019).

While PhET simulations offer significant potential for inquiry-based learning, their effective implementation requires careful consideration. Proper teacher training and support are crucial to ensure that educators can effectively integrate these tools into their teaching practices. Furthermore, the integration of simulations should be adopted to specific educational contexts and learning objectives to maximize their impact. Similarly, while the combination of concept mapping and PhET simulations shows promise, challenges such as the need for adequate training and resources for both students and teachers must be addressed. It's important to emphasize that simulations should not be seen as a replacement for traditional teaching methods. While they can enhance understanding and engagement, they should be used to complement and enrich traditional instruction, providing a more comprehensive and effective learning experience.

Problem-Based Learning (PBL) and Collaborative Learning

PBL strategies, when integrated with PhET simulations, offer a powerful approach to enhancing chemistry education. These simulations significantly enhance students' conceptual understanding of key topics by enabling visual and interactive exploration of chemical phenomena (Arsani *et al.*, 2020). Moreover, PBL encourages the application of knowledge to real-world problems, fostering critical thinking and problem-solving abilities (Hoyland & Hyde, 2023). The interactive nature of PhET simulations can also boost student motivation, making learning more engaging and effective (Garanina, 2020).

Collaboration and diverse learning styles are further enhanced by the use of PhET simulations in PBL. These simulations accommodate various learning preferences, allowing students to engage with content in ways that best suit their individual needs (Arsani *et al.*, 2020). Furthermore, collaborative learning is fostered as students work together to explore and understand the simulations, solidifying abstract concepts and promoting peer-to-peer learning.

The use of PhET simulations within a PBL framework can effectively support learning strategies such as Predict-Observe-Explain. This approach encourages deeper conceptual understanding by prompting students to predict outcomes, observe results within the simulation, and then explain their reasoning (Jere & Mpeta, 2024). Studies have consistently shown that students utilizing PhET simulations demonstrate improved problem-solving skills and can make more accurate predictions based on their understanding of chemical phenomena (Jere & Mpeta, 2024).

Research consistently demonstrates the effectiveness of PhET simulations in enhancing student achievement in chemistry (D'Ottone & Ochonogor, 2017). Studies have shown that students exposed to PhET simulations achieve significantly higher post-test scores compared to those taught through traditional methods (Escuadro, 2024). These findings suggest that the integration of PhET simulations within a well-designed PBL framework can significantly improve student learning outcomes in chemistry.

Despite the demonstrated benefits of PBL and PhET simulations, several challenges hinder their widespread adoption. These challenges include the need for adequately trained facilitators to effectively guide student learning within a PBL framework and the integration of technology, including PhET simulations, into existing curricula (Hoyland & Hyde, 2023).

Furthermore, while PhET simulations offer significant advantages, some learners may still struggle with certain concepts. This indicates the need for additional support and resources to address individual learning needs and ensure that all students can effectively utilize these tools to their full potential.

Active Learning and Scaffolding

Scaffolding, when combined with active learning strategies facilitated by PhET simulations, can significantly enhance student understanding of acid-base chemistry. Scaffolding, combined with hands-on, visual learning through PhET simulations, enables students to explore sub-microscopic representations of acid-base solutions by breaking down complex concepts into manageable steps. This interactive approach significantly improves their ability to understand and analyze abstract concepts such as pH and titration curves, which can be challenging to grasp through traditional lecture-based methods (Nuraida *et al.*, 2021). PhET simulations provide immediate feedback and allow students to experiment at their own pace, fostering a deeper understanding of these concepts.

Scaffolding plays a crucial role in guiding student learning within this framework. It involves providing structured support, such as questioning, prompting, and providing cues, to guide students through learning tasks (Haryati *et al.*, 2024; Tiaradipa *et al.*, 2020). Research has demonstrated the effectiveness of scaffolding in inquiry-based learning, particularly in improving students' science process skills when investigating acid-base solutions (Tiaradipa *et al.*, 2020). PhET simulations can also provide implicit scaffolding, allowing students to explore and experiment with minimal explicit guidance. This approach supports guided-inquiry learning while encouraging productive inquiry without overwhelming students.

While the integration of PhET simulations and scaffolding techniques shows promise, careful consideration must be given to the balance between guided and independent exploration. Implicit scaffolding can be particularly beneficial in large classroom settings, where providing explicit guidance to every student may not be feasible. However, it is crucial to ensure that students possess the necessary foundational skills to effectively engage with exploratory learning environments and benefit from the scaffolded support offered by the simulations.

Simulation-Based Learning (Pre-lab and Post-lab Activities)

PhET simulations have demonstrated significant potential in enhancing chemistry education. Studies by Salame & Samson (2019) have shown that integrating these interactive tools, whether as pre-lab or post-lab activities, can significantly improve student learning outcomes. Simulations enhance understanding by enabling students to visualize complex concepts and actively engage with them, facilitating a deeper grasp of theoretical principles and their real-world applications.

Research by Escudro (2024) indicates that students utilizing PhET simulations exhibit substantial gains in post-test scores compared to traditional teaching methods, highlighting their effectiveness in improving academic attainment. Furthermore, incorporating simulations into a flipped classroom model, as explored by Wu *et al.*

(2021), fosters active engagement and deepens conceptual understanding, leading to significant and lasting knowledge gains.

The interactive nature of simulations, allowing students to experiment with variables and receive immediate feedback, is particularly valuable in preparing them for laboratory experiments. Collaborative simulations, as demonstrated by Watson *et al.* (2020), have been shown to boost student confidence and understanding of fundamental concepts, such as pH, compared to traditional assignments.

While the benefits of simulations are evident, it is crucial to acknowledge the importance of traditional hands-on laboratory experiences in developing essential practical skills. A balanced approach, integrating simulations with in-person laboratory work, can provide a more comprehensive and effective learning experience for students.

Conceptual Inquiry and Concept Mapping (Articles 6, 8)

Research by Ali *et al.* (2021) demonstrates that integrating PhET simulations into the learning of periodic table trends significantly enhances student engagement and understanding. These interactive tools facilitate a deeper comprehension of complex concepts by allowing students to visualize and manipulate elements within a virtual environment, thereby enriching their learning experience.

Conceptual inquiry, which encourages students to question and explore the material, and concept mapping, which helps them organize their understanding, become more effective when used in conjunction with simulations. These strategies enable students to construct and connect abstract concepts more effectively. Studies have shown that students who utilize simulations exhibit enhanced retention and application of chemical equilibrium and periodic trends, demonstrating improved abilities to map relationships between different concepts (Cao *et al.*, 2021; Okrepka, 2020).

PhET simulations provide dynamic representations of periodic trends, such as atomic radii and ionization energies, making these abstract concepts more tangible. This allows students to actively explore the relationships between elements, fostering a better grasp of chemical properties and behaviors through interactive experimentation (Sarwoto *et al.*, 2024). The use of simulations has been linked to increased student interest and motivation in chemistry, as they enable safe and flexible experimentation (Correia *et al.*, 2020; Ali *et al.*, 2021). Moreover, interactive learning environments encouraged by simulations prompt students to formulate questions and make predictions, thereby enhancing their inquiry skills (Correia *et al.*, 2020).

PhET simulations effectively support hands-on learning, allowing students to practice skills relevant to real-world chemistry applications (Sarwoto *et al.*, 2024). Furthermore, they contribute to the development of essential competencies for mastering chemical disciplines, such as identifying cause-effect relationships (Correia *et al.*, 2020). While PhET simulations offer significant benefits, their effectiveness can vary depending on the

instructional context and the integration strategies employed by educators. This underscores the critical role of active teacher involvement in maximizing the potential of these valuable tools.

Visual Learning and Peer Teaching (Article 7)

According to Gupta (2019), visual learning and peer teaching, when integrated with PhET simulations, can significantly enhance student understanding of stoichiometry. These interactive simulations provide a platform that fosters conceptual understanding and problem-solving skills, particularly in chemistry education. The integration of visual tools, such as submicro diagrams, further aids in bridging the gap between abstract concepts and tangible representations, making stoichiometric principles more accessible to students.

Visual learning aids in the comprehension of abstract chemical concepts like stoichiometry by providing dynamic and interactive representations. Peer teaching promotes active engagement and reinforces learning. Research reveals that students who engage in peer teaching demonstrate higher accuracy in solving stoichiometry problems and a deeper conceptual understanding of the subject (Gupta, 2019).

Simulations, such as those developed by Gupta, promote mathematical reasoning and problem-solving in stoichiometry by allowing students to visualize chemical reactions and perform dimensional analysis. Interactive simulations can lead to significant gains in student understanding, as evidenced by improvements in pre- and post-test scores in chemistry courses (Parthiban, 2024).

The use of student-generated submicro diagrams helps students connect symbolic representations of chemical reactions to their underlying processes, enhancing their conceptual grasp of stoichiometry. Peer teaching, facilitated by these visual tools, encourages collaborative learning, where students can explain concepts to one another, reinforcing their understanding.

Furthermore, contextualizing stoichiometry by discussing its relevance in everyday life, using real-world examples, can engage students in active learning methodologies. This contextualization can further motivate students to grasp stoichiometric concepts. While the use of simulations and visual aids is highly beneficial, it is crucial to acknowledge the value of traditional teaching methods. A balanced approach that incorporates both innovative and conventional strategies is essential for effective stoichiometry instruction.

Interactive Lectures and Demonstration-Based Learning (Article 8)

According to Sarwoto *et al.* (2024), PhET simulations serve as an effective and innovative demonstration tool in lectures, effectively illustrating periodic trends and atomic behavior. By providing dynamic visualizations, these interactive simulations enhance student engagement and understanding by making complex concepts more accessible. This approach utilizes PhET simulations as a demonstration tool during

lectures, offering a dynamic way to illustrate periodic trends and atomic behavior. This effectively bridges the gap between theoretical learning and practical application. Research indicated that students demonstrated a more comprehensive understanding of periodic trends and the properties of elements, particularly in relation to abstract periodic concepts.

Summary of Findings

Active, inquiry-based learning approaches have consistently proven effective in enhancing student engagement and fostering a deeper understanding of abstract concepts, such as atomic structure, chemical equilibrium, and molecular bonding. Simulation-based learning, whether implemented pre- or post-laboratory activities, effectively supports hands-on learning experiences, enabling students to grasp practical concepts and apply theoretical knowledge more readily.

Furthermore, collaborative learning, including peer teaching, fosters critical thinking and solidifies understanding. Collaborative problem-solving allows students to exchange ideas, challenge assumptions, and build upon collective knowledge.

Scaffolding techniques play a crucial role in supporting student learning. Scaffolding supports gradual knowledge acquisition by breaking down complex concepts into smaller, more manageable steps, allowing students to progress at their own pace. This gradual approach enhances knowledge retention and reduces cognitive overload, particularly when dealing with challenging concepts.

Conclusion

The review of instructional strategies employed alongside PhET simulations in chemistry education stresses the significant potential of these interactive tools to enhance student learning outcomes. The findings consistently demonstrate that PhET simulations are most effective when integrated with active, inquiry-driven pedagogical approaches, such as guided discovery, problem-based learning, and collaborative activities. These strategies not only facilitate a deeper understanding of abstract concepts but also improve practical application skills, particularly in areas that are traditionally challenging for students to visualize.

Moreover, the systematic analysis of recent studies reveals that the successful implementation of PhET simulations is contingent upon their seamless integration into existing teaching methodologies, including lectures and laboratory exercises. The review highlights the importance of aligning instructional strategies with the specific chemistry topics being taught, ensuring that simulations are used to reinforce and contextualize theoretical knowledge. Finally, this study emphasizes the value of PhET simulations as a transformative educational resource, advocating for their broader adoption in chemistry curricula to foster engagement, conceptual understanding, and skill development among students at various educational levels. Future research should continue to explore

innovative instructional strategies that leverage the full potential of these simulations to further enhance chemistry education.

Limitations

This systematic review does have a few limitations. Initially, by only looking at studies published in the last six years, some key foundational research might have been overlooked. Moreover, since the review only includes studies written in English, this could restrict how broadly the findings apply in various educational settings. Finally, by not considering non-peer-reviewed literature, there's a chance that some creative or new applications of PhET simulations haven't been included.

References

- Ali, N., Ullah, S., & Raees, M. (2022). Interactive cube for effective demonstration of virtual periodic table. *Education and Information Technologies*, 1-20.
- Ayu, I., Anom, A., Punaji, S., Dedi, K., Dasna, I, W. (2020). Problem-based learning strategies using multiple representations and learning styles to enhance conceptual understandings of chemistry. 17(35):860-876. doi: 10.52571/PTQ.V17.N35.2020.72_ARSANI_PGS_860_876.PDF
- Bakolis, A., Stamovlasis, D., & Tsaparlis, G. (2021). Explicit teaching of problem categorization using concept mapping, and an exploratory study of its effect on student achievement and on conceptual understanding—the case of chemical equilibrium problems. *Chemistry Teacher International*, 3(3), 269-284. doi: 10.1515/CTI-2019-0021
- Cao, C., Vernon, R. E., Schwarz, W. E., & Li, J. (2021). Understanding periodic and non-periodic chemistry in periodic tables. *Frontiers in Chemistry*, 8, 813.
- Correia, A. P., Koehler, N., Thompson, A., & Phye, G. (2019). The application of PhET simulation to teach gas behavior on the submicroscopic level: secondary school students' perceptions. *Research in Science & Technological Education*, 37(2), 193-217.
- D'Ottone, L., & Ochonogor, E. C. (2017). Educational explorations of chemical kinetics in a Problem Based Learning context. *Orbital: The Electronic Journal of Chemistry*, 299-307. doi: 10.17807/ORBITAL.V9I4.1049
- Escuadro, B. A. (2024). Physics Education Technology (PhET) Simulation as aid in Instruction in Learning Chemistry: An Experimental Approach. *EPRA international journal of multidisciplinary research*, 64-68. doi: 10.36713/epra17674
- Ganasen, S., & Shamuganathan, S. (2017). The effectiveness of physics education technology (PhET) interactive simulations in enhancing matriculation students' understanding of chemical equilibrium and remediating their misconceptions. *Overcoming Students' Misconceptions in Science: Strategies and Perspectives from Malaysia*, 157-178. doi: 10.1007/978-981-10-3437-4_9

- Garanina, R. M. (2020). Problem-based learning as a means of chemistry education effectiveness improvement at a medical university. *Samara Journal of Science*, 9(4), 282-289. doi: 10.17816/SNV202094303
- Gupta, T. (2019). Promoting mathematical reasoning and problem solving through inquiry-based relevance focused computer simulations: a stoichiometry lab. *Chemistry Teacher International*, 1(1), 20180008.
- Haryanto, H., Asrial, A., Aulia, S., Atri, W., Adhe, S. (2024). Generic science skills: phet applications based on discovery learning. doi: 10.22437/jiituj.v8i1.32441
- Haryati, T., Rusdi, M., Asyhar, R., Hadisaputra, S., & Hasibuan, M. H. E. (2024). The Effect of Scaffolding and Creative Thinking Skills in an Acid and Base Learning Project on Students' Science Process Skills. *Jurnal Penelitian Pendidikan IPA*, 10(3), 1083-1092. doi: 10.29303/jppipa.v10i3.4674
- Hoyland, J., & Hyde, J. (2023). The implementation and effects of contemporary Problem-Based Learning techniques in the field of chemistry. *New Directions in the Teaching of Natural Sciences*, 18(1) doi: 10.29311/ndtns.v18i1.4318
- Jere, S., & Mpetta, M. (2024). Enhancing learners' conceptual understanding of reaction kinetics using computer simulations—a case study approach. *Research in Science Education*, 1-25. doi: 10.1007/s11165-024-10182-5
- Kissi, M., Dewi, M., Astra, I. M. (2024). Increasing Scientific Literacy using a Guided Inquiry Approach assisted by PhET Simulations in Wave Material. *Jurnal Penelitian Pembelajaran Fisika*, doi: 10.26877/jp2f.v15i4.715
- Nuraida, O., Akbar, G. S., Farida, I., & Rahmatullah, S. (2021, April). Using PhET simulation to learning the concept of acid-base. In *Journal of Physics: Conference Series* (Vol. 1869, No. 1, p. 012020). IOP Publishing. doi: 10.1088/1742-6596/1869/1/012020
- Rusdiman, B., Sri, A., Sabar, N. (2024). Enhancing Students' Science Process Skills Through Design Worksheet-Based Inquiry Integrated PhET Simulation on Acid and Base Material. *Jurnal IPA dan pembelajaran IPA*, 8(3):267-285. doi: 10.24815/jipi.v8i3.39762
- Panggabean, F. T. M., Silitonga, P. M., Sutiani, A., Purba, J., & Gultom, R. (2023). Inquiry Based Learning STEM Teaching Materials to Improve Students' Thinking Skills in Stoichiometry. *Jurnal Tadris Kimiya (JTK)*, 8(2), 157-164.
- Parthiban, J. (2024). Enhancing the Science Process Skills through Phet Simulation. *International Research Journal on Advanced Engineering and Management (IRJAEM)*, 2(03), 432-435.
- Salame, I. I., & Samson, D. (2019). Examining the implementation of PhET simulations into general chemistry laboratory. *International Journal of Environmental and Science Education*, 14(4), 207-217.

- Sarwoto, T. A., Jatmiko, B., & Sudiby, E. (2020). Development of online science teaching instrument based on scientific approach using PhET simulation to improve learning outcomes at elementary school. *IJORER: International Journal of Recent Educational Research*, 1(2), 90-107.
- Tiaradipa, S., Lestari, I., Effendi, M. H., & Rusdi, M. (2020). The development of scaffolding in inquiry-based learning to improve students' science process skills in the concept of acid and base solution. *JKPK (Jurnal Kimia dan Pendidikan Kimia)*, 5(2), 211-221. doi: 10.20961/JKPK.V5I2.42420
- Watson, S. W., Dubrovskiy, A. V., & Peters, M. L. (2020). Increasing chemistry students' knowledge, confidence, and conceptual understanding of pH using a collaborative computer pH simulation. *Chemistry Education Research and Practice*, 21(2), 528-535.
- Wu, H. T., Mortezaei, K., Alvelais, T., Henbest, G., Murphy, C., Yeziarski, E. J., & Eichler, J. F. (2021). Incorporating concept development activities into a flipped classroom structure: using PhET simulations to put a twist on the flip. *Chemistry Education Research and Practice*, 22(4), 842-854.
- Yao, L., Wang, J., Liu, C., Chen, Z., & Xu, X. (2024). Exploring Electrochemistry: A Self-Designed Experiment by Students for Electrochemical Impedance Spectroscopy Measurement of Hollow Fiber Membranes. *Journal of Chemical Education*, 101(10), 4345-4352.
- Zohar, A. R., & Levy, S. T. (2019). Attraction vs. repulsion—learning about forces and energy in chemical bonding with the ELI-Chem simulation. *Chemistry Education Research and Practice*, 20(4), 667-684.