



Systematic Review

Effectiveness of PhET Simulations on Learning Outcomes in Science and Chemistry Education: A Systematic Review

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Abstract

The development of digital learning technologies has introduced innovative tools to enhance science and chemistry education, including PhET simulations. This study aims to evaluate the effectiveness of PhET simulations on students' learning outcomes through a systematic literature review following the PRISMA 2020 guidelines. A systematic search of Scopus and Crossref databases was conducted (last search: January 2026) using predefined keywords. Eligible studies were empirical research published between 2020 and 2026 that investigated PhET simulations in science-related education and reported learning outcomes, while non-empirical studies and non-Scopus-indexed articles were excluded. Risk of bias was assessed using an adapted Joanna Briggs Institute critical appraisal tool. Due to heterogeneity in study designs and outcome measures, the results were synthesized using a narrative approach. A total of 14 studies across elementary to higher education levels were included. The findings indicate that PhET simulations consistently improve learning outcomes, particularly academic achievement and conceptual understanding, with effects generally favoring simulation-based instruction over traditional methods. However, higher-order skills and affective outcomes such as motivation and attitude remain less frequently investigated. The evidence is limited by variability in study designs, incomplete reporting of non-cognitive outcomes, and the absence of quantitative synthesis. Overall, PhET simulations demonstrate strong potential as an effective interactive learning medium, although their impact depends on instructional design, teacher facilitation, and technological accessibility.

Keywords: effectiveness; learning outcomes; PhET simulations; science and chemistry education; systematic literature review



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1. Introduction

1.1. The Role of Technology in Science Education

In recent years, the rapid development of information and communication technology has significantly transformed various aspects of life, including education. Educational institutions have increasingly adopted digital learning media to create more interactive, engaging, and meaningful learning experiences, particularly in science and chemistry education [1]. The integration of technology into learning environments is essential to

meet the demands of the digital era and to improve students' understanding of complex scientific concepts.

One prominent example of digital learning innovation is PhET simulations, an interactive computer-based simulation developed by the University of Colorado Boulder. These simulations provide dynamic visual representations of abstract scientific concepts, such as physical laws, chemical reactions, and particle interactions, which are often difficult to observe directly through conventional laboratory methods. Through interactive features, students are able to manipulate variables, observe real-time changes, and connect theoretical knowledge with real-world phenomena, thereby enhancing their conceptual understanding [2].

1.2. The Use of PhET Simulations in Learning

The use of interactive simulations such as PhET offers various pedagogical advantages. Simulations enable students to engage in exploratory and inquiry-based learning processes, where they can conduct virtual experiments, test hypotheses, and draw conclusions based on their observations [3]. This approach not only improves conceptual understanding but also fosters critical thinking and problem-solving skills.

Furthermore, the user-friendly interface and flexibility of simulations support both independent and collaborative learning. As a result, students' motivation and engagement in science and chemistry learning can increase significantly [4].

Previous studies have reported positive impacts of PhET simulations on students' learning outcomes. Research by Ndagijimana et al. [3] demonstrated that PhET simulations significantly improved students' understanding of chemistry concepts. At the elementary school level, studies have shown that simulations can enhance students' engagement and interest in science learning. In addition, integrating simulations with instructional strategies such as problem-based learning and guided inquiry has been found to strengthen conceptual understanding and scientific skills [5,6].

1.3. Challenges in Implementing PhET Simulations

Despite these advantages, several challenges remain in the implementation of PhET simulations. Differences in students' digital literacy levels may lead to variations in learning outcomes [7]. Moreover, teachers' competence in integrating simulations into the learning process is not uniform across educational settings, which may affect the effectiveness of this technology. These variations raise important questions regarding the consistency of the effectiveness of PhET simulations and the factors that influence their successful implementation.

Science and chemistry are often perceived as abstract and difficult subjects for students [8]. Difficulties in understanding fundamental concepts may negatively affect students' academic performance, motivation, and interest in science.

Therefore, evaluating the effectiveness of innovative learning media such as PhET simulations is essential to ensure that technology integration in education can truly enhance learning outcomes [9].

1.4. Research Gap

Although numerous studies have examined the use of PhET simulations, several gaps remain in the existing literature. Many studies have been conducted in specific countries and educational contexts, making it difficult to generalize findings across different geographical settings [10,11]. In addition, prior research tends to focus on particular educational levels, leaving uncertainty regarding whether the effectiveness of PhET simulations is consistent across elementary, secondary, and higher education levels.

Furthermore, most studies emphasize cognitive learning outcomes such as academic achievement and conceptual understanding, while affective aspects, including motivation and attitudes toward learning, receive relatively less attention [4]. These limitations indicate the need for a more comprehensive synthesis of empirical findings.

1.5. Research Objectives and Questions

This study conducts a systematic literature review to synthesize empirical research on the use of PhET simulations in science and chemistry education. This study aims to evaluate the effectiveness of PhET simulations in improving students' learning outcomes, identify the learning outcome variables most frequently influenced, and analyze the distribution of studies across different educational levels and geographical contexts.

Understanding which educational levels receive the greatest research attention is academically important because the effectiveness of PhET simulations may vary according to students' cognitive development, digital literacy, curriculum complexity, and learning needs at different stages of education. Identifying the concentration of studies across educational levels also helps reveal underexplored contexts and existing research gaps, particularly in elementary and higher education settings. Furthermore, this analysis provides valuable insights for future implementation strategies and supports the broader development of simulation-based learning across diverse educational environments.

Specifically, this study aims to:

1. Examine the contribution of PhET simulations to students' conceptual understanding and scientific skills.
2. Identify instructional strategies that enhance the effectiveness of simulations.
3. Explore existing research gaps for future research directions.

Based on the objectives of this study, the research questions are formulated as follows:

1. How effective is the use of PhET simulations on learning outcomes in science and chemistry education based on empirical research findings?
2. Which learning outcome variables are most frequently influenced by the use of PhET simulations in science and chemistry education?
3. Which educational level shows the highest research concentration regarding the use of PhET simulations?

2. Materials and Methods

2.1. Research Design

This study employed a Systematic Literature Review (SLR) method using the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to identify, select, and analyze relevant articles [12]. The PRISMA framework was adopted to ensure a systematic, transparent, and replicable review process, thereby enhancing the validity and reliability of the findings.

The review process consisted of four main stages: identification, screening, eligibility, and inclusion [13]. These stages were designed to ensure that the selected articles were aligned with the research focus on the effectiveness of PhET simulations on learning outcomes in science and chemistry education.

2.2. Data Sources and Search Strategy

The literature search was conducted using Scopus and Crossref through the Publish or Perish software. Scopus and Crossref was selected due to its extensive indexing coverage of international academic publications, including Scopus-indexed journals. The publication period was limited to 2020–2026 to ensure that the selected studies reflected recent developments in digital learning technologies.

The search keywords were constructed using Boolean operators to obtain relevant and specific results. The search string used in this study was as follows: (“PhET Simulation” OR “PhET Simulations” OR “PhET Interactive Simulation”) AND (“effectiveness” OR “impact” OR “effect”) AND (“learning outcomes” OR “academic achievement” OR “student achievement” OR “conceptual understanding”) AND (“science education” OR “chemistry education” OR “physics education”)

2.3. Study Selection Process

To ensure the reliability of the study selection process, an inter-rater validation procedure was applied. The screening and eligibility stages were conducted independently by two reviewers based on predefined inclusion and exclusion criteria.

The eligibility stage involved a full-text assessment of the selected articles based on predefined criteria.

Inclusion criteria:

1. Empirical studies published between 2020 and 2026.
2. Studies that used PhET simulations as the primary instructional variable.
3. Studies conducted in the context of science, chemistry, or physics education. Science education was used as an umbrella term that includes multiple scientific disciplines, particularly chemistry and physics education, because these are the subject areas most commonly associated with the implementation of PhET simulations in the retrieved studies. Chemistry and physics were explicitly mentioned in the inclusion criteria to ensure clarity regarding the dominant disciplinary contexts represented in this review. Although biology is also a major branch of science education, no biology-focused studies met all inclusion criteria during the screening and eligibility stages, particularly regarding empirical focus, learning outcomes, and Scopus indexing requirements. Therefore, biology education studies were not included in the final analysis.
4. Studies that measured student learning outcomes, such as academic achievement, conceptual understanding, or science process skills.

Exclusion criteria:

5. Literature reviews, theoretical papers, or bibliometric studies.
6. Studies that did not involve empirical data collection.
7. Studies that did not examine the effectiveness or impact of PhET simulations.
8. Studies conducted outside science-related educational contexts.
9. Articles not indexed in Scopus.

The inclusion criteria were intentionally designed to be relatively narrow in order to maintain methodological rigor and ensure the relevance and comparability of the selected studies. This review specifically focused on empirical studies investigating the effectiveness of PhET simulations on learning outcomes within science-related educational contexts and published in Scopus-indexed journals. These restrictions were applied to minimize variability in study quality, strengthen the reliability of the synthesized findings, and ensure that the included evidence met internationally recognized academic standards.

As a consequence of these strict eligibility requirements, only a limited number of studies met all inclusion criteria and were included in the final synthesis. Although this reduced the overall number of eligible studies, it enhanced the methodological consistency of the review by ensuring that the included articles addressed comparable research objectives, learning outcomes, and educational contexts. Therefore, the review prioritizes the quality, relevance, and comparability of evidence while acknowledging the narrower scope of the available literature.

The titles, abstracts, and full texts of the retrieved articles were systematically evaluated to determine their relevance. Any discrepancies between reviewers were resolved

through discussion and consensus, thereby minimizing potential bias and ensuring consistency in study selection.

The overall article selection process followed the PRISMA stages and is illustrated in Figure 1.

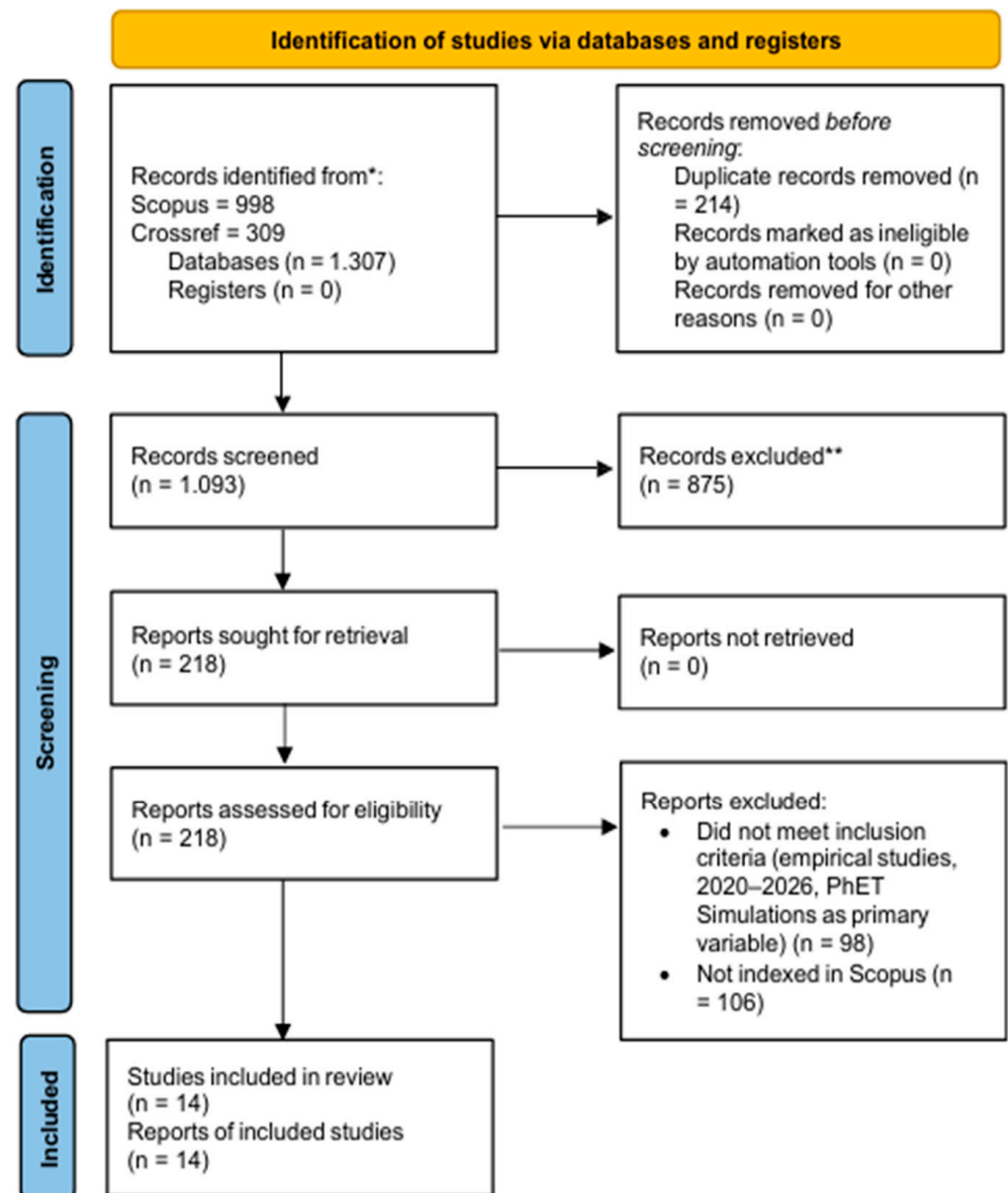


Figure 1. PRISMA Diagram. * Records identified from the Scopus and Crossref databases. ** Records excluded during the title and abstract screening stage.

The article selection process followed the PRISMA stages systematically. The initial search using Scopus and Crossref using Publish or Perish identified 1307 articles based on the predefined keywords [12]. After removing 214 duplicate articles, 1093 articles remained for the screening stage.

During the screening phase, titles and abstracts were reviewed, resulting in the exclusion of 875 articles that were not relevant to the research focus. Consequently, 218 articles were retained for the eligibility stage.

At the eligibility stage, full-text articles were assessed based on the inclusion and exclusion criteria. A total of 98 articles were excluded because they did not meet the predefined criteria. In addition, 106 articles that were not indexed in Scopus were removed.

Finally, 14 articles met all the criteria and were included in the final analysis. The relatively small number of included studies reflects the application of the predefined strict eligibility criteria intended to ensure methodological quality and relevance to the review objectives.

2.4. Data Collection Process

Data extraction was conducted using a standardized data collection form developed by the authors. Two reviewers independently extracted relevant information from each included study, including author(s), year of publication, study design, sample characteristics, intervention details, outcome variables, and key findings. Any discrepancies between reviewers were resolved through discussion and consensus to ensure data accuracy and consistency. No automation tools were used during the data extraction process.

2.5. Risk of Bias Assessment

The risk of bias of the included studies was assessed using an adapted version of the Joanna Briggs Institute Critical Appraisal Tools, which is suitable for evaluating quasi-experimental and related study designs. Six core criteria were applied to assess the methodological quality of each study: (1) comparability of groups, (2) presence of a control group, (3) clarity of the intervention, (4) validity and reliability of outcome measurement, (5) appropriateness of statistical analysis, and (6) control of confounding variables.

Each criterion was rated as “Yes”, “No”, or “Unclear”. The overall risk of bias was determined based on the total number of criteria fulfilled, categorized as low risk (≥ 5 criteria met), moderate risk (3–4 criteria met), and high risk (≤ 2 criteria met).

2.6. Data Synthesis and Assessment of Evidence

This study employed a narrative synthesis approach to integrate findings from the included studies. Due to heterogeneity in research designs, sample sizes, outcome measures, and reporting formats, statistical synthesis (meta-analysis) was not feasible. Therefore, the findings were synthesized qualitatively using a narrative approach. Data were categorized by educational level (Secondary vs. Higher Education) and specific learning outcomes (Cognitive, Affective, or Psychomotor) to provide a comprehensive overview of PhET simulations' effectiveness.

Furthermore, effect measures such as risk ratios, odds ratios, or mean differences were not applied because no statistical meta-analysis was performed, and the findings were synthesized qualitatively using a narrative approach. Reporting bias assessment was also not conducted, as methods such as funnel plots or statistical tests for publication bias are typically used in meta-analysis and were not applicable in this review. Similarly, the certainty of evidence (e.g., using GRADE) was not assessed due to the heterogeneity of study designs and the absence of quantitative synthesis; therefore, formal grading of evidence certainty was considered beyond the scope of this study.

2.7. Registration and Protocol

This review was registered in the Open Science Framework (OSF) and is publicly accessible at: <https://osf.io/63edt> (accessed on 23 April 2026). The review protocol is available at the same link, and no major amendments were made during the review process.

To provide a structured overview of the included studies, Table 1 summarizes the key characteristics of each study, including authors, title, journal, research method, results, and conclusions.

Table 1. Characteristics of Included Studies.

No.	Authors	Title	Journal	Index	Citations	GS Rank	Method	Results	Conclusion
1	Olugbade, D., Oyelere, S. S., & Agbo, F. J. [14]	Enhancing junior secondary students' learning outcomes in basic science and technology through PhET: A study in Nigeria	Education and Information Technologies	Q1	142	1	Pre-test–Post-test Non-Equivalent Control Group Design; <i>t</i> -test analysis	There was a significant improvement in academic performance ($t_{160} = 36.28, p < 0.05$), motivation ($t_{160} = 29.32, p < 0.05$), and attitudes ($t_{160} = 65.36, p < 0.05$).	PhET effectively improves learning outcomes, motivation, and students' attitudes; it is recommended for integration into science learning.
2	Diab, H., Daher, W., Rayan, B., Issa, N., & Rayan, A. [15]	Transforming Science Education in Elementary Schools: The Power of PhET Simulations in Enhancing Student Learning	Multimodal Technologies and Interaction	Q2	25	2	Quasi-experimental; independent samples <i>t</i> -test; two groups (PhET vs. traditional)	The PhET group achieved significantly higher scores and demonstrated better reasoning in problem-solving.	PhET improves conceptual understanding and problem-solving skills in elementary school students.
3	Salame, I. I., & Makki, J. [16]	Examining the Use of PhET Simulations on Students' Attitudes and Learning in General Chemistry II	Interdisciplinary Journal of Environmental and Science Education	Q3	10	6	Quantitative survey (Likert & open-ended); $n = 158$	PhET has a positive impact on attitudes, learning perceptions, and conceptual understanding.	PhET is effective as a complement to traditional laboratories in enhancing understanding of abstract concepts.
4	Rahmawati, Y., Zulhipri, Hartanto, O., Falani, I., & Iriyadi, D. [11]	Students' Conceptual Understanding in Chemistry Learning Using PhET Interactive Simulations	Journal of Technology and Science Education	Q2	89	8	Quantitative; Rasch Model; two-tier diagnostic test ($n = 108$)	An increase in conceptual understanding was identified; however, misconceptions were still found.	PhET supports conceptual understanding but requires further feature development to address misconceptions.
5	Taibu, R., Mataka, L., & Shekoyan, V. [17]	Using PhET Simulations to Improve Scientific Skills and Attitudes of Community College Students	International Journal of Education in Mathematics, Science and Technology (IJEMST)	Q2	2	14	Semester-long project; LSSA survey (pre-post); SPSS; Cohen's d	Large effect size ($d > 0.8$); 88% of students showed positive satisfaction.	PhET enhances scientific skills and promotes positive attitudes toward learning.

Table 1. Cont.

No.	Authors	Title	Journal	Index	Citations	GS Rank	Method	Results	Conclusion
6	Qian, Y. [18]	Exploring the Impact of Teaching Based on PhET Interactive Simulations on Student Learning Motivation	International Journal of Educational Research and Development	Q2	223	16	Quasi-experimental	Significant improvement in motivation (self-efficacy, value, achievement goals).	PhET effectively increases motivation in learning physics.
7	Layson, L. C. [19]	Integration of PhET Interactive Simulations in Online Synchronous and Asynchronous Teaching of Science	International Journal of Trend in Scientific Research and Development (IJTSRD)	Q2	10	17	Two-group pretest-posttest design	Improvement in science process skills; no significant difference between synchronous and asynchronous learning ($p = 0.057$).	PhET effectively improves science process skills in online learning environments.
8	Ndagijimana, J.-B., Mushimiyimana, H., Musengimana, J., Mukama, E., Habimana, O., Manirakiza, P., Munyaruhengeri, J. P. A., Dushimimana, J. C., Khan, S., & Lakind, E. [10]	Contribution of an instructional module incorporating PhET simulations to Rwandan students' knowledge of chemical reactions, acids, and bases through social interactions	Chemical Education Research and Practice	Q1	9	20	Quasi-experimental; pretest–posttest control group; independent t -test; SPSS 26 analysis; FGD	No significant difference in pretest ($p = 0.380$); significant improvement in posttest ($p < 0.001$) in the experimental group.	PhET-based modules effectively improve students' understanding of chemical reactions and acid-base concepts.
9	Najib, M. N. M., Md-Ali, R., & Yaacob, A. [20]	Effects of PhET Interactive Simulation Activities on Secondary School Students' Physics Achievement	SAJSSH	Q1	88	23	Quasi-experimental; pretest-posttest control group; 30 experimental & 30 control	The experimental group showed a significant difference between pretest and posttest; the control group did not.	PhET combined with structured modules and lesson plans improves students' physics achievement.
10	Antonio, R. P., Cruz, B. S., Pagsanjan, E. D. J., & Castro, R. C. [21]	Using PhET Simulations-Integrated Metacognitive Argument-Driven Inquiry to Improve Students' Learning Outcomes in Physics	International Journal of Instruction	Q2	10	39	One-group pretest–posttest; pedagogical action research; Wilcoxon Signed Ranks Test; paired t -test; effect size; thematic analysis	Significant improvement in conceptual understanding and science process skills; attitudes were not quantitatively significant, but interviews indicated positive perceptions.	Integration of PhET within the MADI approach effectively improves physics learning outcomes and science process skills.

Table 1. Cont.

No.	Authors	Title	Journal	Index	Citations	GS Rank	Method	Results	Conclusion
11	Alqawasmi, A. A., Alsalhi, N. R. I., El-Saleh, M. S., Balawi, M., Abu-Attiyeh, J. H., Bani Baker, J. A., Alzboun, N., & Al Gharaibeh, F. [22]	Comparative Effects of PhET Interactive Simulations and Conventional Laboratory Methods (CLM) on Basic Science Process Skills (BSPS) in Physics	ArtsEduca	Q3	1	44	Quasi-experimental; three groups (PhET, CLM, TM); ANCOVA; $n = 93$	PhET and CLM were more effective than traditional methods; no significant difference between PhET and CLM.	PhET effectively improves Basic Science Process Skills and is recommended as an alternative in physics learning.
12	Alsalhi, N. R., Ismail, A. A. K. H., Alqawasmi, A., Abdelkader, A. F. I., Alqatawneh, S., & Salem, O. [23]	The Effect of Using PhET Interactive Simulations on Academic Achievement of Physics Students in Higher Education Institutions	Educational Sciences: Theory & Practice	Q3	6	54	Quasi-experimental; two groups (experimental $n = 69$, control $n = 71$); SPSS 26 analysis	The experimental group achieved higher academic scores; no effect of gender or GPA was found.	The use of PhET significantly improves physics students' academic achievement.
13	Kizito Ndiokubwayo, Jean Uwamahoro, Irénée Ndayambaje [24]	Effectiveness of PhET Simulations and YouTube Videos to Improve the Learning of Optics in Rwandan Secondary Schools	African Journal of Research in Mathematics, Science and Technology Education	Q3	36	55	Quasi-experimental pretest-posttest design with 136 high school students (3 groups: conventional method, PhET-assisted, YouTube-assisted). Instrument: Geometric Optics Conceptual Understanding Test.	The PhET and YouTube groups showed significant improvement compared to the conventional method. Gains: PhET 12%, YouTube 11%, conventional method 2%.	PhET and YouTube are effective in improving optics understanding and are recommended as instructional media.
14	Hasan Özcan, Gülcan Çetin, H. İlker Koştur [25]	The Effect of PhET Simulation-based Instruction on 6th Grade Students' Achievement Regarding the Concept of Greenhouse Gas	Science Education International	Q3	11	61	Quasi-experimental pretest-posttest with control group (45 students); t -test	There was a significant difference between the experimental and control groups ($p = 0.03$).	PhET simulation-based learning improves greenhouse effect understanding more than conventional methods.

3. Results

The initial analysis was conducted to identify the quality of publications based on journal indices as well as the geographical distribution of the research. A total of 14 articles meeting the inclusion criteria were analyzed. Assessment of reporting bias was not performed due to the absence of statistical synthesis. The certainty of evidence was not formally evaluated in this review.

3.1. Risk of Bias Assessment Results

The results of the risk of bias assessment presented in Table 2 shows indicate that the majority of included studies were classified as having a low risk of bias, while a smaller proportion were categorized as moderate risk. No studies were identified as having a high risk of bias. Studies classified as moderate risk generally lacked control groups or did not clearly report procedures for controlling confounding variables. Overall, the included studies demonstrated acceptable methodological quality to support the findings of this review.

Table 2. Risk of Bias Assessment of Included Studies.

No.	Author	Q1	Q2	Q3	Q4	Q5	Q6	Score	Risk
1	Olugbade et al. [14]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low
2	Diab et al. [15]	Yes	Yes	Yes	Yes	Yes	Unclear	5/6	Low
3	Salame & Makki [16]	Yes	No	Yes	Yes	Yes	Unclear	4/6	Moderate
4	Rahmawati et al. [11]	Yes	No	Yes	Yes	Yes	Unclear	4/6	Moderate
5	Taibu et al. [17]	Yes	No	Yes	Yes	Yes	Unclear	4/6	Moderate
6	Qian [18]	Yes	Yes	Yes	Yes	Yes	Unclear	5/6	Low
7	Layson [19]	Yes	Yes	Yes	Yes	Yes	Unclear	5/6	Low
8	Ndagijimana et al. [10]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low
9	Najib et al. [20]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low
10	Antonio et al. [21]	Yes	No	Yes	Yes	Yes	Unclear	4/6	Moderate
11	Alqawasmi et al. [22]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low
12	Alsalihi et al. [23]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low
13	Ndihokubwayo et al. [24]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low
14	Özcan et al. [25]	Yes	Yes	Yes	Yes	Yes	Yes	6/6	Low

3.2. Journal Index Distribution

The analysis of journal index distribution was conducted to identify the quality and reputation level of the publications serving as data sources in this systematic review. The classification of journal indexes is important to demonstrate the credibility of the analyzed findings, as internationally reputable journals generally apply more rigorous peer-review processes and higher methodological standards. Therefore, the index distribution provides an initial overview of the strength of the empirical evidence underlying this research synthesis.

The distribution of journal index levels is presented in Figure 2, which shows that the majority of the selected studies are published in Q2 and Q3 journals, each accounting for 35.71% of the total, while Q1 journals contribute 28.57%. This pattern indicates that research on the effectiveness of PhET simulations is widely disseminated across journals with moderate to high impact levels. The presence of studies in Q1 journals reflects strong academic credibility and highlights the recognition of this topic in high-quality publications. Meanwhile, the dominance of Q2 and Q3 journals suggests that this research area remains accessible and continues to be actively explored, demonstrating its relevance and ongoing development in science and chemistry education.

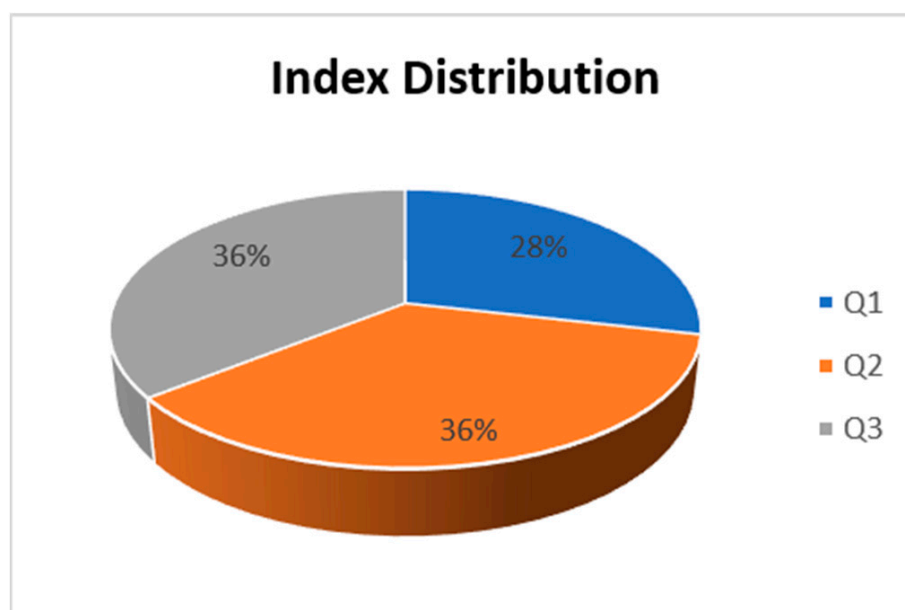


Figure 2. Index Distribution.

3.3. Geographic Distribution of the Included Studies

The analysis of the distribution of countries of origin was conducted to identify the geographical spread of studies examining the effectiveness of PhET in science and chemistry education. This information is essential for understanding the implementation context, characteristics of educational systems, and the global relevance of the findings synthesized in this systematic review. By examining country distribution, it can be determined whether the research is concentrated in specific regions or has developed internationally.

The distribution of study countries of origin is illustrated in Figure 3, demonstrating that the selected studies are geographically diverse and represent multiple regions, including Africa, Asia, the Middle East, and North America. The highest contributions come from the Philippines and Rwanda, each accounting for 14.29% of the total studies, followed by Jordan with a similar proportion. Meanwhile, other countries, including Nigeria, Israel, Lebanon, Indonesia, the United States, China, Malaysia, and Turkey, each contribute smaller proportions of approximately 7.14%. This distribution indicates that research on the effectiveness of PhET simulations has attracted global attention and has been implemented across a variety of educational contexts. The broad geographical representation suggests that PhET simulations are adaptable to different educational systems and learning environments, highlighting their potential for wider application in science and chemistry education worldwide. The distribution of study countries of origin is illustrated in Figure 3, showing that the selected studies are geographically diverse and span multiple regions, including Africa, Asia, and the Middle East. The highest contributions come from the Philippines, Rwanda, and Jordan, each accounting for 14.29% of the total studies, while other countries contribute smaller but equal proportions. This distribution indicates that research on the effectiveness of PhET simulations has gained global attention and is implemented across various educational contexts. The wide geographical spread suggests that PhET simulations are adaptable and relevant in different educational systems, highlighting their potential for broader application in science and chemistry education worldwide.

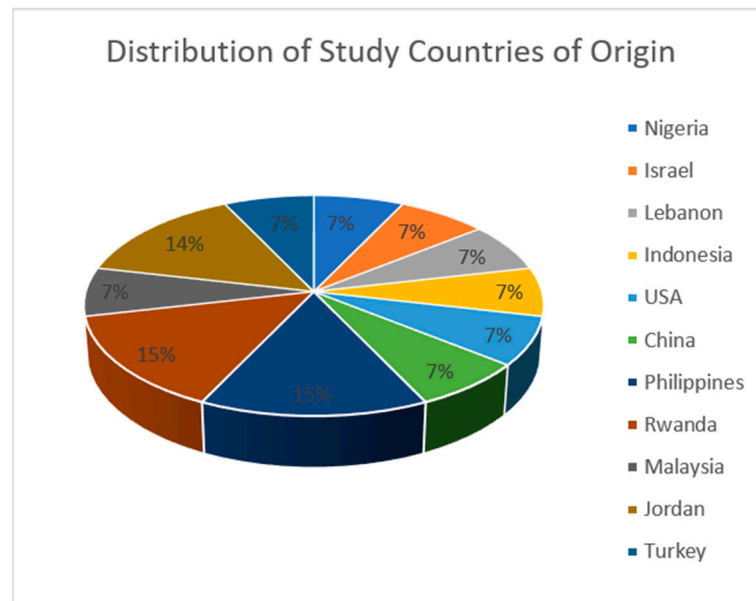


Figure 3. Distribution of Study Countries of Origin.

3.4. Learning Outcome Variables Affected

Based on the synthesis of 14 selected studies, learning outcome variables can be classified into three main domains: cognitive, higher-order skills, and affective. The distribution of these variables is presented in Table 3 below.

Table 3. Distribution of Learning Outcome Variables.

Category	Variable	Studies
Cognitive	Academic achievement/learning outcomes	[14,15,20,21,23–25]
	Conceptual understanding	[10,11,15,16,21,24]
Higher-order skills	Problem-solving skills	[15,21]
	Science process skills	[17,19,21,22]
Affective	Motivation	[14,18]
	Attitude	[14,16,17]

The distribution of learning outcome variables presented in Table 3 shows that cognitive aspects are the most frequently investigated in the selected studies. Academic achievement or general learning outcomes are examined in seven studies [14,15,20,21,23–25], while conceptual understanding is addressed in six studies [10,11,15,16,21,24]. This indicates that most research primarily focuses on measuring students' cognitive performance when using PhET simulations.

In this review, cognitive outcomes primarily refer to academic achievement and conceptual understanding measured through test scores, learning outcomes, or content mastery indicators [14–16,20,21,23–25]. In contrast, higher-order skills refer to more complex competencies, such as problem-solving and science process skills, which involve analysis, reasoning, and the application of knowledge. In cases where studies included higher-order thinking components within broader cognitive achievement measures, the categorization was determined based on the primary outcome emphasis identified by the original authors [15,17,19,21,22]. This classification approach was applied to maintain consistency within the synthesis framework and minimize overlap between categories.

In terms of higher-order skills, science process skills are explored in four studies [17,19,21,22], whereas problem-solving skills receive relatively less attention, appearing in only two studies [15,21]. This suggests that although some studies have begun

to examine more complex competencies, the emphasis on higher-order thinking skills remains limited.

Meanwhile, affective variables such as motivation and attitude are less frequently studied. Motivation is examined in two studies [14,18], while attitude appears in three studies [14,16,17]. This indicates that the affective domain is still underrepresented compared to cognitive aspects. Therefore, this distribution suggests that although PhET simulations have the potential to influence a wide range of learning outcomes, existing research tends to emphasize cognitive aspects more than higher-order skills and affective domains.

3.5. Educational Level with Dominant Effectiveness

Furthermore, it is essential to identify at which educational level the use of PhET demonstrates the most dominant effectiveness. This identification is important to examine the alignment between the characteristics of PhET's interactive simulations and students' cognitive developmental stages, as well as the complexity of science and chemistry content at each level.

The distribution of educational levels from the 14 analyzed studies is presented in Table 4 below.

Table 4. Distribution of Educational Levels.

Educational Level	Studies
Elementary School	[15,25]
Junior High School	[10,14,18,20,21]
Senior High School	[11,19,22,24]
Higher Education	[16,17,23]

The distribution of educational levels is presented in Table 4, indicating that most studies are concentrated at the junior high school with five studies [10,14,18,20,21]. This is followed by senior high school with four studies [11,19,22,24], higher education with three studies [16,17,23], while elementary school contributes the fewest, with two studies [15,25]. This distribution suggests that research on the effectiveness of PhET simulations is more frequently conducted at the secondary education level, particularly in junior and senior high schools. This may be due to the suitability of PhET simulations for supporting conceptual understanding in science subjects at these stages. In contrast, the relatively limited number of studies at the elementary level indicates a potential research gap, highlighting the need for further investigation into the application of PhET simulations in early education contexts.

4. Discussion

4.1. Effectiveness of PhET Simulations on Learning Outcomes (RQ1)

The findings of this systematic literature review indicate that the use of PhET simulations has a consistently positive effect on students' learning outcomes in science and chemistry education. Across the analyzed studies, the majority of empirical evidence demonstrates significant improvements in academic achievement, conceptual understanding, and related learning outcomes when PhET simulations are integrated into instructional practices. For instance, several studies reported statistically significant improvements in students' academic performance following the implementation of PhET-based learning interventions [14,15,20,21,23–25]. These findings suggest that PhET simulations serve as an effective instructional tool for enhancing students' understanding of scientific concepts.

One of the primary reasons for the effectiveness of PhET simulations lies in their ability to visualize abstract scientific phenomena. Science and chemistry often involve concepts

that are difficult to observe directly, such as atomic interactions, molecular structures, or physical processes. PhET simulations provide dynamic and interactive representations of these concepts, allowing students to manipulate variables and observe real-time changes. This interactive visualization helps bridge the gap between theoretical knowledge and practical understanding, thereby facilitating deeper learning. Studies have shown that students who use PhET simulations tend to demonstrate better comprehension and retention of concepts compared to those who rely solely on traditional instructional methods [15,21].

Moreover, the effectiveness of PhET simulations is further enhanced when combined with appropriate pedagogical approaches. Several studies highlight that integrating PhET with structured learning strategies, such as guided inquiry, problem-based learning, or metacognitive frameworks, leads to more significant learning gains [19,21]. This suggests that while PhET simulations are inherently beneficial, their impact is maximized when supported by well-designed instructional scaffolding. In this context, the role of teachers becomes crucial in facilitating meaningful learning experiences and guiding students' exploration of simulation-based environments.

Another important finding is that PhET simulations contribute not only to cognitive learning outcomes but also to the development of higher-order skills. Some studies indicate improvements in students' science process skills, such as analyzing data, interpreting results, and engaging in scientific reasoning processes [17,19,21,22]. In contrast, problem-solving skills are less frequently examined, although some evidence still supports their improvement [15,21]. These skills are essential in science education, as they reflect students' ability to apply knowledge in real-world contexts. The interactive nature of PhET simulations encourages active learning, where students are not merely passive recipients of information but active participants in the learning process.

In addition to cognitive and higher-order outcomes, a limited number of studies also examine affective aspects such as motivation and attitude. Findings suggest that PhET simulations can enhance students' motivation and foster more positive attitudes toward learning science [14,16–18]. However, compared to cognitive outcomes, the affective domain remains underexplored, indicating the need for further investigation in this area.

Despite the overall positive findings, some variations in effectiveness were observed across studies. These variations may be attributed to differences in research design, sample characteristics, and implementation contexts. For example, some studies reported that the effectiveness of PhET simulations depends on factors such as students' prior knowledge, digital literacy, and the availability of technological resources [21]. In addition, the level of teacher expertise in integrating simulations into the curriculum can also influence learning outcomes. Without proper guidance, students may not fully benefit from the interactive features of the simulations.

Furthermore, while most studies report significant improvements in post-test results, some findings indicate that the magnitude of improvement may vary depending on the subject matter and instructional design. This suggests that the effectiveness of PhET simulations is not universally guaranteed but context-dependent. Therefore, it is important to consider contextual and pedagogical factors when implementing simulation-based learning.

Overall, the findings of this review provide strong evidence that PhET simulations are an effective tool for enhancing learning outcomes in science and chemistry education. Their ability to support visualization, promote active learning, and facilitate the development of higher-order thinking skills makes them a valuable addition to modern educational practices. However, their effectiveness is influenced by various factors, including instructional design, teacher facilitation, and technological accessibility. Therefore, future research

should focus on identifying optimal implementation strategies to maximize the benefits of PhET simulations across different educational contexts.

4.2. Learning Outcome Variables Most Frequently Influenced (RQ2)

The analysis of learning outcome variables reveals that PhET simulations predominantly influence cognitive aspects of learning, particularly academic achievement and conceptual understanding. As shown in the results, academic achievement is examined in seven studies [14,15,20,21,23–25], while conceptual understanding is addressed in six studies [10,11,15,16,21,24]. This indicates that the primary focus of existing research is on measuring students' cognitive performance, reflecting the central role of knowledge acquisition in science and chemistry education.

The strong emphasis on cognitive outcomes can be explained by the nature of PhET simulations, which are designed to enhance conceptual understanding through visualization and interaction. By allowing students to explore scientific phenomena in a virtual environment, PhET simulations facilitate meaningful learning processes that go beyond rote memorization. Students are able to construct their own understanding by actively engaging with the content, which aligns with constructivist learning theories. As a result, improvements in academic achievement and conceptual understanding are consistently reported across multiple studies [15,21].

In addition to cognitive outcomes, PhET simulations also contribute to the development of higher-order skills, although to a lesser extent. Science process skills are examined in four studies [17,19,21,22], while problem-solving skills are addressed in only two studies [15,21]. These findings suggest that while PhET simulations have the potential to foster higher-order thinking, this aspect has not been extensively explored in the literature. The development of skills such as critical thinking, problem-solving, and scientific reasoning requires more complex instructional designs, which may explain the limited number of studies focusing on these variables.

The relatively lower emphasis on higher-order skills highlights an important research gap. Given the increasing importance of 21st-century skills in education, future studies should investigate how PhET simulations can be effectively used to promote these competencies. Integrating simulations with inquiry-based learning or problem-based learning approaches may provide opportunities to enhance students' higher-order thinking skills. Therefore, further research is needed to explore the full potential of PhET simulations in developing these skills.

Affective variables, such as motivation and attitude, are the least frequently studied among the three domains. Motivation is examined in two studies [14,18], while attitude is addressed in three studies [14,16,17]. Despite the limited number of studies, the findings consistently indicate positive effects of PhET simulations on students' motivation and attitudes toward learning. The interactive and engaging nature of simulations appears to increase students' interest and enjoyment in learning science, which can have a positive impact on their overall learning experience.

The limited focus on affective outcomes may be due to the challenges associated with measuring these variables, as they often require qualitative or mixed-method approaches. However, affective factors play a crucial role in learning, as they influence students' engagement, persistence, and willingness to learn. Therefore, the lack of extensive research in this area represents another important gap that should be addressed in future studies.

Overall, the distribution of learning outcome variables suggests that while PhET simulations are primarily used to enhance cognitive learning outcomes, they also have the potential to influence higher-order and affective domains. However, these latter aspects remain underexplored, indicating the need for more comprehensive research that considers

multiple dimensions of learning. By expanding the focus beyond cognitive outcomes, future studies can provide a more holistic understanding of the impact of PhET simulations on student learning.

4.3. Educational Level with the Highest Research Concentration (RQ3)

The analysis of educational levels reveals that the majority of studies on the effectiveness of PhET simulations are concentrated at the secondary education level, with five studies focusing on junior high school [10,14,18,20,21]. This is followed by senior high school with four studies [11,19,22,24], and higher education with three studies [16,17,23], while elementary school contributes the fewest, with two studies [15,25]. This distribution indicates a clear research concentration at the secondary level of education.

One possible explanation for this trend is the alignment between the use of PhET simulations and the learning needs at the secondary level. At this stage, students begin to encounter more abstract scientific concepts, particularly in physics and chemistry, which require visualization and interactive learning tools. PhET simulations are well-suited to support conceptual understanding at this level, as they provide dynamic and engaging representations of scientific phenomena. As a result, researchers may be more inclined to implement and study these tools in junior and senior high school settings.

Another factor that may explain this concentration is the balance between technological readiness and curriculum demands. Compared to elementary school students, secondary school students generally have better digital literacy and are more capable of independently operating simulation-based learning tools. At the same time, the curriculum at this level increasingly emphasizes conceptual understanding and problem-solving skills, making the integration of interactive simulations more relevant and effective.

Although higher education also shows a considerable number of studies, it is not the dominant level in this distribution. This suggests that the use of PhET simulations is not limited to advanced learners but is also widely applicable in earlier stages of education, particularly at the secondary level. However, the slightly lower number of studies in higher education may indicate that other advanced learning tools or methods are also being utilized in that context.

Despite the growing use of PhET simulations in secondary and higher education, the limited number of studies at the elementary level highlights a significant research gap. Elementary school students also face challenges in understanding basic scientific concepts, and interactive simulations have the potential to enhance their engagement and comprehension. However, their application at this level remains underexplored.

Several factors may contribute to this gap, including limited access to technological resources in elementary schools, differences in curriculum structure, and concerns about students' readiness to use digital tools. Younger learners may require more structured guidance and supervision when using simulations, which can pose challenges for teachers in terms of classroom management and instructional design.

The findings of this review suggest that while PhET simulations are widely implemented at the secondary level and moderately used in higher education, there is a need to expand research to elementary education. Investigating the effectiveness of simulations across different educational levels can provide valuable insights into how these tools can be adapted to diverse learning needs and contexts.

Therefore, the concentration of research at the secondary education level reflects both pedagogical relevance and practical considerations. However, to achieve a more comprehensive understanding of the effectiveness of PhET simulations, future studies should explore their application across a broader range of educational levels. This will

support the development of more inclusive and effective science-learning strategies that can benefit students at all stages of education.

4.4. Limitations

Despite the rigorous systematic review process, this study has several limitations. First, the inclusion criteria were intentionally narrow, focusing only on empirical studies published between 2020 and 2026, conducted within science-related educational contexts, reporting learning outcomes, and indexed in Scopus. Although these restrictions enhanced the methodological rigor and comparability of the included evidence, they also resulted in a relatively small number of eligible studies ($n = 14$), which may limit the breadth and generalizability of the findings.

Second, the search was restricted to English and Indonesian language publications, which may have excluded relevant studies published in other languages. Third, the review relied primarily on Scopus and Crossref databases, potentially overlooking grey literature or studies published in journals not indexed by these databases. Finally, due to the heterogeneity of study designs, interventions, and outcome measures, a quantitative meta-analysis was not feasible, preventing the calculation of an overall effect size for the effectiveness of PhET simulations.

5. Conclusions

In conclusion, this systematic literature review demonstrates that PhET simulations are an effective instructional tool for enhancing learning outcomes in science and chemistry education, particularly in improving academic achievement and conceptual understanding as dominant cognitive domains. The findings also indicate that PhET simulations have the potential to support higher-order skills, such as science process skills and problem solving, as well as affective outcomes including motivation and attitude, although these aspects remain less frequently examined. Furthermore, the concentration of studies at the secondary education level suggests that PhET simulations are especially relevant in contexts where students encounter more abstract concepts and possess sufficient digital readiness. However, the effectiveness of these simulations is influenced by factors such as instructional design, teacher facilitation, and technological accessibility. Therefore, future research should focus on expanding investigations across underrepresented educational levels, particularly elementary education, and exploring a broader range of learning outcomes to provide a more comprehensive understanding of the role of PhET simulations in diverse educational contexts.

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Abbreviations

The following abbreviations are used in this manuscript:

PhET	Physics Education Technology
SLR	Systematic Literature Review
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses

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