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PAPER

Meta-Analysis of the Effectiveness of PhET Simulations in Physics Education

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ABSTRACT

PhET (Physics Education Technology) is a widely recognized virtual simulation tool for teaching physics. Its integration in classroom instruction facilitates the understanding of abstract concepts, supports the development of innovative ideas, and enables experimentation that is often difficult to achieve in traditional settings. However, existing studies have reported mixed results regarding its effectiveness. To address this, a meta-analysis was conducted on 47 effect sizes extracted from 20 empirical studies published between 2018 and 2023, with a combined sample of 4,563 students across experimental and control groups. The findings indicate that PhET simulations significantly positively impact physics education, with a large overall effect size ($d = 0.83$) compared to traditional approaches. Subgroup analyses further reveal differential effects across educational levels, physics domains, performance outcomes, and learning modes (offline vs. online). These findings demonstrate that PhET simulations significantly enhance physics learning outcomes, particularly at the secondary level and in abstract domains such as electricity and waves. The results highlight that effectiveness is shaped by instructional context and learner characteristics, underscoring the need for targeted integration strategies in both online and offline classrooms.

KEYWORDS

PhET (Physics Education Technology) simulations, physics education, learning outcomes, effect size, meta-analysis

1 INTRODUCTION

Physics learning is learning related to all human activities in everyday life [1]. That is why students already have many relevant experiences with physics learning before learning formally in a school environment [2]. They already interact with the physical world and talk about the world of physics as a discourse in everyday life [3]. In addition to providing convenience to students, it does not slightly influence the conceptions in students' thinking due to the experiences and prior knowledge that

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students bring [4]. It causes learners to experience misconceptions due to holding firm and using the wrong initial understanding to solve problems [5].

Additionally, physics education is widely regarded as challenging due to the abstract nature of the material, the necessity for precise problem-solving abilities, and a strong foundation in math skills [6]. One factor contributing to students' struggles with comprehending physics material is the need for more emphasis on the active role of students in their learning. A practical learning approach should establish an environment that fosters students' understanding of scientific concepts and processes [7]. It can be achieved by providing learning experiences through laboratory experiments, an essential element in the educational process to enhance active roles and support student understanding [8]. However, several challenges that prevent laboratory experiments have been identified, such as lack of information resources, experimental limitations, and safety concerns [9].

The current growth of information and communication technology (ICT) can bridge the gap between teaching and learning processes [7], [10]. PhET (Physics Education Technology) is one of the virtual simulations that facilitates learning physics [11]. PhET virtual simulations help educators facilitate the learning of abstract physics concepts, help students develop powerful ideas, and conduct explorations that are usually not possible in the classroom [12], [13]. Integrating PhET in classroom instruction can aid in establishing a framework for scientific comprehension and is an impactful tool for improving student performance [14].

Several studies have revealed the positive effects of using PhET in education. Researchers have identified that the use of PhET has a significant impact on physics learning, including increased motivation [15], critical thinking skills [16], academic achievement [17], and student interest [18]. However, some other researchers have revealed adverse effects of using PhET in physics education, where students' attitudes towards physics decreased [19], and no improvement was found in motivation for self-efficacy and performance goals [12]. The diverse and sometimes contradictory results reported in previous studies highlight a critical gap in our understanding of the true impact of PhET simulations in physics education. With a comprehensive synthesis of these findings, educators and policymakers can make informed decisions about integrating PhET into the curriculum.

This study aims to address such gaps by conducting a meta-analysis to investigate the overall effectiveness of PhET simulations in improving students' physics learning performance. Specifically, this study aims to answer two main research questions:

- RQ1. How do PhET simulations affect students' physics learning?
- RQ2. What factors will likely influence the outcomes of PhET simulations in physics education?

By synthesizing existing research and identifying critical moderating variables, this study can provide more explicit guidance on using PhET simulations and enhance the physics learning experience. The results of this study are expected to make significant contributions to both academic research and practical applications in the field of physics education.

2 THEORETICAL AND EMPIRICAL BACKGROUND

PhET is an interactive virtual simulation developed by the University of Colorado that connects real-world phenomena with underlying scientific principles [20], [21].

Initially designed for physics, PhET has since expanded to chemistry, mathematics, and earth sciences, providing students with opportunities to visualize, manipulate, and experiment with abstract concepts often difficult to grasp through traditional teaching [22], [23]. By engaging students in exploration and inquiry, PhET promotes phases of learning that include remembering, analyzing, evaluating, and creating, thereby supporting a deeper conceptual understanding and creativity in science learning [11], [24].

Empirical studies consistently show that PhET contributes positively to student outcomes in physics education. Its use has been linked to improvements in conceptual understanding [25], higher-order thinking skills [23], learning motivation [14], and scientific creativity [24]. Research also highlights its benefits across different instructional models such as collaborative creativity learning [24], scaffolding approaches [26], problem-based learning [27], and discovery learning [28]. However, these advantages are strongly mediated by instructional design and teacher expertise. Studies have emphasized that the quality of integration, such as structured worksheets and appropriate scaffolding, plays a central role in ensuring effective learning outcomes [29].

Despite its promise, PhET's impact is not uniformly positive. Some studies have reported no significant improvement in students' motivation or self-efficacy [12], while others noted a decline in students' attitudes toward physics [19]. These contrasting results underscore the importance of pedagogical context and highlight the need for clearer implementation guidelines and teacher training in simulation-based instruction [22], [29]. The open-ended nature of PhET also contributes to variability in outcomes, since community-generated teaching resources often differ in structure and pedagogical quality [30].

Meta-analytic research on virtual simulations, including PhET, remains limited. For example, Chotimah and Festiyed [31] found positive effects of PhET-assisted worksheets on high school physics outcomes. However, they did not employ standardized procedures such as PRISMA, nor did they address potential publication bias, issues that may affect the reliability of their findings [32], [33]. By contrast, Antonio and Castro [34] applied more rigorous methods, including effect size calculation and publication bias analysis, and confirmed the positive impact of virtual simulations on student achievement. However, their study mainly focused on secondary school contexts and covered a broader range of simulations beyond PhET.

Given these gaps, the present study systematically examines the effectiveness of PhET simulations in physics education through a comprehensive meta-analysis. By synthesizing empirical evidence across diverse contexts and identifying potential moderating variables, this study seeks to provide robust insights that can inform both theoretical understanding and practical application of PhET in improving students' physics learning outcomes.

3 METHODS

The objective of this study was to conduct a meta-analysis in order to systematically review and synthesize the findings from relevant research articles published between 2018 and 2023. The objective was to evaluate the impact of PhET simulations on physics education. To ensure the collection of a comprehensive and inclusive set of pertinent literature, a comprehensive search was conducted in a range of renowned databases [35], including Scopus, PubMed, Google Scholar, Taylor & Francis, Wiley Online Library, ScienceDirect, and ERIC. These databases were selected for their comprehensive collections of academic publications across various disciplines, ensuring the inclusion of diverse and relevant studies.

The search strategy involved the use of specific keywords to identify articles related to the use of PhET simulations in physics education. The keywords utilized for the article search were "PhET" AND "Physics" AND ("education" OR "learning" OR "teaching"). The keywords were applied to both the titles and abstracts of the articles in order to maximize the retrieval of relevant studies. The inclusion of both titles and abstracts in the search increased the likelihood of identifying all pertinent literature, thereby capturing studies that explicitly mentioned the use of PhET simulations in the context of physics education.

3.1 Eligibility criteria

To be eligible for inclusion in the meta-analysis, studies had to (1) examine the impact of PhET simulations on learning physics, (2) be written in English, (3) use an experimental, quasi-experimental, or mixed-methods pre/post-experimental research design, and (4) provide complete data suitable for meta-analysis. Studies were excluded if they (1) focused only on PhET simulations without educational references, (2) were not written in English, (3) were categorized as review studies, (4) were published in conference proceedings, (5) did not focus on physics, or (6) lacked the required primary data, such as sample size, mean, and standard deviation.

3.2 Selection process

The data collection process was coordinated using the online systematic review management program Covidence (www.covidence.org), which enables multiple authors to independently conduct systematic review procedures, resolve conflicts, and track progress. At each stage of the study screening, inclusion and exclusion criteria selection, and data extraction, two authors independently piloted the suggested process on ten papers, then discussed the outcomes to assess agreement, refine the process, and ensure methodological consistency. Once the final methodology was agreed upon, it was entered into Covidence and applied to all the articles. The selection of studies proceeded through several stages: (1) removing duplicates, where one author used Covidence to eliminate clear duplicate articles and a second author manually verified the results for accuracy; (2) removing irrelevant articles, where one author excluded studies not meeting the inclusion criteria (e.g., not related to physics or PhET; see section 3.3), and a second author rechecked the decisions, with any discrepancies resolved through discussion, all within Covidence; (3) determining potentially relevant articles, where two authors independently screened titles and abstracts in Covidence, compared results, and resolved conflicts through discussion, with uncertain cases retained for full-text review or, if necessary, referred to a third author; and (4) conducting a full-text review for eligibility compliance, where two authors independently assessed the articles using the inclusion criteria, documented reasons for exclusion, and resolved conflicts through discussion or, if needed, consultation with a third author. The final list of eligible and excluded studies was then compiled, cross-checked with references from included studies and systematic reviews on similar topics, and discussed with the entire authorship group to ensure alignment and consensus.

3.3 Screening process

This study used the PRISMA guidelines to improve the quality of the meta-analysis [36]. We identified 3245 articles from databases. Prior to screening, the automation tool identified and removed 132 duplicate articles. Additionally, we manually checked and deleted nine duplicate records. We then screened through 3114 remaining records based on the titles and abstracts. We excluded 3050 records because there was no physics, no PhET simulation/focus on PhET without educational relevance, conference proceedings, review studies, and not in English. The 62 remaining articles were assessed for eligibility, with 42 studies excluded due to lack of primary data and no experimental quasi-experimental or mixed-methods pre/post-experimental studies. After excluding ineligible literature through screening, we included 20 relevant outcomes in the meta-analysis. All this process is done using Covidence. Figure 1 shows the specific literature screening process.

3.4 Coding scheme

This meta-analysis utilized a coding scheme to classify and analyze data systematically from the selected studies. Following the approach described by Zuo et al. [32], the researchers initially coded 10% of the included articles (n = 20) to resolve any inconsistencies in categorization. Through iterative discussions, a consistent coding framework was established. The final scheme included four categories: grade level, physics subject matter, types of effects of PhET simulation on learning, and learning modes.

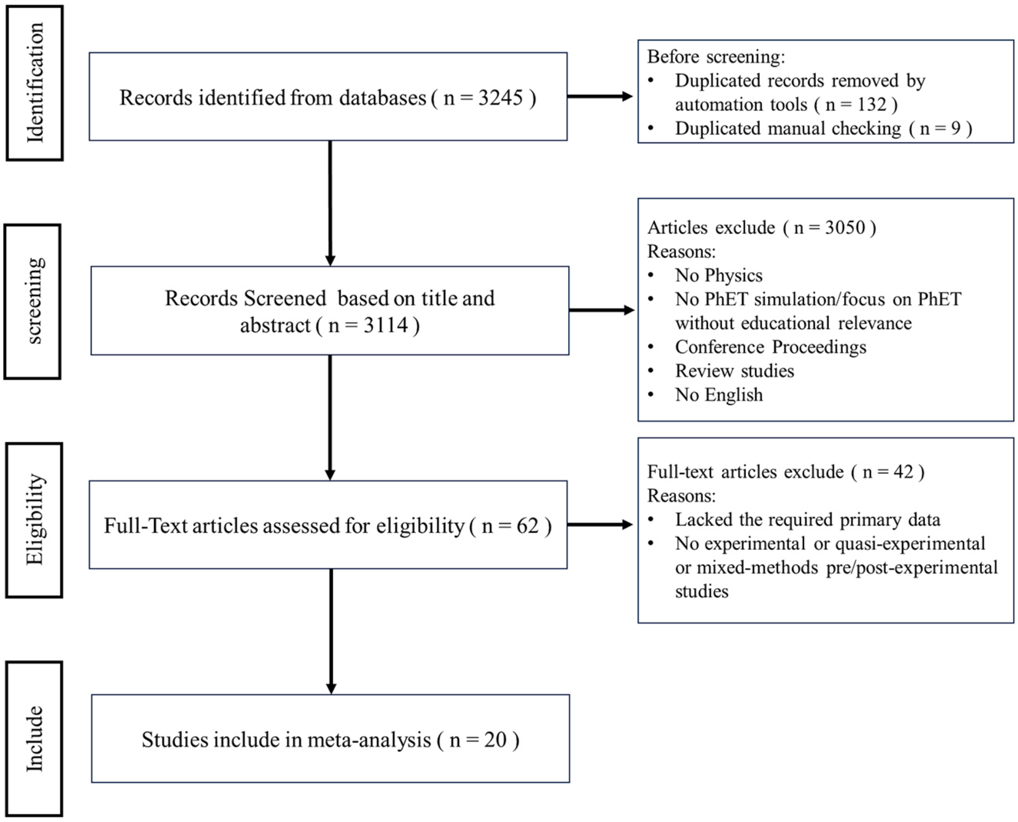


Fig. 1. Diagram of the literature screening process

The first category, grade level, classified the studies based on the participants' educational levels, including elementary school, junior high school, senior high school, and college students. This categorization provided insights into how the effects of PhET simulations varied across different age groups and educational contexts.

The second category, physics subject matter, identified the specific topics addressed in the studies, such as electrostatics, oscillations, waves and optics, electrodynamics, the greenhouse effect, and physical changes. This classification ensured a clear understanding of the physics content where PhET simulations were applied.

The third category, types of effects of PhET simulation on learning, referred to measurable impacts, including achievement, attitude, motivation, critical and creative thinking, and science process skills. These categories were derived from the original studies, ensuring consistency in definitions and alignment with existing literature. For instance, some studies measured achievement using pre- and post-tests aligned with curriculum standards. In contrast, others assessed attitudes and motivation using validated questionnaires such as the Physics Attitude Scale (PAS) [37] or the Students' Motivation Towards Science Learning (SMTSL) [12].

The fourth category, learning modes, categorized studies based on whether PhET simulations were used in online or offline learning environments. This distinction provided insights into how the mode of implementation influenced learning outcomes.

3.5 Effect size and heterogeneity

We use a random effects model to generate the effect size. Then, we interpret the value based on the theory of Cohen's *d*, where $d < 0.20$, $d \geq 0.20$, $d \geq 0.50$, and $d \geq 0.80$ classify the effect sizes as no effect, small, medium, and large [38]. The effect size value is obtained from the standardized mean difference (*d*) generated using the Cochrane Collaboration's statistical software, Review Manager (RevMan) 5.4.

We calculated the Q-value (Chi^2) and the I^2 statistic to assess heterogeneity among the studies. A Q-value higher than the critical value of 32.671 (with 21 degrees of freedom at the 95% confidence interval) and a *p*-value less than 0.05 indicate significant heterogeneity, supporting using a random effects model [39]. The random effects model claims that the effect size may vary due to moderator variables such as level, so it can estimate and generalize the effect size to a larger population even though the study does not have the same functionality. The I^2 value was also examined to quantify heterogeneity, with values of approximately 25% indicating low heterogeneity, 50% indicating medium heterogeneity, and 75% indicating high heterogeneity [39].

3.6 Publication bias

To ensure the accuracy of the calculation outcomes, we employed a funnel plot to test for publication bias, as recommended by Egger et al. [40]. Publication bias occurs when the results of published studies are systematically different from the results of all completed studies on a given topic. This bias can arise due to several factors, including the tendency to publish studies with positive results over those with negative or null results [41]. Detecting publication bias is crucial as it can significantly skew the results and conclusions of a meta-analysis.

The funnel plot was created using RevMan 5.4. A funnel plot is a scatter plot of the effect sizes estimated from individual studies (on the x-axis) against a measure of study precision, typically the standard error (on the y-axis). In the absence of publication bias, the plot should resemble a symmetrical inverted funnel because larger studies with more precise estimates will cluster around the true effect size at the top, while smaller studies will spread out at the bottom due to greater variability [32].

4 RESULTS

During the initial search of the literature, a total of 3,245 articles were identified. However, with the implementation of strict selection processes, only 20 of those articles were deemed eligible for inclusion in the meta-analysis. Notably, some articles reported multiple independent findings. For example, the study by Abou Faour and Ayoubi [37] presented four separate findings from experimental settings. Consequently, the meta-analysis incorporated 47 independent effect sizes from these 20 articles. The combined sample size of the selected studies consisted of 4,563 participants divided into control and experimental groups. For a detailed overview of pertinent data, including the number of studies, grade levels, themes, subfields of physics, and learning modes (refer to Table 1).

Table 1. Studies included in the meta-analysis

No	Author (Year)	k	Grade Levels	Field of Physics	Focus	Learning Modes	Ref.
1	Agyei et al. (2023)	2	Senior high school	EL	MO	Offline	[42]
2	Afafa et al. (2021)	1	Senior high school	OT	CCT	Offline	[43]
3	Al Amri et al. (2020)	2	Senior high school	OWO	ACH	Offline	[44]
4	Yunzal & Casinillo (2020)	1	Senior high school	ELC	ACH	Offline	[7]
5	Banda and Nzabahimana (2023)	8	Senior high school	OWO	ACH	Offline	[12]
6	Oscar Jayanagara and Chandra Lukita (2023)	1	Senior high school	ELC	ACH	Offline	[45]
7	Saputra et al. (2022)	1	Senior high school	OT	CCT	Offline	[46]
8	Yildirim (2020)	1	Junior high school	OT	ACH	Offline	[47]
9	Özcan et al. (2020)	1	elementary	GE	ACH	Offline	[48]
10	Ardisa et al. (2022)	1	Senior high school	ELC	CCT	Offline	[49]
11	Siantuba et al. (2023)	1	college	OT	ACH	Online	[50]
12	Ndihokubwayo et al. (2020)	1	Junior high school	OWO	ACH	Offline	[51]
13	Laurence C (2022)	8	Senior high school	PC	AC/SP	Online	[52]
14	Abou Faour and Ayoubi (2018)	4	Junior high school	OT	AT	Offline	[37]
15	Ng & Chua (2023)	4	Junior high school	OT	AT	Online	[19]
16	Maulani et al. (2020)	1	Senior high school	OT	ACH	Offline	[53]
17	Purfiyansyah et al. (2023)	2	Senior high school	OT	CCT	Offline	[54]
18	Sylvere and Minani (2023)	1	Senior high school	EL	ACH	Offline	[55]
19	Çetinkaya and Kirilmazkaya (2022)	1	elementary	GE	ACH	Offline	[56]
20	Mešić et al. (2021)	1	Junior high school	OT	MO	Offline	[57]

Note: Included studies (k), achievement (ACH), attitude (AT), critical and creative thinking skills (CCT), motivation (MO), science process skills (SP), Electrostatics (EL), Oscillations, Waves, and optics (OWO), Electrodynamics (ELC), Greenhouse effect (GE), Physical changes (PC), Others (OT).

4.1 The impact of PhET simulation on physics learning

Figure 2 presents a funnel plot demonstrating the distribution of effect sizes. The plot shows a generally symmetrical distribution around the mean effect size, with most effect sizes falling within the expected triangular region. This symmetry suggests a low level of publication bias, as supported by the distribution of studies across a range of effect sizes, rather than clustering exclusively around high or low values. While a few effect sizes fall slightly outside the triangular boundary, this deviation likely reflects heterogeneity in the included studies rather than systemic bias. Therefore, the overall conclusions are unlikely to be compromised by publication bias, consistent with prior analyses that found similar patterns [32].

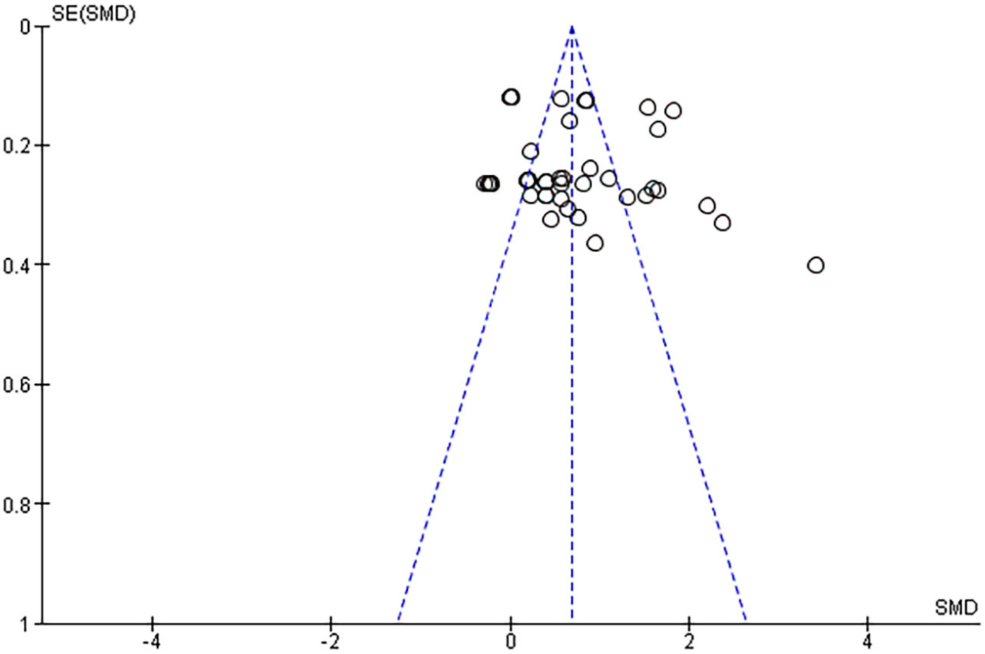
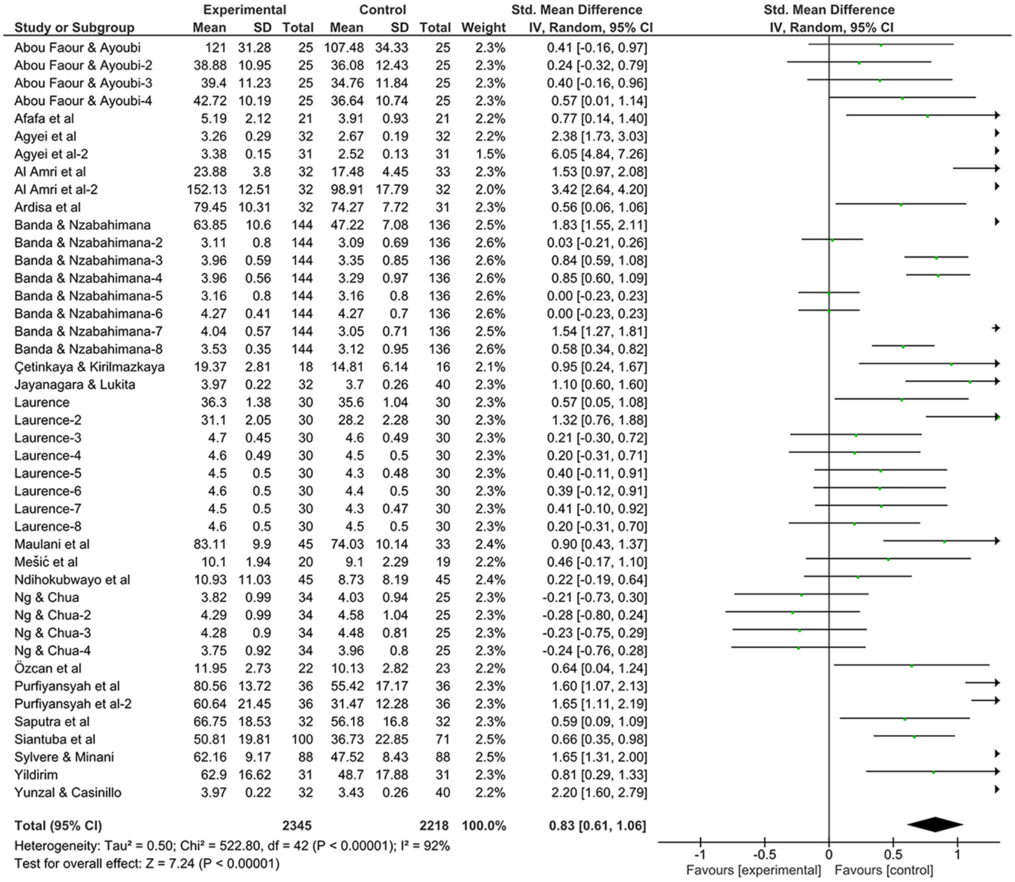


Fig. 2. The funnel plot of the effect of PhET simulation on physics learning

Figure 3 summarizes the effect of using PhET simulation in physics learning with a 95% confidence interval (CI) of 0.61–1.06. The results show that PhET simulation in physics learning is significantly more effective than learning without PhET simulation, with the effect demonstrated by d of 0.83 and the overall effect size indicated by Z-value of 7.24 ($p < 0.001$). Statistical analysis revealed significant heterogeneity in effect size among the 47 included studies ($\text{Chi}^2 = 522.80$), classifying it as high ($I^2 = 92\%$). These results support the consideration of a random effects model for data analysis and highlight the significance of identifying any potential moderator variables through subgroup analysis [32]. The forest plot also highlights the standardized mean difference (SMD) between the experimental and control groups. If the SMD is positive, the experimental group performs better on average than the control group. In this analysis, the overall results favor the experimental group, meaning PhET simulations generally improve learning outcomes. However, some studies may show negative SMD values, which indicate that the control group performs better. When this happens, the forest plot may appear to lean toward "favors control" in certain parts. This variation shows the importance of analyzing subgroups and considering specific conditions that might affect the effectiveness of PhET simulations.



Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Abou Faour & Ayoubi	121	31.28	25	107.48	34.33	25	2.3%	0.41 [-0.16, 0.97]
Abou Faour & Ayoubi-2	38.88	10.95	25	36.08	12.43	25	2.3%	0.24 [-0.32, 0.79]
Abou Faour & Ayoubi-3	39.4	11.23	25	34.76	11.84	25	2.3%	0.40 [-0.16, 0.96]
Abou Faour & Ayoubi-4	42.72	10.19	25	36.64	10.74	25	2.3%	0.57 [0.01, 1.14]
Afafa et al	5.19	2.12	21	3.91	0.93	21	2.2%	0.77 [0.14, 1.40]
Agyei et al	3.26	0.29	32	2.67	0.19	32	2.2%	2.38 [1.73, 3.03]
Agyei et al-2	3.38	0.15	31	2.52	0.13	31	1.5%	6.05 [4.84, 7.26]
Al Amri et al	23.88	3.8	32	17.48	4.45	33	2.3%	1.53 [0.97, 2.08]
Al Amri et al-2	152.13	12.51	32	98.91	17.79	32	2.0%	3.42 [2.64, 4.20]
Ardisa et al	79.45	10.31	32	74.27	7.72	31	2.3%	0.56 [0.06, 1.06]
Banda & Nzabahimana	63.85	10.6	144	47.22	7.08	136	2.5%	1.83 [1.55, 2.11]
Banda & Nzabahimana-2	3.11	0.8	144	3.09	0.69	136	2.6%	0.03 [-0.21, 0.26]
Banda & Nzabahimana-3	3.96	0.59	144	3.35	0.85	136	2.6%	0.84 [0.59, 1.08]
Banda & Nzabahimana-4	3.96	0.56	144	3.29	0.97	136	2.6%	0.85 [0.60, 1.09]
Banda & Nzabahimana-5	3.16	0.8	144	3.16	0.8	136	2.6%	0.00 [-0.23, 0.23]
Banda & Nzabahimana-6	4.27	0.41	144	4.27	0.7	136	2.6%	0.00 [-0.23, 0.23]
Banda & Nzabahimana-7	4.04	0.57	144	3.05	0.71	136	2.5%	1.54 [1.27, 1.81]
Banda & Nzabahimana-8	3.53	0.35	144	3.12	0.95	136	2.6%	0.58 [0.34, 0.82]
Çetinkaya & Kirilmazkaya	19.37	2.81	18	14.81	6.14	16	2.1%	0.95 [0.24, 1.67]
Jayanagara & Lukita	3.97	0.22	32	3.7	0.26	40	2.3%	1.10 [0.60, 1.60]
Laurence	36.3	1.38	30	35.6	1.04	30	2.3%	0.57 [0.05, 1.08]
Laurence-2	31.1	2.05	30	28.2	2.28	30	2.3%	1.32 [0.76, 1.88]
Laurence-3	4.7	0.45	30	4.6	0.49	30	2.3%	0.21 [-0.30, 0.72]
Laurence-4	4.6	0.49	30	4.5	0.5	30	2.3%	0.20 [-0.31, 0.71]
Laurence-5	4.5	0.5	30	4.3	0.48	30	2.3%	0.40 [-0.11, 0.91]
Laurence-6	4.6	0.5	30	4.4	0.5	30	2.3%	0.39 [-0.12, 0.91]
Laurence-7	4.5	0.5	30	4.3	0.47	30	2.3%	0.41 [-0.10, 0.92]
Laurence-8	4.6	0.5	30	4.5	0.5	30	2.3%	0.20 [-0.31, 0.70]
Maulani et al	83.11	9.9	45	74.03	10.14	33	2.4%	0.90 [0.43, 1.37]
Mešić et al	10.1	1.94	20	9.1	2.29	19	2.2%	0.46 [-0.17, 1.10]
Ndihokubwayo et al	10.93	11.03	45	8.73	8.19	45	2.4%	0.22 [-0.19, 0.64]
Ng & Chua	3.82	0.99	34	4.03	0.94	25	2.3%	-0.21 [-0.73, 0.30]
Ng & Chua-2	4.29	0.99	34	4.58	1.04	25	2.3%	-0.28 [-0.80, 0.24]
Ng & Chua-3	4.28	0.9	34	4.48	0.81	25	2.3%	-0.23 [-0.75, 0.29]
Ng & Chua-4	3.75	0.92	34	3.96	0.8	25	2.3%	-0.24 [-0.76, 0.28]
Özcan et al	11.95	2.73	22	10.13	2.82	23	2.2%	0.64 [0.04, 1.24]
Purfiyansyah et al	80.56	13.72	36	55.42	17.17	36	2.3%	1.60 [1.07, 2.13]
Purfiyansyah et al-2	60.64	21.45	36	31.47	12.28	36	2.3%	1.65 [1.11, 2.19]
Saputra et al	66.75	18.53	32	56.18	16.8	32	2.3%	0.59 [0.09, 1.09]
Siantuba et al	50.81	19.81	100	36.73	22.85	71	2.5%	0.66 [0.35, 0.98]
Sylvere & Minani	62.16	9.17	88	47.52	8.43	88	2.5%	1.65 [1.31, 2.00]
Yildirim	62.9	16.62	31	48.7	17.88	31	2.3%	0.81 [0.29, 1.33]
Yunzal & Casinillo	3.97	0.22	32	3.43	0.26	40	2.2%	2.20 [1.60, 2.79]
Total (95% CI)			**2345**			**2218**	**100.0%**	**0.83 [0.61, 1.06]**

Heterogeneity: Tau² = 0.50; Chi² = 522.80, df = 42 (P < 0.00001); I² = 92%

Test for overall effect: Z = 7.24 (P < 0.00001)

Fig. 3. The forest plot of using PhET simulation in physics learning

4.2 The impact of PhET simulation on physics learning at different grade levels

Examining the impact of PhET simulations on acquiring physics at the different levels is crucial. This investigation encompasses elementary, junior high, senior high, and college levels. Table 2 indicates the impact of PhET simulation on physics education, where the senior high school level demonstrated the most noteworthy and statistically significant effect size ($d = 1.00$, $p < 0.001$, CI: 0.74–1.27). Furthermore, the elementary school ($d = 0.77$, $p < 0.01$, CI: 0.31–1.23) and college ($d = 0.66$, $p < 0.001$, CI: 0.35–0.98) levels exhibited positive and significant outcomes. Different outcomes were discovered among students at the junior high school level, with a positive impact but no statistical significance ($d = 0.18$, $p > 0.05$, CI: –0.04–0.41).

Table 2. The impact of using PhET simulations in different grade levels

Grade Levels	k	n	d	Z-Value	CI (95%)
Elementary school	2	79	0.77	3.29**	0.31–1.23
Junior high school	11	627	0.18	1.61^x	–0.04–0.41
Senior high school	33	3886	1.00	7.40***	0.74–1.27
College	1	171	0.66	4.16***	0.35–0.98

Note: $^{**}p < 0.01$, $^{***}p < 0.001$, $^{x}p > 0.05$.

4.3 The impact of PhET simulation on physics learning in various fields of physics

Table 3 shows insights into the impact of implementing PhET simulations in diverse areas of physics, including but not limited to the greenhouse effect, electrodynamics, electrostatics, physical changes, oscillations, waves, and optics. The results demonstrate that the implementation of PhET simulations was most beneficial in the fields of electrostatics ($d = 3.26$, $p < 0.001$, CI: 1.40–5.11), electrodynamics ($d = 1.27$, $p < 0.01$, CI: 0.37–2.17), and oscillations, waves, and optics ($\mathrm{d} = 0.93$, $p < 0.001$, CI: 0.49–1.37), with statistically significant effects. On the other hand, the greenhouse effect ($d = 0.77$, $p < 0.01$, CI: 0.31–1.23) and physical changes ($d = 0.45$, $p < 0.001$, CI: 0.21–0.69) also had positive and significant effects.

Table 3. The impact of using PhET simulation in various fields of physics

Field of Physics	k	n	d	Z-Value	CI (95%)
Greenhouse effect	2	79	0.77	3.29**	0.31–1.23
Electrodynamics	3	207	1.27	2.78**	0.37–2.17
Electrostatics	3	302	3.26	3.45***	1.40–5.11
Physical changes	8	480	0.45	3.65***	0.21–0.69
Oscillations, waves, and optics	11	2459	0.93	4.15***	0.49–1.37
Others	16	1036	0.51	3.50***	0.22–0.79

Note: $^{**}p < 0.01$, $^{***}p < 0.001$.

4.4 The impact of PhET simulation on physics learning in various performance foci

PhET simulation exerts different effects on various focuses in physics learning, so it is essential to conduct further analysis. Table 4 shows that PhET simulation has a strong impact, especially on learning motivation ($d = 2.91$, $p < 0.05$, CI: 0.31–5.51), critical and creative thinking skills ($d = 1.03$, $p < 0.001$, CI: 0.54–1.52), as well as students' learning achievement in physics subject ($d = 1.00$, $p < 0.001$, CI: 0.69–1.30). At the same time, the impact was lower on science process ability ($d = 0.30$, $p < 0.01$, CI: 0.09–0.51). Meanwhile, there was no significant impact on students' attitudes regarding using this simulation ($d = 0.06$, $p > 0.05$, CI: –0.18–0.31).

Table 4. The impact of using PhET simulation in various focuses of physics

Focuses of Physics	k	n	d	Z-Value	CI (95%)
Motivation	3	165	2.91	2.19*	0.31–5.51
Critical and creative thinking skills	5	313	1.03	4.15***	0.54–1.52
Science process skills	6	360	0.30	2.84**	0.09–0.51
Attitude	8	436	0.06	0.52^{x}	–0.18–0.31
Achievement	21	3289	1.00	6.43***	0.69–1.30

Note: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{x}p > 0.05$.

4.5 The impact of PhET simulation on physics learning in various learning models

The comprehensive assessment in Table 5 indicates a positive impact of PhET simulation on both learning models. However, the impact was considerably more significant in the offline learning model ($d = 1.08$, $p < 0.001$, CI: 0.80–1.37) than in the online model ($d = 0.27$, $p < 0.05$, CI: 0.03–0.50).

While the results show statistically significant differences, it is important to highlight that statistical significance (as indicated by p-values) is highly influenced by the sample size (n) [38]. The offline model involved a substantially larger sample (n = 3676) compared to the online model (n = 887), which may partly explain the smaller p-value. However, the effect size (Cohen's d) offers a more meaningful interpretation of the true impact, as it is independent of sample size and reflects the magnitude of the effect itself. The large effect size observed in the offline model ($d = 1.08$) indicates a strong practical impact of PhET simulations on student learning, whereas the smaller effect size in the online model ($d = 0.27$) suggests a modest effect. Therefore, more weight should be given to the interpretation of effect sizes rather than solely relying on statistical significance when evaluating the effectiveness of PhET in different learning contexts.

Table 5. The impact of using PhET simulation in various learning models

Learning Models	k	n	d	Z-Value	CI (95%)
Online Mode	13	887	0.27	2.18*	0.03–0.50
Offline Mode	30	3676	1.08	7.50***	0.80–1.37

Note: *$p < 0.05$, ***$p < 0.001$.

5 DISCUSSION

This meta-analysis confirmed that PhET simulations have a large and significant positive effect on students' physics learning ($d = 0.83$, $p < 0.001$). These findings support earlier studies that emphasize the role of interactive simulations in enhancing student engagement, motivation, and conceptual understanding [14], [23], [25]. The interactive nature of PhET allows students to manipulate variables, test hypotheses, and connect abstract concepts with observable outcomes, making physics learning more accessible and meaningful. However, the substantial heterogeneity across studies ($I^2 > 70\%$) indicates that contextual factors, such as grade level, instructional models, and learning aspects, strongly influence the outcomes.

5.1 Grade levels and physics topics

PhET simulations demonstrated greater effectiveness at the secondary school level than primary or higher education, consistent with previous studies showing adolescents' strong responsiveness to interactive, visual, and exploratory approaches [12], [58]. The effect was particularly strong at the topic level for abstract and mathematically demanding areas such as electricity, oscillations, and waves. These findings highlight that PhET may be most impactful in bridging the gap between concrete experiences and abstract reasoning, especially for learners in transition stages of cognitive development.

5.2 Learning aspects

The analysis revealed that PhET not only improves academic achievement but also supports higher-order thinking skills, including critical and creative thinking [24], [27], [28]. It also positively influences students' motivation and process skills, although effects on attitudes toward physics were not consistently significant. This inconsistency may stem from differences in instructional design, duration of intervention, and the extent to which simulations are integrated with collaborative or inquiry-based learning models. The findings emphasize that simulations are most effective when paired with pedagogical strategies that promote reflection, discussion, and scaffolding [29], [30].

5.3 Learning models and contexts

PhET use in offline or face-to-face settings yielded stronger effects than online contexts. It may reflect the advantages of immediate teacher feedback, structured group activities, and direct scaffolding in classroom environments [59]. Nevertheless, online implementations still produced moderate benefits, suggesting that with proper design, such as adaptive scaffolding and personalized feedback, PhET can remain effective in digital or hybrid learning environments. This finding is particularly relevant in the post-pandemic era, where blended learning models are increasingly adopted.

5.4 Limitations and future directions

Several limitations must be acknowledged. First, the studies included in this meta-analysis were published between 2018 and 2023, which may limit the temporal scope of the findings. This concentration on recent publications reflects current instructional practices but reduces the opportunity to capture earlier trends in the use of PhET simulations. Second, the evidence base is heavily skewed toward secondary school contexts, with relatively few primary or higher education studies. Third, the high heterogeneity across studies indicates substantial variation in design, quality, and reporting standards, which constrains the generalizability of the conclusions. Finally, most studies did not systematically examine moderating variables such as gender, prior knowledge, or teacher expertise.

Future research should address these gaps by (a) expanding the scope to underrepresented levels and educational systems, (b) developing standardized instructional supports for simulation-based learning, and (c) exploring adaptive approaches, such as scaffolding and personalized feedback, that tailor simulations to individual learners.

6 CONCLUSION

This meta-analysis addressed two main research questions regarding using PhET simulations in physics education. The findings show that PhET simulations significantly enhance students' physics learning compared to traditional approaches, with a large overall effect size ($d = 0.83$, 95% CI = 0.61–1.06, $p < 0.001$). It confirms that

PhET simulations generally improve learning outcomes across different educational levels. The effectiveness of PhET simulations is not uniform, but influenced by several contextual and pedagogical factors. Teaching mode (online vs. offline), the level of content difficulty, and students' cognitive ability moderated the learning gains. Subgroup analysis further indicated that the strongest impact was observed among high school students, likely due to their ability to engage with abstract representations. In contrast, junior high students benefited less, possibly due to lower cognitive readiness and limited curricular alignment. This study highlights that PhET simulations can be a powerful instructional tool in physics education when carefully integrated with consideration of student characteristics and instructional context. These insights provide a foundation for designing more effective and targeted learning strategies.

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