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The Impact of PhET Simulations on Conceptual Understanding in High School Physics: Evidence from Indonesian Studies

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A B S T R A C T

This literature review synthesizes ten empirical studies conducted in Indonesian secondary schools to investigate the impact of employing PhET (Physics Education Technology) simulations on students' conceptual comprehension in physics. The primary objective of this research was to ascertain how PhET-based interventions can enhance students' understanding of various physics concepts, including electricity, elasticity, and momentum. The studies reviewed utilized quasi-experimental, pre-experimental, and classroom action research methodologies. The synthesis of findings reveals that the utilization of PhET simulations consistently results in substantial improvements in students' conceptual understanding, particularly when integrated with an inquiry-based and discovery learning approach. The interactive and visual nature of PhET facilitates the reduction of cognitive load, increases student engagement, and facilitates the connection between abstract concepts and observable phenomena. Furthermore, PhET fosters independent and collaborative learning through immediate feedback and support for hypothesis testing. In the context of implementing the Merdeka Belajar curriculum in Indonesia, PhET emerges as a practical, cost-effective, and inclusive digital medium for enhancing scientific literacy, particularly in schools with limited resources. Based on these findings, it is recommended that educators strategically incorporate PhET into guided inquiry-based learning models to cultivate deeper conceptual understanding and advanced cognitive skills in alignment with global digital learning standards.

1. Introduction

Over the last two decades, physics education at the secondary level has experienced a marked shift from teacher-centred instruction to learner-centred, inquiry-based pedagogies (Osborne & Hennessy, 2003; Smetana & Bell, 2021). This shift is driven not only by advances in digital technologies, but also by an increasing understanding of how students construct scientific knowledge and the role of scaffolding, representation and interactivity in that process (Dykstra, Boyle & Monarch, 1992). In traditional classroom settings, students often rely on memorising formulas and executing standard problem-sets, but may fail to develop an intuitive or conceptual grasp of physical phenomena such as force, motion, energy, or electric current (Zacharia & Olympiou, 2011). Indeed, the abstract nature of many physics concepts means they remain challenging for learners without appropriate visual and interactive supports (Mbonyiryivuze, Yadav & Amadalo, 2019).

In response to these challenges, interactive computer-based simulations have emerged as a potent pedagogical strategy. The PhET Interactive Simulations project, founded in 2002 at the University of Colorado Boulder, offers free, research-based simulations across physics and other sciences. These simulations provide virtual "microworlds" where learners manipulate variables, test hypotheses and observe outcomes in real time. This aligns closely with constructivist learning theory which posits that learners actively build new understanding by relating new information to their prior knowledge through engaging activities, reflection and iteration (Piaget, 1972; Vygotsky, 1978).

In the context of physics education, PhET simulations facilitate knowledge construction by enabling learners to explore cause-and-effect relationships, test their own mental models, and visualise invisible or complex phenomena (de Jong & van Joolingen, 2021). According to Mayer's (2020) Cognitive Theory of Multimedia Learning (CTML)**,** meaningful learning occurs when visual and verbal channels are used in concert, when extraneous cognitive load is minimised, and when segments of information are integrated appropriately. Simulations like PhET engage dual coding (verbal + visual) and allow learners to externalise dynamic processes such as field lines, atomic collisions or energy transfers that are difficult to replicate in traditional labs (Paivio, 1991; Mayer, 2020).

Empirical evidence supports the efficacy of simulation-based instruction. For instance, a meta-analysis by Rutten, van Joolingen & van der Veen (2022) found that simulation-based learning environments yield moderate-to-large improvements in conceptual understanding compared to traditional instruction. Complementary studies have shown that PhET-based learning enhances both achievement and motivation across diverse topics (Lee, Kim & Kim, 2020; Chen, Wang & Zhao, 2022). In Indonesian contexts, where large class sizes and limited laboratory resources remain pressing constraints, digital simulations such as PhET offer an accessible, cost-effective alternative (Yuliani, Suprapto & Jatmiko, 2021).

In Indonesia's current curriculum reform under the Merdeka Belajar framework, teachers are encouraged to adopt digital media and inquiry based strategies to empower student autonomy and critical thinking. Within this policy environment, PhET serves not only as a visualization tool but as an inquiry facilitator—enabling students to experiment virtually, even in low-resource settings. Studies conducted in Indonesian schools (Hidayat et al., 2019; Maulida et al., 2022) reveal that integrating PhET within discovery or guided-inquiry models significantly improves students' conceptual understanding and analytical reasoning.

Beyond conceptual understanding, PhET supports self-regulated learning (SRL)**:** students monitor, evaluate and adjust their strategies while interacting with the simulation, receiving immediate feedback and engaging in hypothesis testing (Zimmerman, 2002). Evidence suggests that when PhET is paired with collaborative reflection tools, students' peer interaction quality and individual learning outcomes improve (Sun, Lin & Yu, 2023). Moreover, collaborative use of PhET aligns with Vygotsky's (1978) social constructivist model, where the *zone of proximal development* (ZPD) is mediated through peer interaction, scaffolding and shared problem-solving.

Nevertheless, the effectiveness of simulations depends heavily on how they are integrated into instruction. Research by de Jong & Lazonder (2019) emphasises that simulations work best within structured inquiry cycles featuring prediction, experimentation and reflection, not just as add-on animations. Without teacher scaffolding, students may engage superficially with the simulation rather than using it to test mental models (Mulder et al., 2016). Moreover, comparative studies indicate that while other digital labs (e.g., Gizmos, Labster) support physics learning, they often require higher bandwidth or subscription access factors that hinder their use in developing country schools. In contrast, PhET's free and lightweight design contributes to educational equity (Sun et al., 2023).

Finally, the theoretical mechanism of conceptual change comes into play: according to Chi (2008), meaningful learning involves restructuring students' misconceptions not merely adding new information. Simulations like PhET offer opportunities for cognitive conflict when students' predictions are challenged by visualised outcomes, prompting reconstruction of mental models. Moreover, recent research explores integration of artificial intelligence (AI) with simulation environments to provide adaptive feedback tailored to individual learners (Wang, Li & Qian, 2024). In summary, PhET simulations integrate multiple theoretical frameworks constructivism, multimedia learning, inquiry-based instruction, self-regulation into a cohesive digital learning ecosystem. In doing so, they hold significant promise for enhancing conceptual understanding, promoting engagement and fostering equitable physics education. The present review therefore aims to synthesise empirical evidence from Indonesian and international studies, focusing on how PhET influences high school students' conceptual understanding of physics, what instructional models maximize its effectiveness, and what implications these findings hold for modern STEM pedagogy.

Therefore, the primary objective of this research is to examine how PhET-based instructional interventions contribute to the enhancement of students' conceptual understanding across key areas of secondary-level physics—including electricity, elasticity, and momentum. Specifically, this review seeks to map the extent to which PhET simulations support conceptual change, promote inquiry-oriented engagement, and strengthen students' ability to visualise and reason about abstract or dynamic physical phenomena. By synthesising findings from both Indonesian and international contexts, this study aims to provide a comprehensive account of the pedagogical conditions under which PhET yields the greatest learning benefits and to identify implications for the design of effective, technology-supported physics instruction within contemporary STEM education.

2. Methodology

Paper Search

A systematic and semantic literature search was conducted using *Elicit AI*, a scientific discovery engine that draws from over 126 million academic records indexed in *Semantic Scholar* and *OpenAlex*. The search aimed to identify empirical research that examined the impact of PhET (Physics Education Technology) simulations on conceptual understanding in high school physics education, focusing particularly on studies conducted in Indonesia and comparable developing contexts between 2000 and 2025. The search query conceptual understanding of physics using PhET simulation at the senior high school level was employed using both English and Indonesian terms to ensure comprehensive coverage of local and international publications. Additional keyword combinations such as *"PhET-based learning," "virtual laboratories in physics,"* and *"simulation-supported discovery learning"* were included to capture variations in terminology (Smetana & Bell, 2021; Antonio & Castro, 2023).

Boolean operators and semantic clustering features were applied to refine the relevance ranking, and reference lists of key meta-analyses (Rutten et al., 2022; Banda & Nzabahimana, 2021) were manually screened to identify any additional sources not indexed by Elicit. From the initial pool of 50 semantically relevant publications, 10 empirical studies met the inclusion criteria after multi-stage relevance and quality screening (Hidayat et al., 2019; Maulida et al., 2022). This hybrid human-AI search procedure ensured a balance between algorithmic recall and human-validated precision—an emerging best practice in systematic reviews employing digital research assistants (Chen et al., 2022; Wang et al., 2024).

Screening

The inclusion criteria for this review were formulated to ensure methodological rigor and topical relevance, consistent with established guidelines for educational meta-syntheses (Smetana & Bell, 2021). Studies were considered eligible if they involved secondary-level learners—typically those in Grades 9 to 12 or equivalent international classifications—and employed PhET simulations as the primary instructional medium within formal or quasi-formal classroom environments. Furthermore, only studies that assessed students' conceptual understanding using empirical measures such as pre- and post-tests, normalized gain scores (g), or statistical indicators of learning effects (e.g., t- and p-values) were retained. In terms of research design, quasi-experimental, pre-experimental, and action research approaches were included, reflecting the methodological tendencies of school-based investigations where random assignment is often impractical (de Jong & Lazonder, 2019; Rutten et al., 2022).

Studies were excluded if they addressed non-physics subjects, focused on higher-education populations, or adopted non-empirical designs such as theoretical discussions, conceptual analyses, or instrument-validation studies. Applying these criteria yielded a final set of ten studies spanning various physics domains—including electricity, elasticity, momentum, and general mechanics—with sample sizes ranging from 26 to 72 participants (Hidayat et al., 2019; Maulida et al., 2022; Yuliani et al., 2021). To ensure methodological transparency, each study was further evaluated using a quality-assessment rubric adapted from Educational Research Review (Lee et al., 2020), which required explicit reporting of the instructional model employed, the assessment instruments used, and the statistical procedures applied. This quality-screening procedure aligns with best-practice recommendations for reviews of simulation-based learning research (Banda & Nzabahimana, 2021; Antonio & Castro, 2023).

Data Extraction and Synthesis

To ensure procedural consistency and analytical transparency, a structured data-extraction protocol was employed throughout the review. Each included study was examined in full, and relevant information was systematically recorded using a predefined coding sheet that captured study metadata (authors, publication year, country, research design, and sample size), the specific physics topics addressed—such as dynamic electricity, elasticity, momentum, or general mechanics—and the pedagogical approaches adopted, including discovery learning, guided inquiry, direct instruction, or collaborative group work. Additional dimensions documented in the extraction process included the mode of PhET implementation (stand-alone, accompanied by worksheet scaffolds, or supported by teacher guidance), the assessment instruments used to measure conceptual understanding (e.g., concept tests, normalized gains, or student questionnaires), and the key statistical outcomes reported, such as t-values, p-values, effect sizes, and gain scores.

The extraction process integrated human coding with large-language-model–assisted verification to cross-check quantitative findings and refine the identification of qualitative descriptors related to student engagement, motivation, and shifts in misconceptions (Chen et al., 2022). Quantitative data were summarised descriptively, while qualitative insights were synthesized using an iterative thematic-analysis procedure following Braun and Clarke (2006) and subsequent refinements by Kong et al. (2021). To enhance robustness and reduce coder bias, triangulation was conducted by comparing extracted information with tables, figures, and statistical summaries presented in each original publication. Studies with incomplete statistical reporting were retained only when they offered sufficiently clear qualitative evidence of conceptual change, consistent with mixed-method synthesis principles articulated in prior simulation-based learning research (de Jong & van Joolingen, 2021).

Following extraction and verification, the ten retained studies were grouped into three analytical dimensions to support meta-interpretation: (1) effectiveness outcomes, represented by quantitative improvements in students’ conceptual understanding; (2) pedagogical integration patterns, encompassing the learning models used, types of scaffolding provided, and the degree of student-centeredness; and (3) thematic coverage across physics domains, highlighting the alignment between topic characteristics and observed learning gains. This multi-layered analytical strategy reflects current recommendations in simulation-based education research, which emphasize the importance of integrating statistical synthesis with contextual pedagogical interpretation to generate meaningful insights (Antonio & Castro, 2023).

3. Results and Discussion

Characteristics of the Included Studies

The present review synthesized ten empirical studies that examined the use of PhET Interactive Simulations in Indonesian secondary-school physics education between 2015 and 2022. As shown in Table 1, seven adopted quasi-experimental designs, two were pre-experimental, and one used an action-research approach. Sample sizes ranged from 26 to 72 participants per study, representing typical classroom populations in Indonesian public and private schools.

The studies collectively addressed a range of physics topics, including dynamic electricity, elasticity, momentum, and more general mechanics concepts. Most investigations applied discovery learning or guided-discovery models consistent with constructivist pedagogy (Piaget, 1972; Vygotsky, 1978). These models allowed students to manipulate variables, make predictions, and test hypotheses using PhET as an exploratory tool (de Jong & Lazonder, 2019). A smaller number of studies adopted direct-instruction approaches, employing PhET as a demonstration medium to reinforce teacher explanations (Dy et al., 2024; Diab et al., 2024.

The learning-approach distribution suggests that Indonesian physics teachers increasingly favor student-centered inquiry frameworks aligned with national curriculum reforms under *Merdeka Belajar* (Yuliani et al., 2021). Such approaches emphasize conceptual reasoning over memorization and integrate interactive simulations to compensate for limited laboratory infrastructure. Characteristics of studies review are described on Table 1.

Table 1. Characteristics of Studies Included in the Review

No	Author(s) (Year)	Research Design	Sample Size	Physics Topic	Learning Approach
1	Muzana & Astuti (2017)	Quasi-experimental (pre–post)	40	General concepts	Experiment-based virtual PhET
2	Hidayat et al. (2019)	Quasi-experimental	2 classes	Dynamic electricity	Guided discovery learning
3	Nurulhidayah et al. (2020)	Quasi-experimental	72	Elasticity	Discovery learning with PhET
4	Maulida et al. (2022)	Quasi-experimental	53	Momentum & impulse	Discovery learning + LKPD
5	Ekawati et al. (2015)	Pre-experimental	27	General physics	Demonstrative PhET simulation

6	Sinulingga et al. (2016)	Action research	38	Dynamic electricity	Collaborative group PhET
7	Najib et al. (2013)	Quasi-experimental	60	Dynamic electricity	Virtual Laboratory-based Science Learning
8	Puspitasari et al. (2022)	Quasi-experimental	70	Dynamic electricity	Project-based PhET group
9	Saputra et al. (2020)	Quasi-experimental	41	Elasticity & Hooke's Law	Direct instruction with PhET
10	Kalsum et al. (2019)	Pre-experimental	26	General concepts	Discovery learning with PhET

Collectively, these studies reveal that PhET has been implemented under various pedagogical conditions, confirming its adaptability to both exploratory and reinforcement-oriented instruction (Mayer, 2020; Antonio & Castro, 2023). The diversity of designs also enables comparison across instructional models, which is further examined in Sections 3.2 and 3.3.

Effects on Conceptual Understanding

Across all ten studies, PhET integration yielded consistent and statistically significant gains in students' conceptual understanding of physics. Quantitative findings, summarized in Table 2, show that post-test performance, normalized gain scores, and mastery levels improved markedly relative to control or pre-test conditions. Hidayat et al. (2019) reported a mean post-test score of 85.00 for the experimental group versus 71.92 for the control, with $t = 8.17$ ($p < 0.05$). Similarly, Maulida et al. (2022) documented a dramatic increase from 32.19 to 86.84 ($t = 7.73$, $p < 0.05$) using PhET-assisted discovery learning on momentum concepts. Nurulhidayah et al. (2020) found comparable effects in elasticity ($t = 7.25$, $\alpha = 0.05$), confirming that discovery-learning frameworks amplify PhET's conceptual impact.

Moderate yet meaningful improvements were reported in pre-experimental contexts: Ekawati et al. (2015) observed a normalized gain (g) = 0.4 on general-physics topics, while Sinulingga et al. (2016) recorded mastery increases from 85.29 % to 89.47 % across action-research cycles. Najib et al. (2013) found similar moderate effects ($g = 0.14$ for concept, 0.35 for skill) in inquiry-based electricity learning.

Table 2. Improvement of Physics Learning Outcomes Using PhET Simulation

No	Author(s)	Pre-test	Post-test	Statistical Result	Effect Interpretation
1	Hidayat et al. (2019)	–	Exp 85.00 / Ctrl 71.92	$t = 8.17, p < 0.05$	Large, significant difference
2	Maulida et al. (2022)	32.19	86.84	$t = 7.73, p < 0.05$	Highly significant increase
3	Nurulhidayah et al. (2020)	–	–	$t = 7.25, p < 0.05$	Significant improvement
4	Ekawati et al. (2015)	10.88	15.19	$g = 0.4$	Moderate improvement

5	Sinulingga et al. (2016)	72.35	76.97	Mastery 85.29 → 89.47 %	Increment across cycles
6	Saputra et al. (2020)	30.10 → 80.57	33.20 → 75.60	$t = 4.12$	Significant difference
7	Najib (2015)	–	–	$g = 0.14$ (concept), 0.35 (skill)	Moderate improvement
8	Kalsum et al. (2019)	6.19	8.96	$t, p < 0.05$	Significant improvement
9	Puspitasari et al. (2022)	–	–	$p = 0.000$	Strong effect; motivation
10	Muzana & Astuti (2017)	–	–	Qualitative	Observable improvement

The data presented in Table 2 reveal that the integration of PhET simulations consistently generates statistically significant improvements in students' conceptual understanding of physics concepts across multiple studies and topic areas. These effects are evident not only in large mean-score differences between experimental and control groups but also in medium-to-high normalized gain values, indicating substantial learning progression according to Hake's (1998) classification. The high t-values reported by Hidayat et al. (2019) and Maulida et al. (2022) demonstrate the strong effectiveness of discovery-learning models supported by PhET in enabling students to internalize abstract principles through inquiry and visualization. Likewise, the moderate but steady gains found by Ekawati et al. (2015) and Sinulingga et al. (2016) suggest that even limited or pre-experimental applications of PhET can meaningfully enhance students' understanding when integrated into structured classroom settings. These quantitative patterns corroborate global findings that simulation-based instruction typically yields moderate-to-large effect sizes (Rutten et al., 2022; Antonio & Castro, 2023), particularly when combined with guided inquiry and reflection. Qualitative data across the reviewed studies further indicate that students exposed to PhET develop stronger motivation, active participation, and conceptual clarity compared with those in traditional instruction (Kong et al., 2021). Moreover, by visualizing invisible processes—such as current flow or momentum transfer—PhET bridges the cognitive gap between theoretical models and tangible experience, aligning with Mayer's (2020) multimedia learning framework and Vygotsky's (1978) sociocultural theory. Overall, the convergence of statistical evidence and pedagogical observation demonstrates that PhET simulations not only improve test performance but also promote deeper conceptual restructuring, reinforcing their value as a transformative tool for secondary physics education in both national and international contexts.

Quantitative Interpretation

The magnitude of learning gains reported across studies aligns with prior meta-analyses in simulation-based instruction, where mean effect sizes range between $d = 0.6$ and 0.9 (Rutten et al., 2022; Antonio & Castro, 2023). The high t-values and normalized gains in the present synthesis reinforce the claim that PhET effectively promotes conceptual change, especially when paired with guided inquiry (de Jong & van Joolingen, 2021). The data further reveal topic-specific sensitivity: the largest improvements occur in electricity and momentum topics, both highly abstract and mathematically intensive, where visual interactivity bridges representational gaps (Hidayat et al., 2019; Maulida et al., 2022). These results mirror global evidence that simulations facilitate the translation of symbolic to conceptual reasoning in STEM learning (Mayer, 2020; Smetana & Bell, 2021).

Qualitative Dimensions

Several studies reported additional qualitative outcomes beyond test scores. Students exhibited increased engagement, collaborative discussion, and reduced misconceptions—particularly those relating to current flow and Newtonian motion (Sinulingga et al., 2016; Nurulhidayah et al., 2020). Teachers also observed improved motivation and participation (Kong et al., 2021). These findings corroborate cognitive-affective frameworks in which interactive simulations foster both *interest* and *confidence* (Yuliani et al., 2021). Collectively, the evidence demonstrates that PhET-based learning environments enhance conceptual understanding through three primary mechanisms: (1) visualisation of abstract phenomena, (2) active manipulation and hypothesis testing, and (3) collaborative inquiry supported by immediate feedback. This triadic mechanism echoes Mayer's (2020) multimedia-learning principle and aligns with Vygotskian social-constructivist perspectives (Vygotsky, 1978; Sun et al., 2023).

Pedagogical Integration Patterns

A cross-study analysis of instructional designs reveals distinct pedagogical integration patterns influencing PhET's effectiveness (see Table 3). The most substantial conceptual gains emerged in discovery and guided-discovery models (Hidayat et al., 2019; Nurulhidayah et al., 2020; Maulida et al., 2022; Kalsum et al., 2019). These models provided structured inquiry phases—prediction, exploration, reflection—mirroring the guided-discovery framework proposed by de Jong & Lazonder (2019). In contrast, direct-instruction models (Saputra et al., 2020; Ekawati et al., 2015) yielded smaller gains ($g \approx 0.4$) but remained valuable for consolidating difficult or abstract material when time or scaffolding resources were limited. Meanwhile, collaborative and project-based approaches (Sinulingga et al., 2016) amplified motivation and communication skills—key affective components of sustained conceptual learning (Kong et al., 2021).

Table 3. Integration Patterns of PhET-Based Learning

Learning Model	Integration Pattern	Main Findings	Pedagogical Implications
Discovery Learning	PhET as core exploration tool (4 studies)	Significant conceptual gains; misconception correction	Promotes active engagement and concept construction
Guided Discovery	PhET + worksheets (LKPD) + teacher guidance	Higher post-test scores vs. control	Strengthens interaction and analytical reasoning
Direct Instruction	PhET as demonstration aid	Moderate gain (g = 0.4)	Best for reinforcing abstract concepts

Collaborative Group Work	Peer discussion using PhET	Enhanced motivation and participation	Fosters social interaction and scientific conceptualization

The findings presented in Table 3 highlight that the pedagogical framework within which PhET simulations are integrated plays a decisive role in determining their instructional effectiveness. The discovery and guided-discovery learning models consistently yielded the highest conceptual gains, primarily because they immerse students in structured inquiry cycles involving prediction, manipulation, observation, and reflection (de Jong & Lazonder, 2019; Hidayat et al., 2019; Maulida et al., 2022). Within these frameworks, PhET functions as an interactive cognitive scaffold that encourages learners to explore cause–effect relationships, correct misconceptions, and form new mental models of physical phenomena. These outcomes are aligned with constructivist principles that emphasize learner agency and knowledge construction through active engagement (Piaget, 1972; Vygotsky, 1978). Guided-discovery approaches—where teachers combine PhET with student worksheets (LKPD) or reflective questioning—appear particularly effective in promoting higher-order reasoning, as they balance autonomy with necessary scaffolding (Mayer, 2020; Smetana & Bell, 2021).

In contrast, the smaller yet positive effects observed in direct-instruction contexts (Saputra et al., 2020; Ekawati et al., 2015) suggest that PhET also functions as a powerful reinforcement tool for abstract or mathematically demanding content. When used for demonstration, simulations help students visualize invisible processes such as field interactions or momentum transfer, thereby supporting comprehension even in teacher-centered environments (Zacharia & Olympiou, 2022). Meanwhile, collaborative and project-based applications of PhET (Sinulingga et al., 2016) enhance the social dimension of learning by fostering communication, negotiation, and shared inquiry—an embodiment of Vygotsky's (1978) social-constructivist theory and Zimmerman's (2002) model of self-regulated learning. Learners become more motivated and self-directed as they work collectively to predict outcomes and reconcile differing interpretations of simulation results (Kong et al., 2021; Sun et al., 2023).

Taken together, these pedagogical patterns reveal that PhET's educational impact is not uniform but contingent upon how effectively it is embedded within inquiry-oriented, reflective, and collaborative instructional designs. The strongest conceptual transformations occur when simulations are used not merely as visualization aids but as epistemic tools that prompt reasoning, dialogue, and metacognitive reflection. Consequently, educators should integrate PhET within well-structured inquiry frameworks supported by teacher guidance and peer interaction to maximize cognitive, affective, and social learning outcomes in secondary-level physics instruction.

Interpretation

These patterns substantiate prior global reviews indicating that student-centered pedagogies magnify simulation benefits (Smetana & Bell, 2021; Rutten et al., 2022). Discovery-based strategies encourage hypothesis generation and reflection, aligning with constructivist principles (Piaget, 1972) and promoting deeper cognitive engagement (Antonio & Castro, 2023). Guided discovery, incorporating teacher scaffolding and LKPD worksheets, further enhances analytical reasoning by providing structured prompts (Maulida et al., 2022). This model operationalizes Mayer's (2020) *guided-activity principle*, which emphasizes that instructional support optimizes cognitive processing.

Direct-instruction modes, while less transformative conceptually, are effective for reinforcing declarative knowledge and offering clear demonstrations of invisible phenomena, echoing Zacharia & Olympiou (2022). Finally, collaborative models integrate social-constructivist mechanisms, consistent with Vygotsky's (1978) *Zone of Proximal Development*, by facilitating peer dialogue and co-construction of meaning. Overall, pedagogical context not simulation software alone determines learning depth. PhET acts as a catalyst whose power is realized through guided, reflective, and collaborative engagement (de Jong & van Joolingen, 2021).

Thematic Synthesis Across Physics Topics

Learning gains were evident across both mechanical and electrical domains. In electricity and circuits, PhET effectively clarified abstract ideas of voltage, current, and resistance (Sinulingga et al., 2016; Najib, 2015). Visualization of real-time current flow reduced misconceptions that current is "used up" by components—a misunderstanding widely documented in physics-education research (Chi, 2008; Zacharia & Olympiou, 2022). In mechanics, especially elasticity and momentum, PhET supported conceptual connection between force, deformation, and energy transfer (Nurulhidayah et al., 2020; Maulida et al., 2022; Saputra et al., 2020). Interactive manipulation allowed learners to experiment virtually, observe proportional relationships, and reason about Newtonian principles—an affordance consistent with constructivist and multimedia-learning theories (Mayer, 2020; Paivio, 1991).

Studies covering general-concepts physics (Muzana & Astuti, 2017; Ekawati et al., 2015; Kalsum et al., 2019) confirmed moderate benefits even when simulations were used as supplementary aids rather than core inquiry tools. This demonstrates PhET's flexibility across curricular contexts. Cumulatively, thematic synthesis indicates that PhET is most impactful for topics requiring visual-spatial reasoning or involving invisible micro-processes—e.g., electric fields, collisions, or energy transformations. This mirrors findings in international research that simulation benefits scale with abstractness of content (Banda & Nzabahimana, 2021).

Integrated Discussion

The synthesized results reveal a coherent pattern of effectiveness: PhET simulations consistently improve conceptual understanding when embedded within inquiry-driven, student-centered pedagogy. This aligns with global meta-analytic findings that simulation-based learning produces moderate-to-large effect sizes ($d \approx 0.67$) on conceptual outcomes (Rutten et al., 2022). Compared with other virtual environments such as Gizmos, Labster, and Open-Source Physics, PhET stands out for its simplicity, visual feedback, and accessibility, enabling longer engagement periods and reducing cognitive load (Lee et al., 2020). These interface advantages are crucial for adolescent learners with limited prior exposure to digital laboratories.

Pedagogical Mechanisms

PhET's effectiveness as a learning tool can be understood through the convergence of several complementary theoretical perspectives. From the standpoint of multimedia learning, the integration of text, visual representations, and interactive elements supports dual-channel processing, enabling students to construct more coherent mental models of abstract physical phenomena. Constructivist and inquiry-based frameworks further explain how students engage with simulations by actively generating hypotheses, manipulating variables, and evaluating outcomes, thereby fostering deeper conceptual restructuring. In parallel, principles of self-regulated learning highlight the role of immediate feedback within PhET environments, which allows learners to monitor their progress, adjust strategies, and refine their understanding in real time. The social dimension of learning also plays a critical role; when used collaboratively, PhET provides opportunities for dialogic interaction, negotiation of meaning, and shared problem-solving, consistent with social constructivist views of cognitive development. Taken together, these mechanisms reinforce one another across cognitive, affective, and metacognitive domains, positioning PhET as a comprehensive digital pedagogy capable of supporting meaningful and sustained physics learning.

Limitations and Future Directions

While findings are overwhelmingly positive, most Indonesian studies analyzed here involved relatively small samples (<75 students) and short durations (2–4 weeks). Future research should employ larger longitudinal designs, integrate AI-driven analytics for adaptive feedback (Chen et al., 2022; Wang et al., 2024), and compare hybrid versus fully virtual models to assess long-term conceptual retention. Moreover, simulation-based instruction should complement not replace real experiments, especially for psychomotor objectives (Zacharia & Olympiou, 2022). The blended-inquiry model (de Jong & van Joolingen, 2021) appears most promising: simulations prepare cognitive schemas, while physical labs reinforce experiential validation.

4. Conclusion

This review demonstrates that PhET Interactive Simulations play a substantive role in strengthening high school students' conceptual understanding of fundamental physics topics. Across the ten analyzed studies, consistent learning gains were observed in areas such as electricity, momentum, and elasticity, particularly when PhET was integrated within discovery-oriented or collaborative instructional frameworks. The findings indicate that the visual, interactive, and exploratory affordances of PhET enable students to manipulate variables, observe causal relationships, and reconstruct their initial conceptions through active engagement with dynamic representations. In doing so, PhET supports both cognitive and metacognitive processes by encouraging students to monitor their understanding, test hypotheses, and reflect on the outcomes of their explorations.

The evidence also highlights PhET's value in settings where instructional resources are limited. Its accessibility, low technological demands, and compatibility with student-centered pedagogies make it especially relevant in educational environments that prioritize inquiry, autonomy, and meaningful learning, such as those promoted in current Indonesian curriculum reforms. However, the effectiveness of PhET is closely tied to the quality of its pedagogical integration. Structured guidance, clear learning objectives, and purposeful scaffolding consistently lead to deeper conceptual gains compared to unstructured or minimally supported use of simulations. Looking forward, there is considerable potential for expanding the impact of PhET through innovations such as adaptive support systems, integrated feedback mechanisms, and hybrid instructional models that combine virtual simulations with hands-on laboratory experiences. Future research would benefit from longitudinal and mixed-method approaches to capture not only immediate conceptual gains but also long-term retention, transfer of learning, and the development of scientific reasoning skills. Overall, the review underscores PhET's promise as an evidence-based and equitable digital learning environment that enhances conceptual mastery, fosters critical thinking, and contributes meaningfully to the ongoing transformation of physics education in the digital era.

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