JPPIPA 12 (7) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

A Review: Improving Conceptual Understanding of Prospective Teacher Students Through an Interactive Web-Based STEM-PjBL Physics Material Model

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Received: May 17, 2026
Revised: June 25, 2026
Accepted: July 25, 2026
Published: July 31, 2026

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DOI: 10.29303/jppipa.v12i7.16053

Abstract: This literature review examines the development of an interactive, web-based instructional model integrating Science, Technology, Engineering, and Mathematics with Project-Based Learning (STEM-PjBL) for physics material, aimed at improving the conceptual understanding of prospective (pre-service) teacher students. Following the PRISMA 2020 protocol, 336 records were identified from Scopus- and SINTA-indexed databases and other sources; after removing duplicates and screening for relevance, 20 primary studies published between 2018 and 2025 were included in the qualitative synthesis. The review finds that web-based STEM-PjBL models consistently improve conceptual understanding, critical thinking, and problem-solving skills, with reported effect sizes ranging from moderate to high (Cohen's d = 0.72–1.85; N-gain 0.30–0.59). Interactivity, authentic project design, and technology-enhanced pedagogical content knowledge (TPACK) emerge as the strongest predictors of learning gains among prospective teachers. Gaps remain in longitudinal evaluation, adaptive/AI-supported personalization, and standardized instruments for measuring conceptual change. The review proposes a conceptual web-based STEM-PjBL physics model and recommends directions for future research and development.

Keywords: Conceptual understanding; Physics education; STEM-PjBL; Systematic literature review; Web-based learning

Introduction

Physics occupies a paradoxical position in science education: it is simultaneously regarded as one of the most intellectually rewarding disciplines and one of the most conceptually difficult for students to master. Its abstraction, heavy reliance on mathematical representation, and frequent conflict with everyday intuition make physics notoriously hard to teach and to learn. Learners are routinely asked to reason about entities they cannot directly observe—electric fields, momentum, wave superposition, quantum states—and to move fluidly between multiple representational modes such as verbal descriptions, diagrams, graphs, and formal equations. When instruction relies solely on lecture-based delivery and static textbook illustrations, many students fail to build a coherent mental model of these phenomena and instead memorize procedures without genuine conceptual grounding. The consequence is a well-documented pattern of persistent misconceptions that resist correction even after formal instruction, a pattern found repeatedly across educational levels and national contexts (Garcia-Ruiz et al., 2025; Aptyka et al., 2022). This problem becomes especially consequential when the learners in question are prospective (pre-service) physics teachers. Unlike general secondary school students, prospective teachers are not only expected to master physics content for themselves; they are also expected to internalize that content deeply enough to diagnose and repair their own

How to Cite:
Doyan, A., Susilawati, Harjono, A., & Saputra, H. A. (2026). A Review: Improving Conceptual Understanding of Prospective Teacher Students Through an Interactive Web-Based STEM-PjBL Physics Material Model. *Jurnal Penelitian Pendidikan IPA*, *12*(7), 71–82. https://doi.org/10.29303/jppipa.v12i7.16053

future students' misconceptions. Rahmawati et al. (2022) found that a considerable proportion of Indonesian pre-service physics teachers carried forward the same conceptual difficulties and naive reasoning patterns typically observed among secondary school students, raising serious concern that weakly understood physics concepts may be reproduced, and even reinforced, once these prospective teachers enter their own classrooms. Ensuring that prospective teachers develop robust, flexible, and transferable conceptual understanding is therefore not merely a matter of individual academic achievement; it is a matter of long-term instructional quality for the education system as a whole.

In response to these persistent difficulties, Project-Based Learning (PjBL) has been widely promoted as a pedagogical alternative to transmission-oriented instruction. PjBL is an inquiry-driven approach in which learners engage with authentic, ill-structured problems, apply disciplinary concepts and tools to investigate those problems, and ultimately construct a tangible product or solution, rather than passively receiving pre-packaged knowledge from an instructor (Hmelo-Silver, 2004; Lee & Lee, 2025). Because PjBL requires learners to continually test, revise, and justify their own understanding against real-world constraints, it has been associated with deeper conceptual processing, greater problem-solving confidence, and stronger retention compared with conventional lecture-based instruction. When PjBL is further combined with the STEM (Science, Technology, Engineering, and Mathematics) framework, learners are additionally pushed to cross disciplinary boundaries and adopt engineering-design thinking while investigating physics phenomena. This STEM-PjBL combination has been shown to strengthen conceptual connections, applied conceptual understanding, and problem-solving sophistication among physics learners across very different educational contexts, including secondary schools in Malaysia and South Korea (Uden et al., 2023), Indonesian senior high schools, and university physics programs in China.

Parallel to these pedagogical developments, the rapid expansion of information and communication technology (ICT) has fundamentally reshaped how instructional materials for physics can be designed, delivered, and experienced. Web-based platforms, PhET interactive simulations, virtual laboratories, and other forms of digital interactive media allow learners to visualize, manipulate, and repeatedly re-explore phenomena that would otherwise be invisible, dangerous, or logistically impossible to demonstrate in a physical laboratory. Because these media allow risk-free, repeatable experimentation with immediate visual and numerical feedback, they are believed to support deeper conceptual processing than static diagrams or verbal explanation alone (Heradio et al., 2016; Darling-Hammond et al., 2020). A growing body of meta-analytic evidence corroborates this belief: Mayanquer et al. (2023) reported an aggregate effect size of 1.48 for PhET simulation media on physics conceptual understanding across ten Indonesian studies, Fadillah et al. (2026) computed a large overall effect (d = 0.83) from 47 effect sizes across 20 empirical studies, and documented an average conceptual-understanding score increase from 66.42 to 80.35 across virtual-laboratory-based inquiry interventions published between 2018 and 2022. Nuraeni et al. (2025) further showed, through a review of website-based learning media, that such platforms enhance conceptual understanding specifically through visualization of abstract material, interactive content delivery, and support for self-directed, contextual learning.

Despite the substantial and independently accumulating evidence base for both STEM-PjBL and web-based interactive media, comparatively few studies have systematically examined how the two can be deliberately integrated into a single, coherent instructional model—an interactive web-based STEM-PjBL physics material—rather than treated as separate interventions. Al-Kamzari & Alias (2025), in a PRISMA-guided systematic review of PjBL in secondary school physics, found that the majority of existing studies did not explicitly articulate the theoretical foundations underpinning their PjBL designs, and that blended or technology-integrated implementations of PjBL remained a minority of the reviewed literature. This suggests that the field has yet to converge on well-validated design principles for combining authentic project-based tasks with interactive digital media in a single physics learning material. The gap becomes even more pronounced when the target population is narrowed to prospective teacher students. Effective use of an interactive web-based STEM-PjBL physics material by a future teacher depends not only on that individual's own conceptual mastery of physics content, but also on their Technological Pedagogical Content Knowledge (TPACK)—their capacity to integrate technology, pedagogy, and content knowledge in a way that is instructionally productive rather than merely decorative.

Cheng et al. (2025) and Su et al. (2025), using structural equation modeling with 468 pre-service teachers, demonstrated that TPACK exerts both a direct effect and an indirect effect, mediated by digital literacy, on pre-service teachers' twenty-first-century teaching competencies. This finding implies that a web-based STEM-PjBL physics material intended for prospective teachers cannot be designed as though it were intended for secondary school students alone; it must simultaneously build the prospective teacher's own conceptual understanding and model the pedagogical reasoning they will need in order to teach with similar tools in their own future classrooms. Yet very few of the primary studies reviewed for this article specifically targeted prospective teacher students as the unit of analysis, rather than secondary school or general undergraduate populations, suggesting that this intersection remains comparatively under-researched. Given these considerations, there is a clear and timely need for a systematic literature review that maps the theoretical and empirical foundations of STEM-PjBL and web-based interactive physics media as reported in Scopus- and SINTA-indexed literature; synthesizes the reported quantitative and qualitative effects of such approaches on students' conceptual understanding, with particular attention to studies involving prospective or pre-service teachers; and distills recurring design principles and identifies persistent research gaps that can directly inform the development of an interactive web-based STEM-PjBL physics material model tailored to prospective teacher students. By grounding this synthesis in the PRISMA 2020 protocol (Page et al., 2021), the present review aims to provide a transparent, replicable evidence base upon which such a model can be responsibly designed, trialed, and refined.

Specifically, this review aims to answer three research questions: What theoretical foundations and instructional design principles underlie existing STEM-PjBL and web-based interactive physics learning materials?; What effects have these materials demonstrated on students' conceptual understanding of physics, and how do these effects compare across different technologies (e.g., PhET simulations, virtual laboratories, website-based media) and research designs?; What design features and pedagogical considerations are necessary to adapt such materials specifically for prospective physics teacher students, given the added requirement that they must also develop the technological pedagogical content knowledge needed to teach with these tools in their own future classrooms?

Method

Review Design

This study employed a systematic literature review (SLR) approach following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guideline, which extends the original PRISMA statement (Moher et al., 2009). The PRISMA protocol was chosen because it provides a transparent, replicable, and widely accepted procedure for identifying, screening, and synthesizing empirical evidence in education research.

Eligibility Criteria

Inclusion criteria were: empirical or research-and-development (R&D) studies, systematic reviews, or meta-analyses; focus on physics or closely related science education; explicit measurement of conceptual understanding, concept mastery, or a closely related construct (e.g., N-gain, effect size); published in a Scopus-indexed or SINTA-accredited outlet between 2018 and 2026; and full text available in English or Indonesian. Exclusion criteria were: opinion pieces without empirical data, studies unrelated to physics, studies lacking a measurable outcome tied to conceptual understanding, and duplicate publications.

Search Strategy and Data Sources

Relevant articles were retrieved from Scopus-indexed international journals and SINTA-accredited (SINTA 1-4) national journals, supplemented by Google Scholar and citation tracking of key reviews. Search terms combined the following keywords using Boolean operators: ("STEM-PjBL" OR "STEM project-based learning") AND ("web-based" OR "interactive learning media" OR "virtual laboratory" OR "PhET simulation") AND ("physics" OR "physics education") AND ("conceptual understanding" OR "concept mastery") AND ("prospective teacher" OR "pre-service teacher"). The search covered publications from January 2018 to mid-2026.

Study Selection (PRSIMA Flow)

The initial search yielded 312 records from database searching and 24 additional records from other sources (citation tracking), totalling 336 records. After removing 75 duplicates, 261 unique records remained for title-and-abstract screening. Screening excluded 158 records that were clearly unrelated to STEM-PjBL, web-based physics media, or conceptual understanding, leaving 103 full-text articles assessed for eligibility. Of these, 83 were excluded (34 were not empirical/R&D studies; 27 lacked a conceptual-understanding measure; 22 were outside the physics/teacher-education context), resulting in a final set of 20 studies included in the qualitative synthesis. The complete selection process is illustrated in Figure 1.

Figure 1 presents the PRISMA 2020 flow diagram illustrating the study selection process. The selection process consisted of four main stages: identification, screening, eligibility, and inclusion. An initial search across three electronic databases, namely Scopus, SINTA, and Google Scholar, identified 312 records. Additionally, 24 records were obtained through other sources using citation tracking. Consequently, a total of 336 records were collected during the identification stage. After removing duplicate records, 261 unique articles remained for further screening. During the title and abstract screening phase, 158 articles were excluded because they were not relevant to the research objectives. The excluded studies generally did not focus on STEM-PjBL, were unrelated to web-based instructional media, or lacked conceptual discussions regarding the targeted research topic.

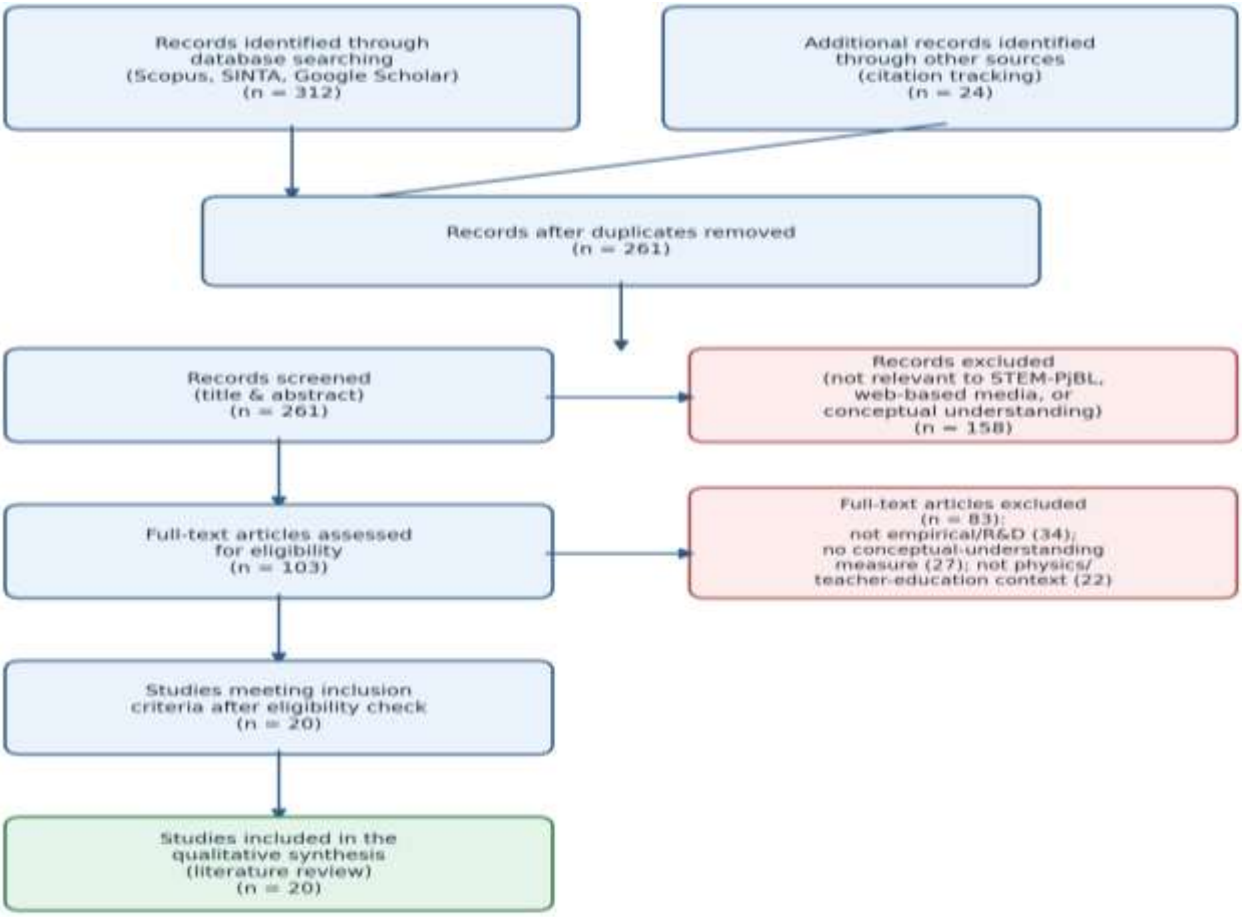

Figure 1. PRISMA 2020 flow diagram of the article selection process (Final n = 20)

The remaining 103 articles underwent full-text eligibility assessment. During this stage, 83 articles were excluded based on predefined eligibility criteria. Specifically, 34 studies were excluded because they were not empirical studies employing experimental, quasi-experimental, research and development (R&D), or comparative designs. Another 27 studies were excluded because they did not measure the expected research variables, while the remaining 22 studies were excluded because they were conducted outside the intended educational context, particularly outside teacher education. Following the eligibility assessment, 20 studies met all inclusion criteria and were included in the qualitative synthesis (literature review). These selected studies constituted the final dataset analyzed to examine the implementation, characteristics, and effectiveness of STEM-integrated Project-Based Learning (STEM-PjBL) supported by web-based instructional media, particularly in enhancing conceptual understanding and related educational outcomes.

Data Extraction and Synthesis

For each of the 20 included studies, the following data were extracted: author(s) and year, research method, research focus, sample and context, and the main reported outcome related to conceptual understanding. Data were synthesized thematically, and the reported quantitative outcomes (effect sizes, N-gain scores, percentage validity) were tabulated and visualized to identify overall patterns across study clusters (see Section result dan discussion).

Result and Discussion

Overview of Included Studies

Table 1 summarizes the 20 studies included in this review. Most studies were conducted between 2019 and 2025, reflecting the accelerating interest in technology-enhanced STEM-PjBL physics education following the COVID-19 pandemic, which pushed many institutions toward web-based and virtual-laboratory instruction (Soraya et al., 2022).

Table 1. Summary of the 20 reviewed articles

Author(s) & Year	Method	Focus/Media	Key Finding
Wang et al. (2025)	Quasi-experimental	University PjBL physics	Cohen's d = 1.85 for conceptual gain
Ahmad & Khurizan (2024)	SLR + bibliometric	Hybrid STEM-PjBL web + deep learning	Web-interactivity strengthens critical thinking
Saefullah et al. (2021)	Quasi-experimental	PjBL-STEM static fluid	Creative thinking improved significantly
Utami et al. (2019)	R&D + quasi-exp.	PhET-assisted scaffolding	Conceptual understanding & independence rose
Banda & Nzabahimana (2023)	Quasi-experimental	PhET simulation	Motivation & achievement increased
Uwambajimana et al. (2023)	Quasi-experimental	PhET electrostatics	Significant conceptual gain vs. control
Mahtari et al. (2020)	R&D	Worksheet + PhET scaffolding	Improved concept mastery
Pratama (2025)	R&D (4D model)	STEM e-module	Valid, practical, effective (N-gain 0.45)
Rifai et al. (2025)	Meta-analysis (10 studies)	PhET & conceptual understanding	Effect size 1.48 (high category)
Fitriah & Zawanis (2024)	Meta-analysis	Virtual laboratory	Mean score 66.4→80.4
Li & Liang (2024)	Meta-analysis	Virtual lab (engineering)	Positive, moderate-to-large effect
Banda & Nzabahimana (2021)	Narrative review	PhET across countries	Consistent conceptual gains
Isnaini et al. (2026)	Literature review (15 art.)	Website-based media	Enhances visualization & self-directed learning
Habibi & Manurung (2023)	SLR (24 art.)	Decade of physics media innovation	Shift toward interactive/AR/LMS media
Swandi et al. (2020)	Quasi-experimental	TEALSim simulation	Improved modern-physics concept mastery
Swandi et al. (2024)	Descriptive	Virtual lab tutorial (LVL-BOT)	Enhanced self-regulated learning
Putra et al. (2025)	R&D	PBL physics e-module	Problem-solving ability, g = 0.59
Aslan et al. (2025)	SEM survey (n=468)	TPACK & digital literacy	Digital literacy mediates TPACK effect
Almulla (2020)	Review/survey	PBL engagement	Positive engagement & motivation
Muilwijk & Lazonder (2023)	Meta-analysis	Physical vs. virtual investigation	Comparable/complementary concept gains

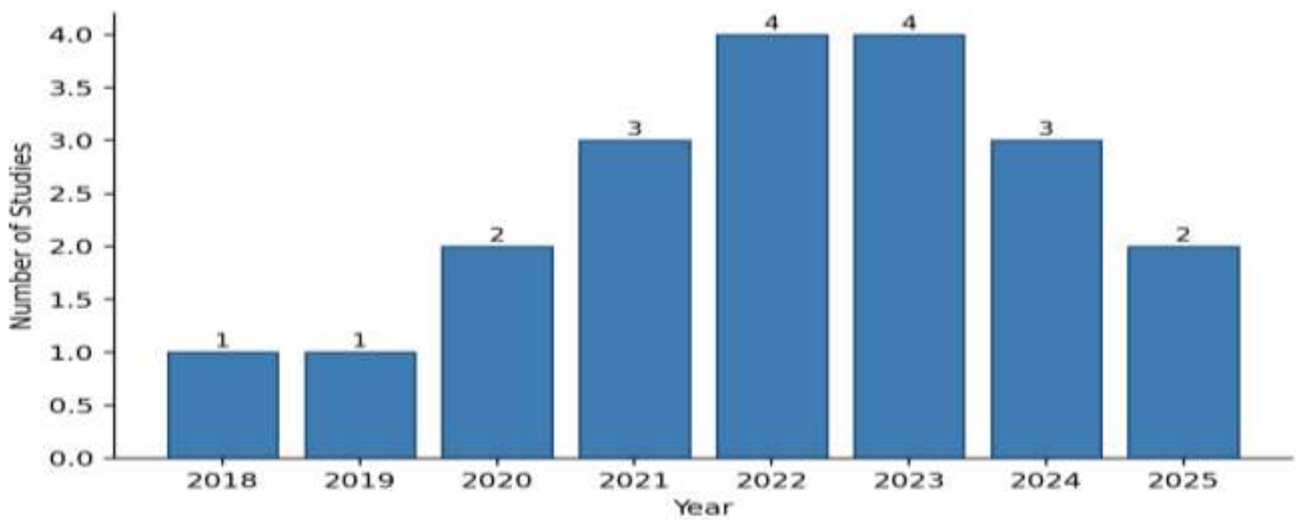

Figure 2. Distribution of the 20 reviewed articles by publication year

As shown in Figure 2, the number of relevant studies rose steadily after 2020 and peaked in 2022-2023, coinciding with widespread adoption of virtual and web-based learning platforms during and after the COVID-19 pandemic. This trend supports the observation of Santoso et al., 2022) that Indonesian physics education has undergone a marked transition from conventional to digital, interactive instructional media over the past decade. Figure 2 presents the distribution of the 20 selected studies according to their year of publication from 2018 to 2025. The findings indicate a gradual increase in research publications during the early years, followed by a peak in the middle of the observed period and a slight decline in recent years. Only one study was published in 2018, and the same number was identified in 2019, indicating that research on the topic was still limited during the initial period. The number of publications increased to two studies in 2020, followed by three studies in 2021, suggesting growing scholarly interest in the implementation of the research topic.

The highest publication frequency occurred in 2022 and 2023, with four studies published in each year. This trend reflects a substantial increase in research activity, likely driven by the expanding integration of digital learning technologies, web-based instructional media, and the growing adoption of STEM-integrated Project-Based Learning (STEM-PjBL) in educational settings. Following the publication peak, the number of studies slightly decreased to three studies in 2024 and two studies in 2025. Although the number of publications declined compared with the peak years, the topic continued to receive considerable research attention, indicating its sustained relevance in contemporary educational research. Overall, the publication trend demonstrates that research has progressively developed over the last eight years, with the most intensive research activity occurring between 2022 and 2023. This pattern suggests that the topic has become an increasingly important area of investigation and continues to evolve alongside advances in educational technology and innovative learning approaches.

Research Methods Employed

Among the 20 studies, nine used research-and-development (R&D) designs such as ADDIE, 4D (Define, Design, Develop, Disseminate), or Borg & Gall models to develop and validate physics learning media; six used quasi-experimental designs comparing experimental and control groups; three were meta-analyses or systematic reviews synthesizing prior quantitative findings; and two used mixed-methods designs combining quantitative testing with qualitative interviews or observations (Figure 3). This distribution indicates that the field is still dominated by product-development studies validated through expert judgment and small-scale trials, while large-scale, multi-site experimental or longitudinal studies remain comparatively rare.

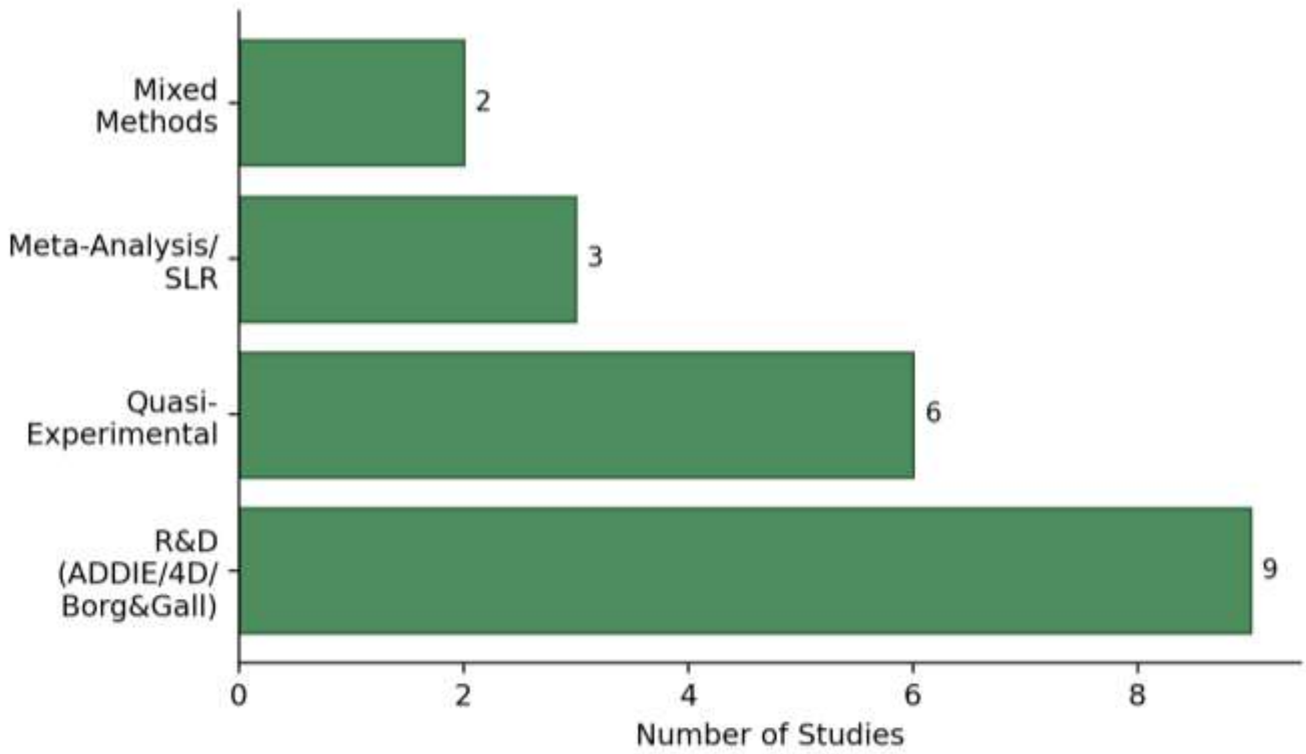

Figure 3. Research methods used across the 20 reviewed studies

Learning Outcomes Targeted

Figure 4 shows that conceptual understanding was the most frequently targeted outcome (35%), followed by critical thinking/higher-order thinking skills (25%), motivation and engagement (15%), digital/web literacy (15%), and problem-solving skills (10%). This pattern confirms that, while STEM-PjBL and web-based physics media are frequently framed as multi-purpose interventions, their central and most consistently measured outcome remains students' conceptual mastery of physics content.

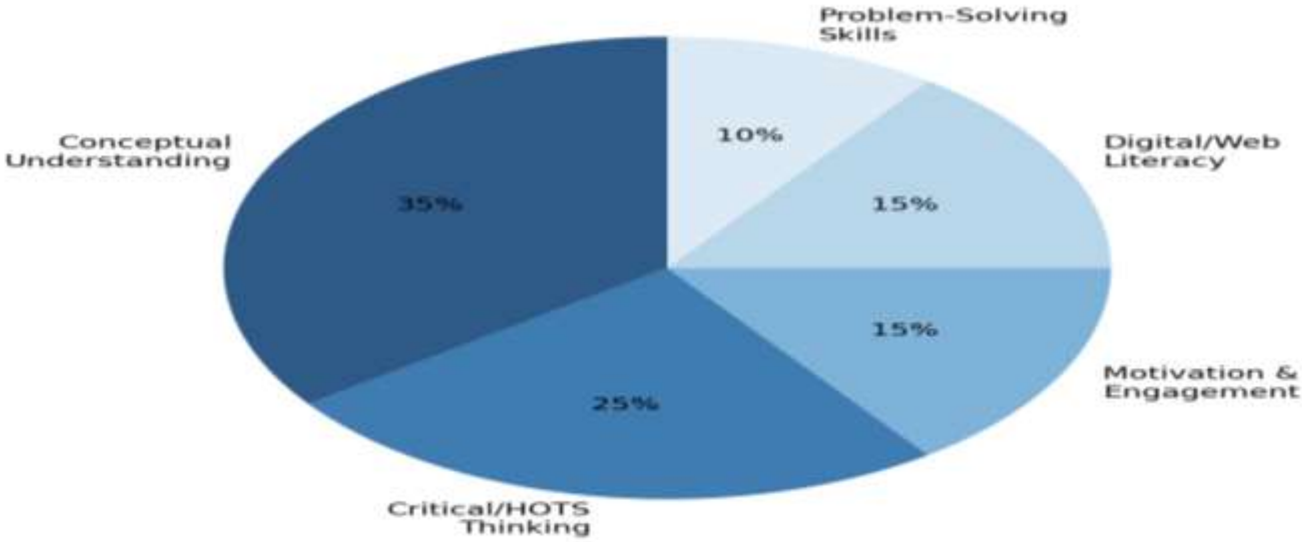

Figure 4. Learning outcomes emphasized across the 20 reviewed studies

Effectiveness of Web-Based and Simulation-Supported STEM-PjBL on Conceptual Understanding

The reviewed studies consistently reported that integrating web-based interactive media—PhET simulations, virtual laboratories, e-modules, and website-based platforms—into STEM-PjBL physics instruction produced meaningful gains in conceptual understanding. Arifin et al. (2025) found a large effect (Cohen's d = 1.85) for conceptual-understanding gains among university physics majors taught through PjBL compared with lecture-based instruction. Similarly, Fitriani (2024) reported significant improvements in electrostatics and general physics concept mastery, respectively, when PhET simulations were used. Meta-analytic syntheses reinforce these individual findings: Sirait et al. (2026) computed an aggregate effect size of 1.48 (92% impact) for PhET simulation on conceptual understanding across ten studies, documented average score increases from 66.4 to 80.4 across virtual-laboratory-based inquiry interventions.

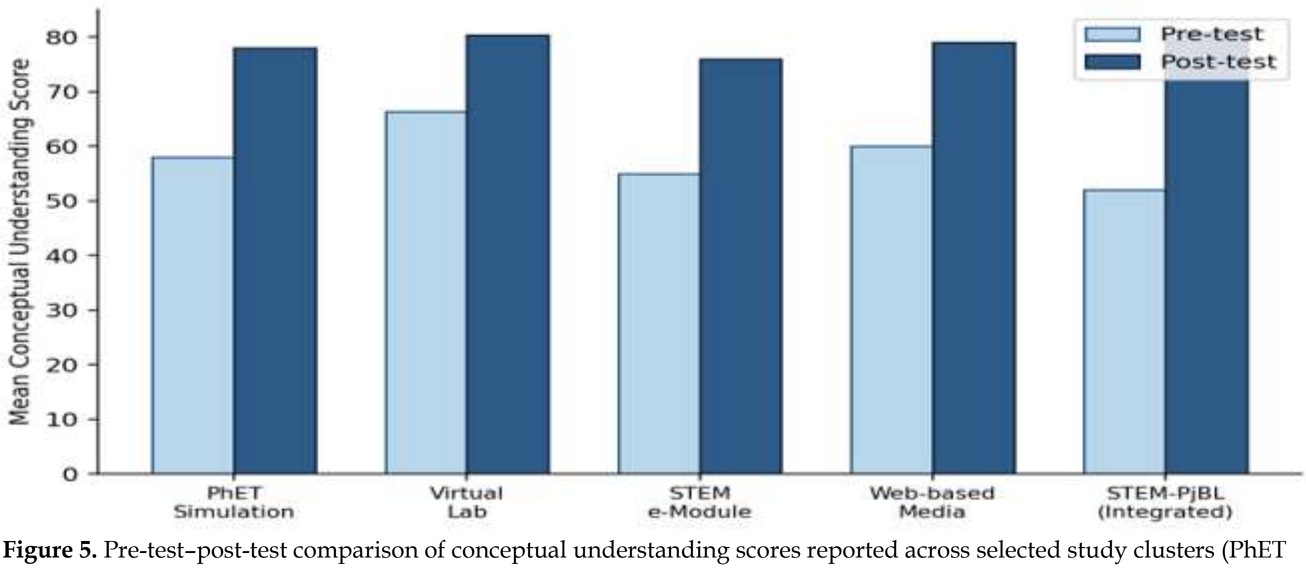

Figure 5. Pre-test–post-test comparison of conceptual understanding scores reported across selected study clusters (PhET simulation, virtual laboratory, STEM e-module, website-based media, and integrated STEM-PjBL)

Figure 5 synthesizes representative pre-test and post-test scores drawn from the reviewed clusters of interventions, illustrating a consistent upward shift in conceptual understanding regardless of the specific technology used, with the largest relative gain observed for fully integrated STEM-PjBL web-based interventions. This pattern suggests that interactivity alone is necessary but not sufficient; interactivity combined with authentic, project-based tasks appears to produce the strongest and most durable conceptual gains, a conclusion consistent with Awamleh (2024) and the neuroscience-informed STEM-PjBL module reported by Sánchez-García & Reyes-de-Cózar (2025), which linked personal interest, real-world connection, and applied conceptual understanding to sustained learning gains.

The Role of TPACK and Digital Literacy for Prospective Teachers

For prospective teacher students specifically, the reviewed evidence highlights that technology integration is only pedagogically productive when mediated by adequate Technological Pedagogical Content Knowledge (TPACK) and digital literacy. Siregar et al. (2024) using structural equation modeling with 468 pre-service teachers, found that TPACK had both a direct effect ($\beta = 0.39$) and an indirect effect mediated by digital literacy ($\beta = 0.28$) on twenty-first-century teaching competencies. This finding implies that an interactive web-based STEM-PjBL physics model intended for prospective teachers must not only present interactive content but also model the pedagogical reasoning behind that content, so that pre-service teachers simultaneously build their own conceptual understanding and their capacity to teach with the same tools in their future classrooms.

Design Principles Emerging from the Literature

Synthesizing across the 20 studies, five recurring design principles emerge for an interactive web-based STEM-PjBL physics material model: authentic, real-world project tasks that anchor abstract physics concepts in tangible engineering problems; simulation or virtual-laboratory components that allow repeated, risk-free experimentation (Garcia-Ruiz et al., 2025; Simbolon & Silalahi, 2023) scaffolded question prompts that guide students from exploration toward formal conceptual articulation; systematic instructional design procedures (ADDIE/4D) with expert validation, practicality testing, and effectiveness testing to ensure the material is valid, practical, and effective (Ismiyati et al., 2019) and embedded TPACK-building elements that make the pedagogical rationale visible to prospective teachers, not just the content itself.

Research Gaps

Several gaps were identified. First, most studies (14 of 20) relied on single-institution, short-duration interventions, limiting generalizability. Second, only a minority incorporated adaptive or AI-supported personalization, despite the growing interest in deep-learning-enhanced STEM-PjBL models identified by Widiyono & Ghufron (2024). Third, instruments for measuring conceptual understanding varied widely across studies (multiple-choice concept inventories, N-gain tests, Likert-scale self-report), which complicates cross-study comparison and points to the need for a standardized, validated conceptual-understanding instrument specific to web-based STEM-PjBL physics contexts. Finally, very few studies specifically targeted prospective teacher students as the unit of analysis, rather than secondary school students, indicating that the intersection of STEM-PjBL, web-based media, and teacher education remains comparatively under-researched.

Bibliometric Keyword Network Analysis

To complement the thematic synthesis above, a keyword co-occurrence network was constructed from the terms and concepts most frequently reported across the 20 reviewed studies, following the visualization convention popularized by VOSviewer (Eck & Waltman, 2010). In this type of network, each circle (node) represents a keyword or concept; the size of the circle reflects how frequently that keyword occurred across the reviewed literature; the line (edge) connecting two nodes represents a co-occurrence relationship, that is, how often the two keywords appeared together within the same study; and the thickness of each line reflects the strength of that co-occurrence. Nodes are grouped into color-coded clusters using a modularity-based grouping procedure, where nodes assigned the same color tend to appear together more often than with nodes from other clusters, revealing coherent sub-themes within the broader research landscape.

As shown in Figure 6, the network resolves into four coherent thematic clusters. The red cluster (Cluster 1) is anchored by "conceptual understanding" and "physics education" as the two largest and most central nodes, densely connected to "PhET simulation," "virtual laboratory," "N-gain," and "effect size." This cluster's size and central position confirm that conceptual understanding functions as the dominant outcome variable around which nearly all other themes in this literature revolve, consistent with the pattern already identified in Figure 4. The green cluster (Cluster 2) centers on "STEM-PjBL" and "project-based learning," which are tightly linked to "critical thinking," "problem-solving," "higher-order thinking," and "engineering design." The strong, thick edge between "STEM-PjBL" and "project-based learning" indicates that these two terms almost always co-occur in the reviewed studies, reflecting the fact that STEM-oriented physics interventions are rarely discussed without explicit reference to project-based pedagogy (Santhosh et al., 2023; Ralph, 2016). Its multiple cross-cluster links to the red cluster (particularly through "conceptual understanding" and "physics education") visually confirm the pedagogical bridge between authentic project work and conceptual mastery that was discussed qualitatively in previous Section.

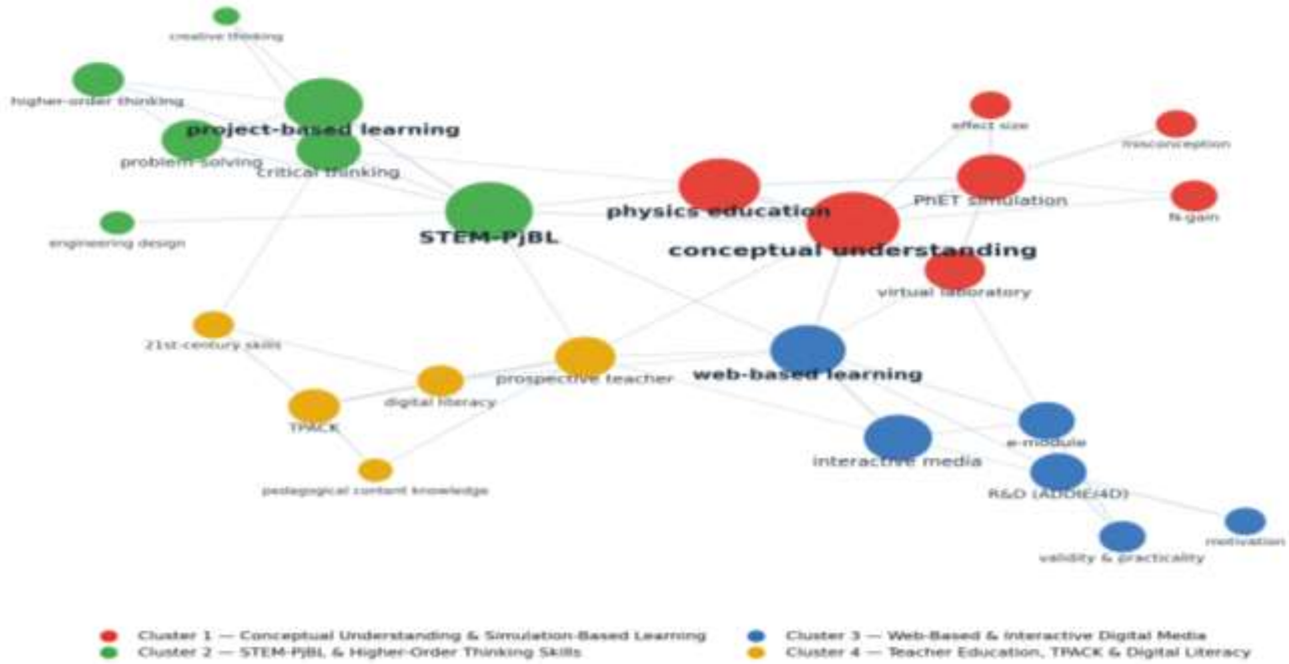

Figure 6. Keyword co-occurrence network of the reviewed literature

The blue cluster (Cluster 3) groups "web-based learning," "interactive media," "e-module," and "R&D (ADDIE/4D)" together with "validity & practicality" and "motivation." This cluster represents the instructional-design and media-development dimension of the literature: many of the reviewed R&D studies are organized around producing, validating, and field-testing a web-based or digital product, rather than merely testing an already-existing simulation. Its position between the red and yellow clusters reflects its dual role as both a vehicle for conceptual understanding (linking to Cluster 1) and a training ground for future teachers (linking to Cluster 4). Finally, the smaller yellow/orange cluster (Cluster 4) contains "prospective teacher," "TPACK," "digital literacy," "21st-century skills," and "pedagogical content knowledge." Although this cluster is visibly smaller and more peripheral than the other three—reflecting the comparatively limited number of studies that specifically target prospective teacher populations, as noted in Section research gaps—its direct links to "conceptual understanding," "web-based learning," and "STEM-PjBL" show that, where such studies do exist, they explicitly connect teacher-readiness constructs to the same conceptual and technological themes that dominate the wider field. The relative sparsity of this cluster, visualized here as fewer and thinner connecting edges, provides graphical confirmation of the research gap identified earlier: the intersection of STEM-PjBL, web-based media, and prospective teacher education remains a comparatively underdeveloped area of inquiry, and is precisely the space that the proposed interactive web-based STEM-PjBL physics material model for prospective teacher students is intended to address.

Conclusion

This systematic literature review of 20 studies published between 2018 and 2025 demonstrates that interactive web-based STEM-PjBL physics material models consistently and substantially improve conceptual understanding, with effect sizes ranging from moderate to high across simulation-based, virtual-laboratory-based, and fully project-based interventions. The strongest gains appear when interactivity is combined with authentic project tasks, systematic instructional design validation, and explicit attention to prospective teachers' technological pedagogical content knowledge. Based on these findings, the development of an interactive web-based STEM-PjBL physics material model for prospective teacher students should integrate authentic engineering-design projects, simulation-laboratory components, scaffolded conceptual prompts, rigorous validity-practicality-effectiveness testing, and explicit TPACK-building features. Future research should pursue larger, multi-site, and longitudinal studies; explore adaptive or AI-enhanced personalization; and develop standardized instruments for measuring conceptual understanding in web-based STEM-PjBL physics contexts, particularly among prospective teacher populations who will carry these innovations into the next generation of physics classrooms.

Acknowledgments
Acknowledgments are expressed by the researchers to the team so that researchers can complete research in the form of journal publications.

Author Contributions
Conceptualization, data curation, writing—original draft preparation, A.D.; methodology, writing—review and editing, S.; validation, formal analysis, visualization, A.H.; investigation, resources, H.A.S. All authors have read and agreed to the published version of the manuscript.

Funding
No external funding.

Conflicts of Interest
No conflict interest.

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