



Conceptual Model of Computer Utilization in 21st Century Science Learning: Grounded Theory-Informed Literature Review

Yuniar Fahmi Lathif ^{1*}, Muhammad Gibran Alif Prasetya ², Ahmad Alfian Risydan Yasin ³

^{1*} Master Program in Elementary Madrasah Teacher Education (PGMI), Universitas Islam Negeri Salatiga, Salatiga City, Central Java Province, Indonesia.

^{2,3} Master of Science Education Program, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Semarang City, Central Java Province, Indonesia.

Corresponding Email: yuniarfl@uinsalatiga.ac.id ^{1*}

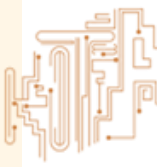
Article History:

Received: 24 January 2026; Revised: 6 February 2026; Accepted: 15 February 2026; Published: 1 March 2026.

Abstract

The use of computers in science education continues to be dominated by technocentric approaches that treat technology as an end in itself rather than a means of learning. This research aims to deconstruct prevailing research trends and construct a new conceptual model explaining how computers can be used effectively in 21st-century science learning. Using a Systematic Literature Review (SLR) design with the PRISMA 2020 protocol, this study selects and analyzes high-quality articles from reputable databases. Data analysis followed a Grounded Theory-Informed approach to extract recurring patterns and build theoretical propositions inductively. Three fundamental dimensions emerged to form the new conceptual model: (1) Teacher Agency and Ecosystem Readiness as determinant input variables that precede hardware availability; (2) Hybrid Pedagogy and Distributed Scaffolding as the core process mechanism that bridges physical and digital learning experiences; and (3) Methodological Adaptability as a moderator variable that adjusts instructional strategies to the complexity level of the subject matter. This study concludes that technology effectiveness is not deterministic – it depends on an adaptive pedagogical ecosystem built around teacher capacity and contextual design. These findings carry strategic implications for curriculum developers and policymakers: prioritize discipline-specific teacher professional development, and design learning environments that pair virtual simulations with real-world experiments.

Keywords: Systematic Literature Review; Grounded Theory; Science Learning; Computer Integration; 21st Century Education.



1. Introduction

The integration of computer technology in Natural Sciences (IPA) learning has become an urgent imperative in the 21st century to facilitate higher-level thinking skills, such as science literacy and scientific reasoning (Akbari *et al.*, 2025). Education today demands a shift from conventional methods to digital pedagogy that utilizes Artificial Intelligence (AI), Augmented Reality (AR), and virtual simulations to create immersive and contextual learning experiences (Efendi & Asrizal, 2025; Zandri *et al.*, 2025). While the potential of digital technologies in increasing student engagement and conceptual understanding is significant, implementation in the field is often hampered by infrastructure gaps and a lack of coherent pedagogical direction (Abdjul *et al.*, 2025; Ariansyah *et al.*, 2025). This phenomenon shows that computer use in science education remains largely technical and instrumental – without a strong conceptual foundation to support in-depth scientific inquiry (Fayzullina *et al.*, 2025). A systematic mapping of how these technologies can be effectively woven into the science curriculum is therefore overdue (Farooq *et al.*, 2024).

Given the complexity and variability of technology use across different educational settings, the Systematic Literature Review (SLR) approach offers something that isolated field studies cannot: a broad view of the entire research terrain (Hadi *et al.*, 2025). SLR allows researchers to synthesize findings from a wide range of empirical studies, identify global patterns, and evaluate the effectiveness of technological interventions at a scale no single case study can achieve (Subhananto & Ibrahim, 2026). The method is especially useful for filtering the noise from thousands of recent publications and establishing a grounded understanding of effective digital pedagogy trends (Zulfiani *et al.*, 2025). A literature review informed by Grounded Theory goes one step further – it allows the development of new theoretical propositions rooted directly in existing empirical data (Lawrence, 2022). Without this kind of systematic synthesis, model-building efforts risk recycling ineffective practices or overlooking innovations that have already demonstrated results (Ilma *et al.*, 2023).

Recent research from 2020 to 2025 shows a marked surge in publications on advanced technologies such as generative AI and Deep Learning in science education, offering new possibilities for personalized and adaptive learning (Ayuni *et al.*, 2024; Ridlo *et al.*, 2019). Empirical data consistently show that interactive media and virtual simulations improve student motivation and cognitive outcomes – but they also raise unresolved questions about ethics, algorithmic bias, and the shifting role of the teacher (Krishnan & Joshith, 2024; Kurniawan *et al.*, 2024). Research trends also point to a persistent digital divide and an urgent need for teacher digital competence that goes beyond basic technical skills toward meaningful pedagogical integration, commonly referred to as TPACK (Khoerunnisa & Fathurochman, 2025; Nur Khasanah *et al.*, 2025). Meanwhile, Mobile Learning and virtual laboratories are gaining traction as practical alternatives where physical facilities fall short (Bashith *et al.*, 2025; Galimova *et al.*, 2025).

Despite this volume of research, the literature remains fragmented. Most studies are confined to specific tools – AR, virtual labs, simulation software – or specific educational levels, without offering a model that cuts across these boundaries (Mahmud *et al.*, 2025; Prayoga *et al.*, 2025). There is a real gap: existing frameworks rarely explain the mechanisms by which technology transforms



students' scientific reasoning in any substantive way (Mujriati *et al.*, 2025). Inconsistencies in findings about technology's impact on critical thinking across different student populations further signal that current instructional designs need re-examination (Risma Fadliyatul Maulidyah *et al.*, 2025; Zan *et al.*, 2023). What is absent is a model that connects constructivist learning theory with current technological capabilities in a way that is both theoretically coherent and practically usable (Saseendran & Thomas, 2025).

This SLR is designed to address that absence. By synthesizing the literature systematically, identifying patterns across findings, and analyzing the conditions under which computer use in science learning actually works, this study builds a new conceptual model derived from the data itself. The goal is not merely to summarize what exists, but to construct a theoretical account of the relationships between key variables – inputs, processes, and outcomes – in a form that practitioners and researchers can actually use. The primary contribution expected from this study is a conceptual model that enables educators, policymakers, and curriculum designers to understand, plan, and carry out more effective computer-based interventions in science learning. The academic and practical relevance of these findings is substantial: they provide a theoretical foundation for technology-based pedagogy and offer concrete guidance for anyone working to make 21st-century science education more effective and equitable.

2. Methodology

2.1 Research Design

This study applies the Systematic Literature Review (SLR) to identify, assess, and critically synthesize literature on computer use in science learning. The research procedure adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol, integrated with Watase UAKE software for automated metadata search and filtering management, to ensure transparency, validity, and reproducibility throughout the data selection process (Page *et al.*, 2021). The approach is qualitative-descriptive in nature, aimed at aggregating recent empirical evidence to detect pedagogical patterns, technological trends, and significant research gaps in the existing literature (Kraus *et al.*, 2020), thereby enabling the construction of evidence-based conceptual models that support 21st-century skill development (Hamadi & El-Den, 2023). Through rigorous systematic synthesis of prior research findings, the study not only maps the current state of knowledge but also establishes a new theoretical foundation for technology integration in effective science education (Rethlefsen *et al.*, 2021).

2.2 Literature Search Strategy

The literature search was conducted systematically through the Scopus database, selected for its strict content curation standards and broad citation coverage – both essential for ensuring the empirical quality of the data (Gusenbauer, 2022). To manage metadata efficiently and accurately, this study used Watase UAKE, a collaborative research platform specifically designed to support SLR protocols. The Keyword Identification feature in Watase UAKE was used to search, de-duplicate, and pre-filter articles based on extracted metadata, ensuring a transparent data selection flow consistent with PRISMA 2020



standards (Page *et al.*, 2021). To capture the dynamics of post-pandemic technology integration, literature inclusion was strictly limited to publications from 2020 to 2025 (Arini & Purwandari, 2025).

The identification process in Watase UAKE used a combination of targeted keywords addressing technology implementation in science education: "Role of Computer in Science Education", "Integrating Computer in Science Education", "Implementation Computer in Science Learning", and "Utilization of Computers in 21st Century Learning in Science Education" (Lee *et al.*, 2022). Searches were focused on the Title, Abstract, and Keywords fields (Title-Abs-Key) using Boolean operators (AND, OR) to broaden terminology coverage while maintaining relevance to 21st-century science learning (Singh, 2025). This structured approach enabled more accurate literature mapping, facilitating the detection of research gaps and the construction of a solid theoretical synthesis (Rethlefsen *et al.*, 2021).

2.3 Inclusion and Exclusion Criteria

The article selection process follows the PRISMA 2020 protocol, carried out with the support of Watase UAKE software. From an initial identification in the Scopus database, 260 articles were found matching the search keywords. To ensure data quality and relevance, strict inclusion and exclusion criteria were applied. Inclusion criteria covered journal articles indexed in Scopus (Q1–Q4), with full-text access, published between 2020 and 2025. Exclusion criteria were applied through Watase UAKE's automation features and manual filtering. A total of 139 articles were removed as duplicates, and 30 articles were excluded for falling outside the specified year range. Articles without abstracts (n=2), those that could not be retrieved (n=1), and articles not relevant to computer integration in science learning (n=27) were also excluded. This multi-stage screening process yielded 10 final articles eligible for synthesis (Page *et al.*, 2021). The selection parameters are summarized in Table 1 below.

Table 1. Inclusion and Exclusion Criteria (Based on the Watase UAKE Protocol)

Criteria	Inclusions (Selected)	Exclusion (Discarded)
Database Source	Scopus (Single database)	Non-Scopus / Grey Literature
Year of Publication	2020–2025	Outside 2020–2025 (Automated removal, n=30)
Journal Quality	Indexed International Journal (Q1–Q4)	Unindexed or Predatory Journals
Document Status	Original Research Articles & Reviews	Duplicates (n=139), No Abstract (n=2), Editorials
Availability	Full text accessible	Full text not found (n=1)
Topic Relevance	Focus on computer integration in science education	Non-specific topics in science education (n=27)

2.4 Literature Selection Procedure

The literature selection followed a systematic multi-stage screening mechanism to ensure the accuracy, validity, and quality of the articles analyzed. The process began with an initial identification in the Scopus database, yielding 260 potential articles. A first-stage screening using Watase UAKE's automation features eliminated duplicate articles (n=139), articles outside the study year range (n=30), and documents with technical issues such as missing abstracts (n=43).



Articles passing technical screening (n=38) were then manually reviewed by title and abstract for substantive relevance to computer integration in science education, resulting in the exclusion of 27 articles due to contextual mismatches. In the final full-text eligibility stage, 1 of the 11 remaining articles could not be downloaded, leaving 10 articles fully eligible for final synthesis. All procedures are transparently documented to ensure the replicability of the review process. The results of the literature selection are visualized through the PRISMA flowchart, which maps the number of articles identified, screened, excluded, and accepted at each stage, as shown in Figure 1.

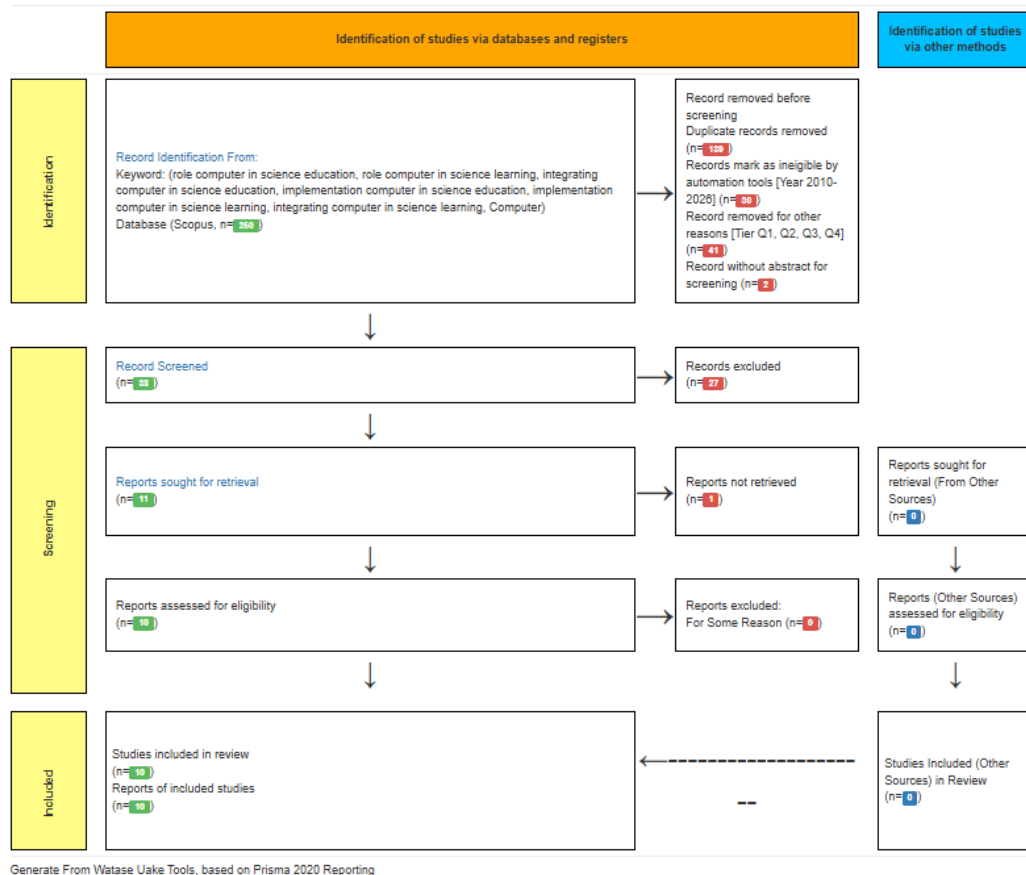


Figure 1. Article Selection PRISMA Diagram.

3. Results and Discussion

3.1 Results

3.1.1 Literature Profile Reviewed

The selected articles span the period 2020–2023. Publication trend analysis shows a distribution that peaked in 2021, with a relatively stable output in subsequent years. This pattern indicates that the integration of technology in science education is a relevant and actively developing topic, driven largely by the urgent need for distance and hybrid learning solutions that emerged after the pandemic. Publication quantity peaked in 2021, accounting for 40% of total articles. Despite a decrease in volume in 2022 and 2023, the consistent presence of studies each year confirms that computer integration in science learning



remains an active research concern. The peak in 2021 almost certainly reflects the academic community's response to the COVID-19 pandemic, when researchers were under pressure to test the viability of virtual tools such as PhET simulations and e-modules as substitutes for physical classroom instruction.

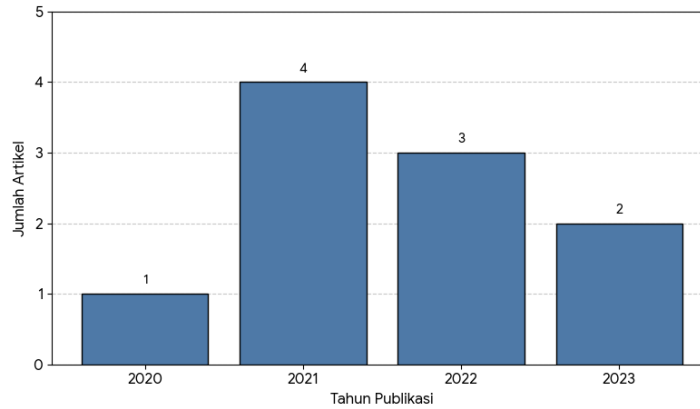


Figure 2. Distribution of Publications by Year

The literature distribution map in Figure 2 reveals a striking pattern: 90% of studies come from authors affiliated with Indonesian educational institutions. This concentration points to a specific national urgency – adapting the local curriculum to digital demands while navigating real infrastructure constraints. The international studies in the sample serve as a useful comparative reference. From a subject focus standpoint, there is a discernible shift from Physics-specific studies (40%) toward broader Science/STEM integration (60%), suggesting that researchers are beginning to treat technology not as a subject-specific aid but as a general learning environment. This rich but geographically concentrated body of empirical data provides a strong methodological foundation for applying the Grounded Theory approach in this study, which aims to synthesize scattered practical findings into a complete Conceptual Model – filling the theoretical gap that previous "tool-centric" studies have left unaddressed.

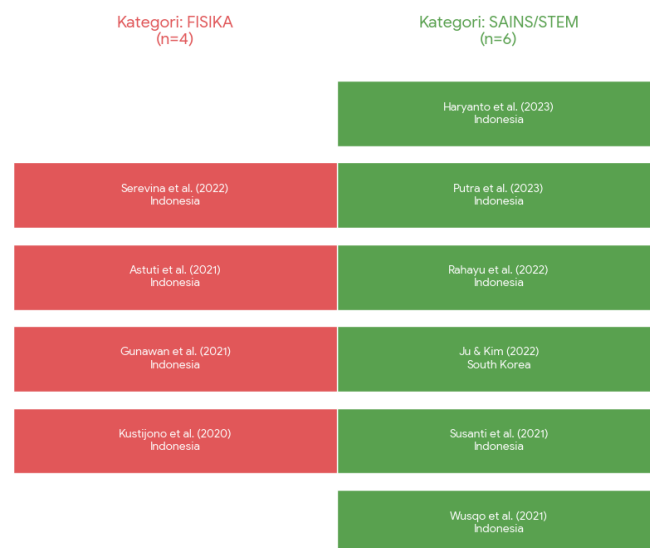


Figure 3. Literature Distribution Map: Authors, Affiliates, Countries, and Categories



The methodological pyramid in Figure 4 illustrates the current depth of analysis in the field. The widest base is occupied by Experimental/Quantitative methods (50%), providing solid empirical evidence about what works in terms of technology's effect on learning outcomes. The middle layer – Review/SLR studies (30%) – indicates that the field has accumulated enough data to warrant synthesis. The narrow top of the pyramid, occupied by R&D research (20%), and the complete absence of purely theoretical work, expose a critical gap. There is plenty of evidence that technology *can* work. What is missing is a theoretical account of *why* and *under what conditions* it works. This study addresses that gap directly through the Grounded Theory-Informed Literature Review approach.

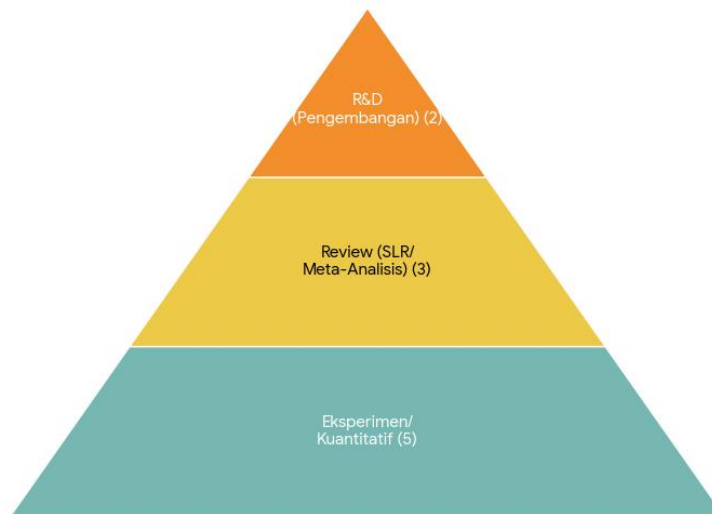


Figure 4. Methodological Hierarchy

3.1.2 Synthesis of Key Findings

The analysis of 10 selected articles followed an inductive approach to build a defensible conceptual model. This synthesis identifies key elements (inputs), interaction processes, and outcomes that appear consistently across the data, and examines the conditions that shape their effectiveness.

Table 2. Literature Synthesis Table: Variable Mapping for Conceptual Models

Researcher (Year)	Purpose & Context	Research Methods	Key Input/Process Variables	Outcomes & Theoretical Contributions
Scanlon & Connolly (2021)	Exploration of new CS subjects (Ireland)	Qualitative Case Studies (Figurationa l Sociology)	Input: Teacher & Student Agency. Process: Teacher-student interdependence (figuration)	Curriculum success depends on teacher-student agency negotiation, not curriculum documents alone
Klieger et al. (2010)	Laptop integration (1:1 Program) in	Qualitative Case Studies	Input: Teacher attitude, Discipline training.	Laptop integration requires cultural change and subject-specific



	science teachers	(Grounded Theory)	Process: Tiered technical & pedagogical support	training, not general IT training
Flogie et al. (2025)	Professional development (PD) of teachers for CS	Qualitative (Teacher Reflection)	Input: Teacher Competence. Process: Cross-disciplinary collaboration, sustained PD	PD raises student motivation and supports CS integration into science/mathematics curricula
Samon & Levy (2021)	Complex systems learning (Chemistry)	Quasi-Experimental (4 conditions)	Process: Computer Model + Physical Lab combination (Hybrid)	The hybrid approach (Physical + Digital) outperforms any single-mode approach for abstract concept understanding
Wu & Pedersen (2011)	Science inquiry with simulation (Supervolcano)	Factorial Experiment	Process: Continuous computer scaffolding + early teacher metacognitive scaffolding	The combination of teacher (metacognitive) and computer (procedural) support produces the strongest inquiry skill outcomes
Zimmerman et al. (2019)	Outdoor science learning	Case Study (Ethnographic Video)	Process: Contextual mobile use, "Sense-making talk"	Mobile technology bridges physical environments and science concepts through active dialogue
Rutten et al. (2012)	Review of computer simulation in science education	Systematic Literature Review	Input: Information visualization. Process: Substitution vs. Lab Supplement	Simulations are most effective as supplements to traditional instruction or pre-lab preparation
Zendler & Klein (2018)	Instruction methods for CS (Search Queries)	Experiment (SPF-2x2.2)	Process: Programmed Instruction vs. Reciprocal Teaching	Structured methods (Programmed Instruction) outperform reciprocal teaching for basic



				procedural skill acquisition
Zendler & Reile (2018)	Instruction methods for CS (QR Codes)	Experiment (SPF-2x2.2)	Process: Direct Instruction vs. WebQuest	Direct Instruction outperforms open inquiry (WebQuest) for specific technical material
Fouh <i>et al.</i> (2012)	Visualization of Algorithms in CS	Literature Review	Process: Engagement Level (Viewing vs. Constructing)	Visualization only works when students actively build or manipulate – passive viewing yields little

3.2 Discussion

3.2.1 Thematic/Conceptual Analysis

The thematic analysis, conducted through a Grounded Theory-Informed Literature Review approach, first identifies Teacher Readiness and Agency Ecosystem as a foundational theme functioning as an input variable in the conceptual model. The data are consistent on this point: technology effectiveness does not begin with hardware. It begins with people. Scanlon & Connolly (2021) and Klieger *et al.* (2010) both show that the success of computer curriculum integration depends heavily on the negotiation of "agency" between teachers and students, and on the readiness of school culture to absorb change. When systemic support is absent – particularly the kind of discipline-specific professional development (Disciplinary-specific PD) emphasized by Flogie *et al.* (2025) – technological interventions tend to fall short of any transformative learning objective. Teachers who receive only generic IT training consistently report difficulty connecting digital tools to the specific conceptual demands of their subject. The technology sits in the classroom; the pedagogy does not change.

The second central theme shaping the *Process* dimension of this model is Integrated Pedagogy. The literature does not support a clean separation between physical and digital learning. Samon & Levy (2021) and Zimmerman *et al.* (2019) both demonstrate that understanding of complex, abstract science concepts is most reliably achieved through a hybrid approach – computer simulation placed alongside physical laboratory work or outdoor exploration. Within a 21st-century learning framework, technology is not a replacement for real experience. It functions as a cognitive bridge, making abstract phenomena visible and manipulable before or alongside direct encounter with the physical world.

The effectiveness of this hybrid process is then shaped by Distributed Scaffolding and Methodological Adaptability, which operate as moderator variables. Wu & Pedersen (2011) make the case clearly: the most productive arrangement divides the support role, with computers providing procedural scaffolding while teachers supply metacognitive guidance. Students who received both continuous computer-based procedural support and early teacher-based metacognitive scaffolding performed best on scientific inquiry skill measures – neither alone was sufficient. Zendler & Reile (2018) and Fouh *et al.* (2012) add a further condition: instructional methods must be selected based on the nature of the material. Structured, direct instruction works for basic procedural knowledge;



active construction and manipulation are required for deeper conceptual understanding. This is not a contradiction – it is a call for deliberate adaptability. Taken together, this thematic synthesis produces a coherent Conceptual Model of Computer Utilization, connecting input variables (teacher agency and ecosystem readiness), process mechanisms (hybrid pedagogy and distributed scaffolding), and a moderating condition (methodological adaptability) in a single causal logic. The model does not claim that any particular technology produces learning. It claims that learning occurs when the right pedagogical conditions are in place – and that technology, used well, can extend what those conditions make possible.

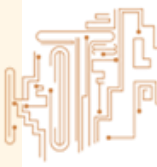
3.2.2 Identification of Research Gaps

A systematic reading of the literature reveals a persistent theoretical problem: previous research tends to be isolated on specific variables without offering a model that accounts for their interaction. Most studies examine the technical effectiveness of a particular tool (Rutten *et al.*, 2012), compare partial instructional methods (Zendler & Klein, 2018), or analyze teacher agency in isolation (Scanlon & Connolly, 2021). None of them explain how ecosystem readiness, hybrid pedagogy, and learning outcomes interact as a system. The empirical evidence exists; the theoretical architecture to house it does not. There are also inconsistencies in empirical findings regarding the relative superiority of inquiry-based versus direct instruction methods – contradictions that no existing single theory has adequately resolved. This creates a clear need for a conceptual model capable of reconciling these differences based on the specific complexity demands of 21st-century science learning materials. From a methodological standpoint, the Grounded Theory approach applied to literature review for theory-building purposes remains rare in this field. The existing literature is dominated by experimental hypothesis-testing studies and descriptive reviews that summarize trends without performing substantive conceptual abstraction. This study fills that gap by transforming fragmented empirical findings into coherent theoretical propositions. The primary contribution is a Conceptual Model of Computer Utilization that closes the theoretical gap and provides a strategic foundation for adaptive, discipline-grounded science pedagogy.

4. Conclusion

This research constructed a "Conceptual Model of Computer Utilization in 21st Century Science Learning" through the Grounded Theory-Informed Literature Review approach. Based on a thorough synthesis of the selected literature, this study concludes that the effectiveness of technology integration in science education is not a matter of technological determinism, but rather the result of complex systemic interactions. The main findings show that learning success is shaped by three main pillars: (1) Teacher Agency and Ecosystem Readiness as the foundational input variables; (2) Integration of Hybrid Pedagogy as the process variable that bridges physical and digital learning experiences; and (3) Methodological Adaptability as the moderator variable that calibrates instructional strategies to the complexity demands of the content.

These findings directly challenge the technocentric assumption that computers can substitute for teachers or physical laboratories. The data show otherwise: technology functions optimally as a cognitive partner within a



distributed scaffolding system, where structured instruction and constructivist inquiry are applied selectively based on content requirements. The practical implication for education policy is a clear shift in priority – away from hardware procurement and toward investment in discipline-specific teacher professional development. For practitioners, this model calls for learning designs that do not treat virtual simulations and real experiments as alternatives, but as complementary modes that together build richer conceptual understanding of abstract science material.

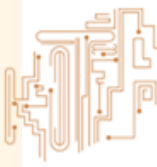
This study is not without limitations. The analyzed literature is geographically concentrated, with 90% of studies originating from Indonesian institutional contexts, and the number of final articles included in the synthesis is relatively small. Both factors may affect the generalizability of the model to settings with more extreme digital divides. Future research should test the empirical validity of this conceptual model through large-scale experimental or longitudinal studies. Further investigation is also needed to understand how students' socio-cultural variables interact with hybrid pedagogical designs across more diverse educational environments.

References

- Abdjul, T., Fatima, S., Mahmud, A. P. M., Pilobu, M., Lahalik, M. F. D., Awila, A. A., Bulilingo, M. R., & Stiosarint, Y. (2025). Utilizing technology as a solution to science learning problems in junior high schools: A literature review. *Reflection Journal*, 5(1), 428–437.
- Ariansyah, A., Bilad, M., Sutarto, S., Kurnia, N., Alaydrus, K., Pathan, P., Azmi, I., & Sharov, S. (2025). Pedagogical negotiation in an unequal digital ecosystem: A case study of science education in higher education. *International Journal of Ethnoscience and Technology in Education*, 2, 243–258. <https://doi.org/10.33394/ijete.v2i2.17366>
- Ayuni, R., Jaedun, A., Zafrullah, Z., & Ramadhani, A. (2024). Trends in the use of artificial intelligence in science education: Bibliometric & Biblioshiny analysis (1975–2024). *Jurnal Penelitian Pendidikan IPA*, 10, 740–756. <https://doi.org/10.29303/jppipa.v10i10.7846>
- Bashith, A., Amin, S., Aliman, M., Kurniawan, M., Jubba, H., & Maulidiah, L. (2025). Utilizing a virtual laboratory based on mobile learning: Implementation for social science education students in Indonesia to improve learning outcomes. *Educational Process: International Journal*, 15. <https://doi.org/10.22521/edupij.2025.15.181>
- Efendi, E., & Asrizal. (2025). Research trends and opportunities in integrating augmented reality and deep learning into science education: A bibliometric analysis. *Jurnal Penelitian Pendidikan IPA*, 11, 1–11. <https://doi.org/10.29303/jppipa.v11i7.11988>



- Farooq, E., Zaidi, E., & Shah, M. (2024). The future classroom: Analyzing the integration and impact of digital technologies in science education. *Jurnal Penelitian dan Pengkajian Ilmu Pendidikan: e-Saintika*, 8, 280–318. <https://doi.org/10.36312/esaintika.v8i2.1957>
- Fayzullina, A., Filippova, A., Garnova, N., Astakhov, D., Kalmazova, N., & Zaripova, Z. (2025). Artificial intelligence in science education: A systematic review of applications, impacts, and challenges. *Contemporary Educational Technology*, 17, ep613. <https://doi.org/10.30935/cedtech/17519>
- Flogie, A., Lipovec, A., & Škrobar, J. (2025). Integrating computer science and informatics education in primary schools: Insights from a Slovenian professional development initiative. *Sustainability*, 17(20), 9068. <https://doi.org/10.3390/su17209068>
- Fouh, E., Akbar, M., & Shaffer, C. (2012). The role of visualization in computer science education. *Computers in the Schools*, 29(1), 95–117. <https://doi.org/10.1080/07380569.2012.651422>
- Galimova, E. G., Sergeeva, O. V., Zheltukhina, M. R., Sokolova, N. L., Zakharova, V. L., & Drobysheva, N. N. (2025). Mobile learning in science education to improve higher-order thinking skills and communication skills: Scoping review. *Frontiers in Communication*, 10, 1624012. <https://doi.org/10.3389/fcomm.2025.1624012>
- Gusenbauer, M. (2022). Search where you will find most: Comparing the disciplinary coverage of 56 bibliographic databases. *Scientometrics*, 127(5), 2683–2745. <https://doi.org/10.1007/s11192-022-04289-7>
- Hadi, K., Sudatha, I. G., Suartama, I. K., & Santosa, M. (2025). Biology learning based ICT in Indonesia: A systematic literature review. *Jurnal Penelitian Pendidikan IPA*, 11, 36–44. <https://doi.org/10.29303/jppipa.v11i6.11778>
- Hamadi, M., & El-Den, J. (2023). A conceptual research framework for sustainable digital learning in higher education. *Research and Practice in Technology Enhanced Learning*, 19, 1. <https://doi.org/10.58459/rptel.2024.19001>
- Ilma, A., Wilujeng, I., Widowati, A., Nurtanto, M., & Kholifah, N. (2023). A systematic literature review of STEM education in Indonesia (2016–2021): Contribution to improving skills in 21st century learning. *Pegem Journal of Education and Instruction*, 13, 134–146. <https://doi.org/10.47750/pegegog.13.02.17>
- Khoerunnisa, I., & Fathurochman, A. (2025). Teachers' digital skills research trends: A Scopus bibliometric study (2020–2025). *IQRO: Journal of Islamic Education*, 8, 1321–1340. <https://doi.org/10.24256/iqro.v8i3.8894>
- Klieger, A., Ben-Hur, Y., & Bar-Yossef, N. (2010). Integrating laptop computers into classroom: Attitudes, needs, and professional development of science teachers – a case study. *Journal of Science Education and Technology*, 19(2), 187–198. <https://doi.org/10.1007/s10956-009-9191-1>



- Kraus, S., Breier, M., & Dasí-Rodríguez, S. (2020). The art of crafting a systematic literature review in entrepreneurship research. *International Entrepreneurship and Management Journal*, 16(3), 1023–1042. <https://doi.org/10.1007/s11365-020-00635-4>
- Krishnan, K., & Joshith, V. P. (2024). Pedagogical incorporation of artificial intelligence in K-12 science education: A decadal bibliometric mapping and systematic literature review (2013–2023). *Journal of Pedagogical Research*. <https://doi.org/10.33902/JPR.202429218>
- Kurniawan, A., Jumadi, J., Kuswanto, H., & Syar, N. (2024). The 21st century education: A systematic literature review of transforming learning methods to foster critical thinking skills through augmented reality in science learning. *Jurnal Eduscience*, 11, 601–622. <https://doi.org/10.36987/jes.v11i3.6438>
- Lawrence, J. (2022). The strategic drivers influencing teachers' integration of ICT in teaching and learning environment. *The Educational Review, USA*, 6, 300–311. <https://doi.org/10.26855/er.2022.07.004>
- Lee, S. J., Francom, G., & Nuatomue, J. (2022). Computer science education and K-12 students' computational thinking: A systematic review. *International Journal of Educational Research*, 114, 102008. <https://doi.org/10.1016/j.ijer.2022.102008>
- Mahmud, A., Mursalin, M., Abdjul, T., Masrid, M., Yusuf, M., & Odja, A. (2025). A virtual laboratory to improve the effectiveness of interactive learning media on science process skills and science literacy in the competency aspects of dynamic electricity. *Jurnal Penelitian Pendidikan IPA*, 11, 1441–1450. <https://doi.org/10.29303/jppipa.v11i11.13531>
- Maulidyah, R. F., Aulia, E., & Mahdiannur, M. A. (2025). Implementation of inquiry learning model in improving critical thinking skills in science learning. *Journal Central Publisher*, 2(12), 3012–3021. <https://doi.org/10.60145/jcp.v2i12.578>
- Mujriati, A., Purwoko, A., & Savalas, L. (2025). A systematic review of scientific inquiry research: Trends in science literacy and critical thinking (2016–2025). *Current Educational Review*, 1, 110–121. <https://doi.org/10.56566/cer.v1i3.404>
- Nur Khasanah, A., Septiyanto, A., Jumadi, Wilujeng, I., & Hidayah, E. (2025). Analysis of pre-service science teachers' technological pedagogical content knowledge (TPACK). *Journal of Science Education Research*, 9, 62–74. <https://doi.org/10.21831/jser.v9.i1.72907>



- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Prayoga, B. G., Wardani, S., Harniangsih, H., Subali, B., & Widiati, N. (2025). Literature review on the application of interactive media in science learning in elementary schools for the period 2020–2025. *Journal of Educational Sciences*, 9(4), 2084–2100. <https://doi.org/10.31258/jes.9.4.p.2084-2100>
- Rethlefsen, M., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M., & Koffel, J. (2021). PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. *Systematic Reviews*, 10, 39. <https://doi.org/10.1186/s13643-020-01542-z>
- Ridlo, Z. R., Ningsih, S. P. A., & Anggraini, A. L. (2019). Computational thinking and deep learning on science education framework: A systematic review. *Science Education International*, 36(4), 480–489.
- Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education*, 58(1), 136–153. <https://doi.org/10.1016/j.compedu.2011.07.017>
- Samon, S., & Levy, S. T. (2021). The role of physical and computer-based experiences in learning science using a complex systems approach. *Science & Education*, 30(3), 717–753. <https://doi.org/10.1007/s11191-020-00184-w>
- Saseendran, A., & Thomas, M. (2025). Integration of design thinking and educational technology into science education: A conceptual framework for the development of sustainability competencies. *Journal of Educational Technology Development and Exchange*, 18, 91–116. <https://doi.org/10.18785/jetde.1804.05>
- Scanlon, D., & Connolly, C. (2021). Teacher agency and learner agency in teaching and learning a new school subject, Leaving Certificate Computer Science, in Ireland: Considerations for teacher education. *Computers & Education*, 174, 104291. <https://doi.org/10.1016/j.compedu.2021.104291>
- Singh, A. (2025). Revisiting challenges and issues in ICT integration in science education: A qualitative study. *IOSR Journal of Research & Method in Education*, 30(7), 54–62. <https://doi.org/10.9790/0837-3007035462>
- Subhananto, A., & Ibrahim, R. (2026). The implementation of digital media in integrated learning in schools: A systematic literature review from 2020 to 2025. *Jurnal Ilmiah Mandala Education*, 12(1), 193–206. <https://doi.org/10.58258/jime.v12i1.10173>



- Wu, H.-L., & Pedersen, S. (2011). Integrating computer- and teacher-based scaffolds in science inquiry. *Computers & Education*, 57(4), 2352–2363. <https://doi.org/10.1016/j.compedu.2011.05.011>
- Zan, A. M., Asrizal, Amnah, R., Helma, & Hidayati. (2023). Effects of digital science teaching materials on conceptual understanding and 21st century skills: A meta-analysis. *Jurnal Penelitian Pendidikan IPA*, 9(12), 1306–1315. <https://doi.org/10.29303/jppipa.v9i12.5536>
- Zandri, S. W., Arnelis, Suherman, Harisman, Y., & Yerizon. (2025). Innovative digital pedagogies in mathematics and science learning. *Jurnal Penelitian Pendidikan IPA*, 11(5), 68–72. <https://doi.org/10.29303/jppipa.v11i5.11390>
- Zendler, A., & Klein, K. (2018). The effect of direct instruction and web quest on learning outcome in computer science education. *Education and Information Technologies*, 23(6), 2765–2782. <https://doi.org/10.1007/s10639-018-9740-4>
- Zendler, A., & Reile, S. (2018). The effect of reciprocal teaching and programmed instruction on learning outcome in computer science education. *Studies in Educational Evaluation*, 58, 132–144. <https://doi.org/10.1016/j.stueduc.2018.05.008>
- Zimmerman, H. T., Land, S. M., Maggiore, C., & Millet, C. (2019). Supporting children's outdoor science learning with mobile computers: Integrating learning on-the-move strategies with context-sensitive computing. *Learning, Media and Technology*, 44(4), 457–472. <https://doi.org/10.1080/17439884.2019.1667823>
- Zulfiani, Z., Suwarna, I. P., Zaky, R. A., Islami, E., & Sari, I. J. (2025). Trends in SAMR research in teaching and learning from 2019 to 2024: A systematic review. *International Journal of Advanced and Applied Sciences*, 12(4), 99–106.