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# Integrating AI with Constructivist Pedagogy for Science Education in Marginalized Regions: A Systematic Review

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**ABSTRACT**

Enhancing 21st-century competencies in frontier, remote, and disadvantaged (3T) regions remains challenging due to limited infrastructure, restricted digital access, and the need for culturally relevant science learning. This study employs a systematic literature review of selected peer-reviewed studies published between 2011 and 2025 to examine how constructivist-based science learning integrated with digital technology and artificial intelligence (AI) can support equitable education in low-resource contexts. The findings indicate that effective technology-enhanced learning in 3T regions is pedagogy-driven rather than technology-driven, grounded in the integration of constructivism, progressivism, and social reconstructionism. AI, learning management systems, and interactive digital media can support personalized learning, formative assessment, and the development of scientific literacy, numeracy, and digital literacy when embedded within adaptive instructional frameworks. However, the literature also reveals significant feasibility constraints related to digital access, teacher readiness, and ethical considerations. Therefore, context-aware, low-bandwidth, and teacher-mediated digital solutions are essential to ensure equitable and sustainable science learning in 3T regions.



## INTRODUCTION

Current global developments demand education to play a strategic role in preparing human resources who are adaptive, creative, and globally competitive. The 21st-century learning paradigm emphasizes fundamental literacies, higher-order thinking, creativity, communication, collaboration, character development, and digital literacy as key competencies for Indonesian learners. National policies, including the National Education Standards and Graduate Competency Standards, highlight problem-solving, technological literacy, and scientific thinking as essential skills for students (Ministry of Education, Culture, Research, and Technology, 2022).

Despite these efforts, literacy and numeracy achievements in Indonesia remain challenging. The 2022 PISA results indicate that students' reading, mathematics, and science performance has not reached the OECD average, with significant disparities between urban and remote regions (OECD, 2023). Variations in learning quality are particularly evident in frontier, remote, and disadvantaged (3T) regions, where limited resources and infrastructural constraints hinder student learning outcomes (BPS, 2023; Ministry of Education, Culture, Research, and Technology, 2023). Science learning is especially affected, as it requires experimentation, observation, and access to scientific resources. Students in 3T regions often face challenges such as limited laboratory facilities, inadequate digital media, restricted internet access, and low technological literacy, which hinder scientific literacy, numeracy, and process skills (Farhatin, 2025; Falah & Hadna, 2022; Fismariza & Ofianto, 2025).

Constructivist approaches offer a promising pathway for resource-limited settings, as they emphasize active, collaborative, and reflective learning while leveraging local context and student-centered activities. Studies show that models such as project-based learning (PjBL) and problem-based learning (PBL) enhance critical thinking, creativity, motivation, and scientific literacy (Amsal Alhayat et al., 2023; Nurhasnah et al., 2022; Sutaryani, 2024). Meanwhile, advances in digital technology and artificial intelligence (AI) provide opportunities to support personalized learning, automated feedback, and interactive resources (Zawacki-Richter et al., 2019; 2023). However, technology adoption in 3T regions faces constraints including limited infrastructure, low teacher readiness, and unequal access to devices (Thamrin, 2024; Raharjo, 2025).

Therefore, this systematic literature review seeks to answer: *What principles and strategies from constructivist learning theory, when integrated with AI and digital technology, are most viable and effective for developing 21st-century competencies in science education within 3T regions?* By synthesizing existing studies, this review aims to provide a preliminary framework for context-sensitive, AI-enhanced, constructivist science learning, offering theoretical guidance and practical insights for schools, policymakers, and curriculum developers in marginalized and resource-limited regions.

## METHOD

This study employed a systematic literature review to synthesize current knowledge on constructivist-based science learning integrated with artificial intelligence (AI) and digital technology to enhance 21st-century competencies in frontier, remote, and disadvantaged (3T) regions. The review focused on three key areas: (1) constructivist learning theory in science education, (2) the application of AI and educational technology, and (3) strategies for developing 21st-century skills in low-resource contexts.

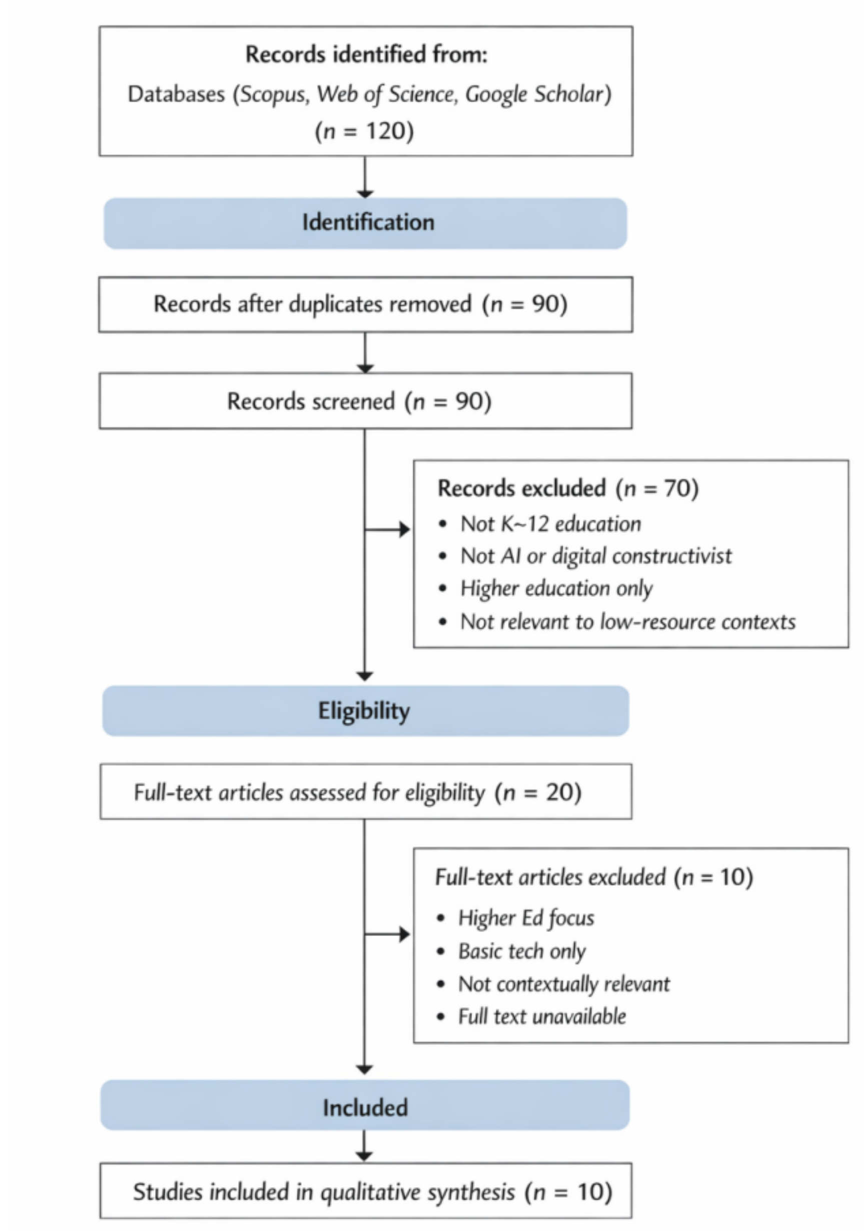
### Search Strategy

A comprehensive literature search was conducted in Scopus, Web of Science, and Google Scholar for publications published between 2011 and 2025. Keywords and Boolean operators included: ("constructivist" OR "project-based learning" OR "problem-based learning") AND ("artificial intelligence" OR "AI" OR "educational technology") AND ("remote area" OR "disadvantaged" OR "3T") AND ("science education").

A PRISMA 2020 guided screening process was applied. Records were identified, screened for duplicates and relevance, assessed for eligibility, and 10 studies met all inclusion criteria and were included in the final systematic review. Additional relevant literature was used to support the theoretical and contextual discussion but was not treated as primary units of systematic analysis.

The study selection process followed the PRISMA 2020 guidelines, including identification, screening, eligibility assessment, and inclusion. The detailed screening process is presented in Figure 1.

**Figure 1.** *PRISMA 2020 Flow Diagram of Study Selection*




## Inclusion and Exclusion Criteria

Inclusion criteria were: (1) empirical or conceptual studies published between 2015 and 2024; (2) a focus on K–12 science education; (3) explicit discussion of constructivist pedagogy integrated with AI or digital technology; and (4) studies conducted in underserved or low-resource educational settings, including 3T regions.

Exclusion criteria included: (1) studies not published in English or Indonesian; (2) research focused exclusively on higher education; (3) studies limited to basic ICT use without personalization or adaptive features; and (4) articles without full-text access.

### Data Analysis

All included studies were analyzed using thematic analysis and comparative synthesis. The analysis involved open coding of key concepts from each study, followed by grouping codes into preliminary themes such as AI-supported personalization, contextualized content design, and collaborative learning. Themes were iteratively compared across studies to identify recurring patterns, conceptual relationships, and tensions. The synthesized findings were then integrated into a conceptual framework for AI-enhanced, constructivist science learning in 3T school contexts, emphasizing the development of critical thinking, creativity, communication, and collaboration as core 21st-century competencies.

### Limitations

As a conceptual systematic review, this study does not empirically test the proposed framework. In addition, the findings are constrained by the limited availability of empirical studies explicitly conducted in marginalized or remote 3T contexts, particularly those examining AI-supported constructivist learning. Future research is therefore recommended to conduct implementation-based and evaluative studies to examine the practical feasibility and effectiveness of the proposed framework in real classroom settings.

## RESULT AND DISCUSSION

### Results

Following the PRISMA-guided screening process, 10 studies were included in the final systematic review from an initial pool of 120 records identified through Scopus, Web of Science, and Google Scholar. The selected studies consist of empirical research (n = 6) and review or conceptual studies (n = 4) that explicitly address constructivist-based science learning integrated with artificial intelligence (AI) or digital technology in underserved or low-resource contexts, including 3T regions in Indonesia and comparable settings globally.

These studies represent a range of methodological approaches, including qualitative case studies, mixed-methods research, policy analyses, and systematic or narrative reviews, reflecting the interdisciplinary nature of research on technology-enhanced learning and educational equity. Table 1 presents a summary of the included studies, detailing their contextual setting, study type, methodology, technology focus, and key findings related to constructivist learning principles and issues of access and equity.

**Table 1.** *Summary of Included Studies in the Systematic Literature Review*

| Author, Year | Context / Country | Study Type | Methodology | Technology Focus | Key Findings (Constructivism & Equity) |
|---|---|---|---|---|---|
| Farhatin (2025) | Indonesia (3T regions) | Empirical | Qualitative policy & field analysis | Digital learning platforms | Digital access gaps limit constructivist science learning and widen inequality |
| Falah & Hadna (2022) | Indonesia (3T regions) | Empirical | Mixed methods | Online learning technologies | Technology mitigates learning loss when contextually adapted |
| Fismariza & Ofianto (2025) | Indonesia (remote schools) | Empirical | Qualitative case study | Educational technology | Technology improves access with teacher mediation |
| Raharjo (2025) | Indonesia | Review | Narrative literature review | Artificial Intelligence | AI enables personalization but raises ethical and infrastructure challenges |
| Thamrin (2024) | Indonesia | Empirical | Qualitative policy analysis | Digital transformation initiatives | Equity-oriented digitization constrained by infrastructure gaps |
| Zawacki-Richter et al. (2019) | Global | Systematic Review | SLR | AI in education | AI research lacks pedagogical and equity focus |
| VanLehn (2011) | Global | Review | Meta-analysis | Intelligent Tutoring Systems | ITS supports constructivist learning when pedagogically guided |
| Redecker (2017) | Global / Europe | Conceptual | Framework analysis | DigCompEdu | Teacher digital competence is critical for equitable learning |
| OECD (2021a) | Global | Report | Comparative analysis | Educational technology | Digital divides persist across regions |
| OECD (2021b) | Global | Assessment report | Large-scale assessment | Digital-supported learning | Rural contexts show persistent science and numeracy gaps |

## Discussion

*Theoretical Foundation and Philosophical Orientation of Technology-Enhanced Science Learning*

The synthesis of the ten included studies indicates that the integration of AI and digital technology in science learning within 3T contexts is consistently framed through learner-centered and equity-oriented pedagogical perspectives. Empirical and review studies conducted in Indonesian 3T regions and comparable low-resource settings emphasize that technology functions most effectively when aligned with constructivist principles, where learners actively engage with content, collaborate, and connect learning to real-life contexts (Farhatin, 2025; Falah & Hadna, 2022; Fismariza & Ofianto, 2025).

Across the reviewed studies, progressivist and social reconstructionist orientations implicitly underpin discussions of technology use. Several studies highlight that digital learning initiatives in marginalized regions are not value-neutral; rather, they are closely tied to broader goals of reducing educational inequality and supporting social inclusion (Thamrin, 2024; OECD, 2021a). In this sense, technology-enhanced science learning is positioned as a potential instrument for social transformation, provided that access barriers and contextual constraints are explicitly addressed.

While AI-based personalization and intelligent tutoring systems are reported to enhance feedback quality and learner engagement (VanLehn, 2011; Raharjo, 2025), the literature also underscores significant tensions between pedagogical ideals and implementation realities. Limited infrastructure, uneven teacher readiness, and contextual mismatches frequently constrain the realization of constructivist learning environments in remote schools (Farhatin, 2025; Thamrin, 2024). This synthesis suggests that philosophical commitments to active learning and equity must be operationalized through context-sensitive instructional designs rather than technologically ambitious solutions.

*Learning Program Development in Low-Resource Contexts*

1. Learning Objectives and Competency Orientation

   The reviewed studies indicate that learning objectives in technology-enhanced science education for 3T regions increasingly emphasize higher-order thinking skills, scientific literacy, and digital competence rather than content mastery alone. Empirical findings show that when digital tools are used to support inquiry, problem-solving, and contextual exploration, students demonstrate improved engagement and conceptual understanding (Falah & Hadna, 2022; Fismariza & Ofianto, 2025).

These objectives align with broader competency-based education frameworks, particularly those emphasizing critical thinking, collaboration, and learner autonomy in marginalized contexts (OECD, 2021b). However, the studies caution that such objectives remain aspirational unless supported by realistic technological infrastructures and sustained teacher facilitation.

2. Learning Materials and Content Design

Analysis of the included studies reveals that effective learning materials in 3T contexts prioritize contextual relevance and modularity. Rather than relying on high-end digital simulations, several studies emphasize the importance of adaptable materials that combine text, visuals, and simple interactive elements compatible with low-bandwidth conditions (Farhatin, 2025; Thamrin, 2024).

While AI, LMS, and multimedia platforms are acknowledged as valuable supports for personalization and resource distribution (Raharjo, 2025; Redecker, 2017), the literature consistently highlights that their pedagogical impact depends on how well content reflects learners' local environments and experiences. This finding reinforces the centrality of constructivist content design over technological sophistication.

3. Technology-Supported Teaching Modules

The reviewed literature suggests that technology-based teaching modules in 3T regions function most effectively when designed as flexible ecosystems rather than fixed systems. LMS platforms are frequently identified as central hubs for communication and documentation, while AI tools provide supplementary support through adaptive feedback and learning analytics (Zawacki-Richter et al., 2019; Raharjo, 2025).

However, comparative evidence indicates that advanced technologies such as AR/VR remain largely experimental or aspirational in low-resource schools due to infrastructure constraints (OECD, 2021a). Consequently, the synthesis points to a pedagogical threshold in which simpler, teacher-mediated technologies yield more consistent benefits than fully automated or immersive systems.

4. Assessment Practices

Assessment-related findings across the ten studies emphasize formative, feedback-oriented approaches supported by digital platforms. LMS-based quizzes, reflective tasks, and project documentation are reported to enhance transparency and learner engagement when aligned with constructivist pedagogy (Falah & Hadna, 2022; Zawacki-Richter et al., 2019).

At the same time, equity concerns emerge in relation to digital assessment, particularly where access to devices and connectivity is uneven (Farhatin, 2025; OECD, 2021b). This highlights assessment not merely as a technical process but as an ethical practice that must be adapted to ensure fairness in marginalized learning environments.

*Feasibility, Ethics, and Access Inequality*

A dominant theme across the reviewed studies is the tension between the pedagogical promise of digital and AI-supported learning and its practical feasibility in 3T contexts. While AI-driven personalization and data-informed instruction are frequently advocated in the literature (Raharjo, 2025; Zawacki-Richter et al., 2019), multiple studies caution that unreliable electricity, limited internet connectivity, and scarce digital devices significantly restrict implementation (Farhatin, 2025; Thamrin, 2024).

From an ethical perspective, the synthesis indicates that technology adoption in marginalized regions carries the risk of reinforcing existing inequalities if access and digital literacy gaps are not explicitly addressed. Reports from OECD (2021a; 2021b) further confirm that rural and low-resource contexts consistently lag behind in benefiting from educational technology initiatives. As a result, the reviewed studies collectively argue for prioritizing pragmatic, low-bandwidth, and offline-capable solutions supported by strong teacher mediation.

*Policy Alignment and Systemic Implications*

The analysis of the ten studies suggests that national and international policy frameworks promoting digital transformation in education can only be effective in 3T regions when they are translated into pedagogically grounded and context-aware implementation strategies. Rather than viewing policy alignment as a guarantee of success, the literature highlights the need for coherence between policy goals, instructional design, and local feasibility conditions (OECD, 2021a; Redecker, 2017).

Overall, the findings reveal a consistent pattern: while constructivist and equity-oriented pedagogical principles strongly support the integration of digital technology and AI in science learning, their realization in 3T contexts depends less on advanced technological adoption and more on ethical, contextual, and realistically implementable designs. This synthesis underscores a critical shift in emphasis from technology-driven innovation toward pedagogy-driven, equity-conscious educational transformation.

## CONCLUSION

This systematic literature review contributes a synthesized conceptual framework that reframes the integration of digital technology and artificial intelligence (AI) in science learning for frontier, outermost, and disadvantaged (3T) regions as a pedagogy-driven rather than technology-driven endeavor. The review demonstrates that effective and equitable technology-enhanced science learning in low-resource contexts is consistently grounded in the philosophical integration of progressivism, constructivism, and social reconstructionism, which collectively emphasize active knowledge construction, contextual relevance, and social justice. This synthesis advances existing scholarship by showing that technological innovation alone is insufficient unless it is embedded within coherent pedagogical designs that are responsive to learners' sociocultural and environmental realities.

The findings further indicate that AI, learning management systems (LMS), and interactive digital media can support the development of scientific literacy, numeracy, digital literacy, and 21st-century competencies when implemented through adaptive instructional design frameworks such as ADDIE. However, the review also reveals substantial constraints that limit the direct transferability of advanced technology-based models to 3T contexts. The feasibility of the proposed framework depends critically on the availability of basic digital infrastructure, sustained teacher professional development, and contextually relevant, low-bandwidth, and offline-capable learning resources. In the absence of these enabling conditions, the literature consistently warns that technology integration may inadvertently reinforce existing educational inequalities rather than mitigate them.

At the policy and system level, this review provides insight into the relationship between national digital education initiatives and classroom-level implementation. The analysis suggests that the success of digital transformation policies particularly those promoting student-centered and technology-enhanced learning is contingent upon implementation strategies that are pedagogically grounded, ethically informed, and explicitly designed to address access disparities in marginalized regions. Educational equity in 3T areas, therefore, is less a function of technological sophistication and more a result of deliberate alignment between philosophical foundations, instructional design, and contextual feasibility.

Finally, this review identifies key directions for future research. There remains a pressing need for empirically grounded implementation studies that move beyond conceptual models to examine how low-tech, offline-first, and teacher-mediated AI-supported learning designs function in real 3T classroom settings. Further research is also required to identify the specific teacher competencies, institutional supports, and professional learning structures necessary to operationalize this integrated framework effectively. Comparative studies across varying levels of technological access in low-resource schools are particularly important to establish realistic thresholds of feasibility and educational impact. Addressing these gaps will be essential for translating the proposed conceptual framework into sustainable, ethical, and equitable science learning practices in 3T regions.

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