Integrative Trends in Future-Ready Education: STEM, ESD, and Artificial Intelligence in Jakarta's Primary Schools

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Abstrak

Di tengah dinamika global yang semakin kompleks, integrasi STEM (Sains, Teknologi, Teknik, dan Matematika), Pendidikan untuk Pembangunan Berkelanjutan (ESD), dan Kecerdasan Buatan (AI) dalam pendidikan dasar menjadi krusial. Penelitian campuran ini mengkaji penerapan ketiga pendekatan tersebut di sekolah dasar Jakarta melalui survei terhadap 50 guru dan wawancara mendalam dengan 5 pemimpin sekolah. Temuan menunjukkan bahwa meskipun kesadaran akan STEM, ESD, dan AI tergolong tinggi, implementasinya masih tidak merata, dengan hambatan seperti kurikulum yang kaku, kurangnya pelatihan guru, dan kesenjangan infrastruktur—terutama untuk AI. Studi ini juga mengidentifikasi praktik inovatif lokal yang muncul sebagai contoh keberhasilan. Implikasinya menekankan perlunya dukungan kebijakan sistematis, penguatan pedagogi, dan kolaborasi multidisiplin untuk mewujudkan pendidikan yang berkelanjutan dan siap menghadapi masa depan. Keterbatasan studi mencakup ukuran sampel yang kecil, yang memerlukan penelitian lanjutan untuk generalisasi yang lebih luas.

Kata kunci: Pendidikan STEM; Pendidikan untuk Pembangunan Berkelanjutan (ESD); Kecerdasan Buatan (AI); pendidikan dasar; integrasi kurikulum; pembelajaran interdisipliner; pengembangan guru; kesenjangan digital.

Abstract

Amid increasingly complex global dynamics, the integration of STEM (Science, Technology, Engineering, and Mathematics), Education for Sustainable Development (ESD), and Artificial Intelligence (AI) in primary education is crucial. This hybrid research study examines the implementation of these three approaches in Jakarta primary schools through a survey of 50 teachers and in-depth interviews with five school leaders. Findings indicate that while awareness of STEM, ESD, and AI is high, implementation remains uneven, with barriers such as a rigid curriculum, lack of teacher training, and infrastructure gaps—particularly for AI. The study also identifies emerging local innovative practices as examples of success. Implications emphasize the need for systematic policy support, strengthened pedagogy, and multidisciplinary collaboration to achieve sustainable and future-ready education. Limitations of the study include the small sample size, which requires further research for broader generalization

Keywords: STEM education; Education for Sustainable Development (ESD); Artificial Intelligence (AI); primary education; curriculum integration; interdisciplinary learning; teacher development; digital divide.

1. INTRODUCTION

In today's fast-changing world, education is expected to do more than just transmit knowledge. It must prepare learners to navigate uncertainty, solve complex problems, and contribute meaningfully to a sustainable future (Pettig & Ohl, 2023). As the demands of the twenty-first century continue to evolve, there is increasing pressure on educational systems to transform both in content and delivery. This transformation includes equipping students not only with strong foundations in science, technology, engineering, and mathematics (STEM), but also with the values and competencies related to sustainability, commonly framed under Education for Sustainable Development (ESD) (Setiawan et al., 2025). At the same time, the emergence of Artificial Intelligence (AI) is reshaping how education is delivered, accessed, and personalized across learning environments (Tapalova & Zhiyenbayeva, 2022).

The integration of STEM, ESD, and AI in educational contexts is seen as a strategic and necessary response to the complex challenges of our time. STEM education emphasizes critical thinking, innovation, and real-world problem-solving (Rachmadtullah et al., 2023), while ESD focuses on empowering students to become responsible global citizens with awareness of environmental, economic, and social sustainability (Windiyani et al., 2025). On the other hand, AI offers technological affordances that can support personalized learning, streamline assessment, and provide intelligent support for both students and teachers (Alam & Mohanty, 2023). When these three domains are combined thoughtfully, they have the potential to create more dynamic, relevant, and future-ready learning ecosystems.

Recent studies show promising developments in each of these domains. Xu and Ouyang (2022) provide a systematic review of AI applications in STEM education, highlighting the roles of intelligent tutoring systems, learning analytics, and adaptive feedback tools in enhancing learning outcomes. Similarly, research by Habibaturrohmah et al. (2023) and Fathurrohman et al. (2023) demonstrates how the integration of STEM with sustainability-oriented content can improve students' critical thinking, environmental literacy, and collaborative skills. The role of AI in supporting sustainability education is also gaining attention, with researchers exploring how machine learning and adaptive systems can foster more equitable and accessible learning environments (Akhmetova et al., 2025; Strielkowski et al., 2025).

However, despite the growing body of literature on these topics, most studies still treat these three areas in isolation. Research on AI in education tends to focus narrowly on algorithmic efficiency or technological design (Bulathwela et al., 2024), while studies on STEM and ESD often overlook how emerging technologies can amplify or complicate their implementation (Hung & Pan, 2025). There is a lack of empirical work that examines how STEM, ESD, and AI are being adopted in an integrated and meaningful way within actual educational practice. Moreover, while policy documents often advocate for transformative and interdisciplinary learning, practical integration at the classroom level remains inconsistent and poorly understood.

This gap in the literature points to an urgent need for comprehensive investigation. Specifically, there is limited understanding of how far and in what ways STEM, ESD, and AI are being applied together in educational settings. Without such understanding, efforts to innovate in education risk being fragmented, inequitable, or misaligned with the real needs of learners and educators. Therefore, this study aims to explore the extent of integration of STEM, ESD, and AI in educational practice. The objectives are to identify how these approaches are being implemented, to examine the depth and coherence of their integration, and to analyze the challenges and enabling factors that influence their adoption. By doing so, this research seeks to contribute empirical insights that can inform policy and practice in shaping a more holistic, inclusive, and future-oriented education system.

2. LITERATURE REVIEW

2.1. STEM Education in Contemporary Curricula

STEM education represents an interdisciplinary approach that merges science, technology, engineering, and mathematics into cohesive learning experiences. It aims not only to develop content knowledge but also to nurture 21st-century skills such as critical thinking, creativity, collaboration, and communication (Bybee, 2013; Kelley & Knowles, 2016).

Recent studies underscore that many educational systems have begun integrating STEM into formal and informal learning environments. In the United States, for instance, the "Next Generation Science Standards" (NGSS) emphasize engineering practices alongside scientific inquiry, encouraging the shift toward transdisciplinary learning (NGSS Lead States, 2013). Similar efforts are seen in Europe and Asia through project-based learning models and national STEM strategies (Marginson et al., 2013; Özçakır Sümen & Çalışıcı, 2022).

Despite the growing interest, the implementation of STEM education remains uneven. Research by Schweingruber et al. (2014) points out that while some schools adopt integrated STEM curricula, others treat it as separate subject enrichment. Key challenges include limited teacher training in interdisciplinary pedagogy (Roehrig et al., 2021), lack of instructional resources, and assessment systems that are not aligned with integrated learning outcomes (Le et al., 2023). Moreover, gender disparity and socio-economic factors continue to influence participation in STEM fields, raising concerns about equity and inclusivity (EL-Deghaidy et al., 2025).

Consequently, although STEM is widely promoted, its operationalization requires deeper structural and pedagogical shifts. There is also a growing recognition of the need to link STEM with real-world challenges—such as sustainability and ethical technology use—which leads to discussions about integrating it with other educational trends such as ESD and AI.

2.2. ESD: Education for Sustainable Development

Education for Sustainable Development (ESD) is a framework that equips learners with values, competencies, and skills to address global environmental, economic, and social challenges. Rooted in the Decade of Education for Sustainable Development (2005–2014), ESD has been embedded into the United Nations' 2030 Agenda for Sustainable Development, particularly in SDG 4.7, which calls for education that promotes sustainable lifestyles, human rights, and global citizenship (United Nations Educational, 2017).

ESD has evolved from a purely environmental focus to a broader transdisciplinary approach that connects science, ethics, culture, and civic engagement. Leicht et al. (2018) assert that ESD emphasizes transformative learning by encouraging critical reflection, systems thinking, and participatory problem-solving. Despite policy-level advocacy, the practical implementation of ESD faces significant hurdles. In many educational settings, ESD is taught as discrete modules or extracurricular projects, lacking full curricular integration (Balsiger et al., 2017). Teachers often report a lack of training, assessment tools, and institutional support to adopt ESD pedagogies effectively (Lohmann et al., 2021). Additionally, balancing ESD's normative goals with existing content-heavy curricula presents further tension (Evans et al., 2017).

Nevertheless, promising practices are emerging. Whole-school approaches, where sustainability is embedded into school culture and operations, show potential for systemic change (Mogren et al., 2019). Furthermore, connecting ESD with digital technology and innovation opens new pathways for engagement and scalability.

2.3. Artificial Intelligence in Educational Practice

Artificial Intelligence (AI) is rapidly transforming the educational landscape by enabling more personalized, adaptive, and efficient learning processes. AI tools in education are being utilized for a variety of functions, such as intelligent tutoring systems (ITS), learning analytics, automated feedback, natural language processing, and curriculum recommendation engines (Zawacki-Richter et al., 2019). One of the most prominent applications is adaptive learning, where AI algorithms adjust content delivery based on learner performance and preferences. Systems like Carnegie Learning and Squirrel AI are being adopted to support differentiated instruction, especially in mathematics and language learning (Holmes et al., 2019). In addition, AI-powered assessment tools can provide real-time feedback, help detect learning difficulties, and reduce teacher workload.

However, the integration of AI is not without concern. A growing body of literature has pointed out ethical, privacy, and accountability challenges in AI adoption (Luckin, 2018; Williamson et al., 2020) . The use of AI in classrooms also raises questions about the role of human educators, student data governance, and the risk of algorithmic bias. Moreover, there is a digital divide in access to AI tools, particularly in low-resource educational contexts. Another critical issue is pedagogical alignment. Studies argue that the effectiveness of AI depends on its alignment with human-centered learning theories (Roll & Wylie, 2016). When AI is treated merely as a technical add-on rather than a pedagogical partner, its impact becomes limited. Therefore, meaningful integration of AI requires not only technical infrastructure but also teacher digital literacy, ethical oversight, and instructional redesign.

3. METHOD

3.1. Research Design

This study employed a mixed-methods approach, combining quantitative survey data with qualitative interviews and document analysis to examine the extent to which STEM, ESD, and AI are integrated in educational settings. The rationale for this approach lies in its ability to capture both the breadth and depth of application, allowing for triangulation of results (Creswell & Creswell, 2017).

3.2. Participants and Sampling

The study targeted educators and school administrators across primary education in Jakarta. A *purposive sampling* technique was used to select participants from institutions that have declared initiatives or programs aligned with STEM, ESD, or AI education. A total of 50 respondents completed the online questionnaire, and 5 participants were selected for in-depth interviews based on their leadership roles or program involvement.

3.3. Instruments

The primary instrument for the quantitative phase was a structured questionnaire consisting of Likert-scale items (1 to 5) assessing the perceived frequency, depth, and contextual integration of STEM, ESD, and AI in teaching practices. The questionnaire was validated by three educational experts and yielded a Cronbach's alpha of 0.87, indicating high internal consistency.

For the qualitative phase, a semi-structured interview guide was developed to explore deeper insights into institutional strategies, perceived challenges, and innovation drivers related to STEM, ESD, and AI. Questions were aligned with themes identified in the literature.

3.4. Data Collection Procedures

Data collection occurred in June 2025. Surveys were distributed via institutional mailing lists and educational networks to reach a broad base of participants across various school settings. Interviews were conducted online and audio-recorded with participant consent, allowing for in-depth exploration of individual and institutional perspectives on STEM, ESD, and AI integration. To complement the primary data, one round of on-site observation was conducted at a selected primary school. This visit provided contextual insights into the actual teaching environment, classroom practices, and infrastructural conditions—especially those related to digital and environmental education facilities. Observational field notes were used to triangulate findings from the survey and interviews. In addition, relevant policy documents, institutional reports, and curriculum plans were collected and analyzed. This document analysis enabled a more holistic understanding of how STEM, ESD, and AI are formally positioned within institutional mandates and national education strategies.

3.5. Data Analysis

Quantitative data were analyzed using descriptive statistics and cross-tabulation. Mean scores and frequency distributions were computed to identify patterns in the implementation of STEM, ESD, and AI. Qualitative data from interviews and documents were analyzed through thematic analysis, following the Braun and Clarke (2006) framework. Coding was performed inductively, with emerging themes mapped to the research objectives. Inter-coder reliability was ensured through peer debriefing and reflexive memoing.

4. RESULT AND DISCUSSION

4.1. Quantitative Findings

The quantitative findings from the survey of 50 elementary school teachers in Jakarta offer valuable insights into the current state of STEM, ESD, and AI integration in primary education. The data suggest that while awareness of these educational paradigms is relatively high, their practical implementation remains limited and inconsistent across schools.

Table 1. Survey results on STEM, ESD, and AI implementation (N = 50)

Indicator	STEM	ESD	AI
% Respondents who have heard of the concept	94%	82%	76%
% Respondents who have applied the concept	58%	44%	26%
Frequency of integration (Mean, 1–5 scale)	3.14	2.71	2.39
Depth of application (Mean, 1–5 scale)	2.95	2.56	2.30
Contextual relevance (Mean, 1–5 scale)	2.93	2.79	2.59
Overall integration score (Mean)	**3.01**	**2.69**	**2.43**

As shown in Table 1, the majority of respondents reported having heard of STEM (94%), followed by ESD (82%) and AI (76%). However, this familiarity did not necessarily translate into practice. Only 58% of teachers claimed to have applied STEM in their teaching, while the numbers were significantly lower for ESD (44%) and AI (26%). These figures reflect a noticeable gap between conceptual awareness and practical application, indicating a need for more systemic and targeted professional development programs.

In terms of frequency of integration, STEM scored the highest with a mean of 3.14 on a 5-point Likert scale, followed by ESD (2.71) and AI (2.39). Similarly, the depth of application mirrored this trend, with STEM scoring 2.95, ESD 2.56, and AI trailing at 2.30. Contextual relevance—the degree to which these frameworks were embedded within real-world and local educational contexts—was also highest for STEM (2.93), suggesting that science and math-related content is more easily adapted into classroom activities than sustainability topics or AI concepts.

The overall integration score, which averages frequency, depth, and contextual relevance, further reinforces this pattern. STEM education, while still not fully embedded, shows relatively higher implementation (M = 3.01) than ESD (M = 2.69) and AI (M = 2.43). These results indicate that although efforts are being made to integrate these frameworks, particularly STEM, their application remains modest and largely fragmented.

4.2. Qualitative Insights

To complement the quantitative findings, semi-structured interviews were conducted with five educational leaders from primary schools in the Jakarta area, including two principals, two curriculum coordinators, and one education supervisor. The interviews aimed to explore participants' perceptions, challenges, and strategies related to the integration of STEM, ESD, and AI in their institutional contexts.

Overall, respondents demonstrated a high level of awareness regarding the growing importance of integrative educational trends, particularly STEM and ESD. However, the implementation landscape remains fragmented and hindered by systemic and contextual challenges.

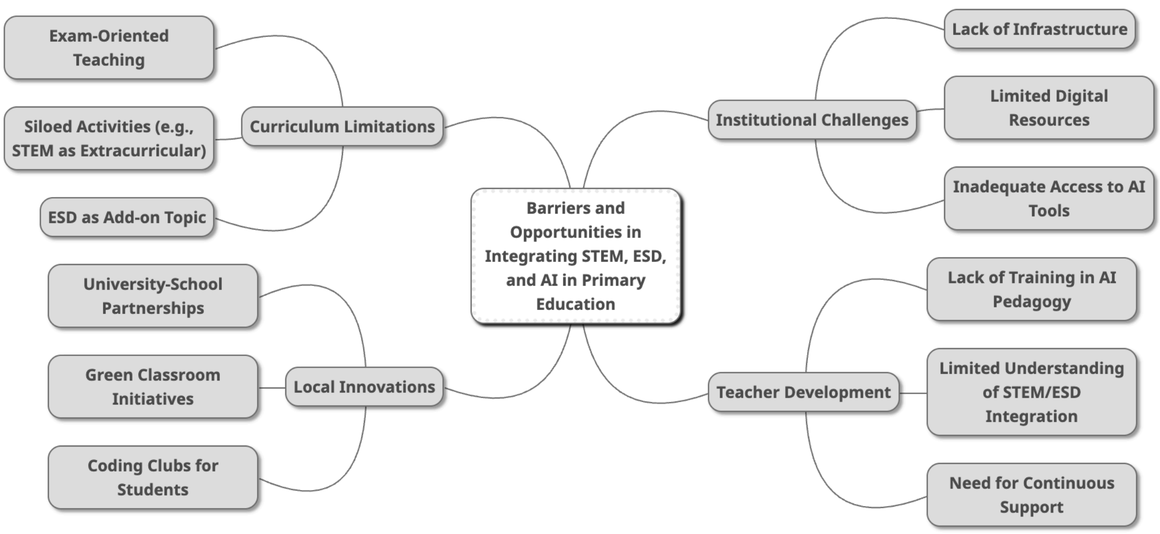

Figure 1. Thematic map of perceived barriers and opportunities in integrating STEM, ESD, and AI in primary education

4.2.1. Institutional Readiness and Capacity Gaps

A major theme emerging across all interviews was the limited institutional readiness to adopt and scale STEM, ESD, and particularly AI-related content. Participants consistently referred to a lack of technological infrastructure, insufficient teacher capacity, and inaccessibility to instructional resources as major constraints. These challenges were especially pronounced in the context of AI, where participants admitted a clear knowledge and technology gap.

"We recognize the importance of AI, but we are not yet equipped with the tools or knowledge to embed it meaningfully into our lessons." — Participant 3

This theme reflects a systemic issue that goes beyond a single innovation. Even for STEM and ESD—which are relatively more familiar—educators often lack the tools, training, and support needed to integrate these concepts in a way that is sustained and pedagogically coherent. The findings suggest that institutional gaps in capacity—spanning human, material, and technical domains—pose a fundamental barrier to innovation.

4.2.2. Curriculum Rigidity and Limited Flexibility

Another consistent issue raised by participants was the inflexibility of the existing national curriculum, which remains highly exam-oriented and fragmented. This rigidity hinders the integration of interdisciplinary and cross-cutting themes such as sustainability, computational thinking, and real-world problem-solving.

"Our curriculum is so tightly packed and exam-driven that there's little room for new approaches. We do have science clubs and competitions, but those are not really part of classroom teaching." — Participant 1

Most participants shared that ESD is often treated as a supplementary or extracurricular theme, delivered through isolated events such as environmental campaigns or thematic weeks. Similarly, while some schools had initiated STEM activities (e.g., robotics clubs or science fairs), these remained peripheral, and not embedded into the daily instructional core. The absence of systemic alignment between curriculum content and innovation goals significantly undermines the long-term potential of integration.

4.2.3. Teacher Professional Development Needs

The third theme underscores the urgent demand for structured and context-relevant professional development programs. Participants highlighted that teachers often lack not only content knowledge in STEM, ESD, or AI—but also the pedagogical frameworks needed to teach them effectively.

"Even if teachers have heard about STEM or ESD, they don't really know how to teach it, or how it fits with what they already have to cover." — Participant 4

Several participants emphasized that current training opportunities are either generic or optional, and rarely address the practical integration of emerging topics. There was a strong call for ongoing, scaffolded training, ideally delivered in collaboration with universities or educational technology providers. Without intentional upskilling, teachers may remain passive recipients of policy, unable to translate high-level goals into classroom reality.

4.2.4. Emerging Good Practices and Localized Innovation

Despite the above challenges, all participants cited examples of grassroots-level innovations and local partnerships that show promise. One school had collaborated with a nearby university to host weekend coding sessions for students, while another had implemented a "green classroom" initiative that incorporated ESD themes into daily routines, such as recycling, school gardening, and sustainable behavior.

"We may not have a full AI program, but through partnerships we've been able to expose our students to basic coding and problem-solving." — Participant 5

These examples demonstrate that innovation is possible, especially when school leaders are proactive and when support from external stakeholders exists. However, these practices remain isolated, often dependent on individual leadership and localized conditions, and lack the structural support needed for wider replication or scaling.

4.3. Document Analysis

A comprehensive document analysis was conducted on a selection of national and institutional policy documents, curriculum frameworks, school development plans, and annual reports from the participating educational institutions. This analysis aimed to triangulate data obtained from surveys and interviews, offering an additional layer of evidence regarding the degree to which STEM, ESD, and AI are conceptually and operationally embedded in the education system.

The analysis revealed that STEM and sustainability education (ESD) were frequently mentioned in institutional vision and mission statements, particularly in references to fostering "future-ready learners," "21st-century competencies," or "environmental stewardship." However, these references were largely aspirational in nature, lacking in concrete implementation strategies, action plans, or assessment metrics. For instance, one school's strategic plan included a goal to "enhance students' science and technology competencies," but no accompanying curriculum map or pedagogical framework was found to support this objective.

Regarding Education for Sustainable Development (ESD), themes such as climate change, community engagement, and responsible consumption were often included under "cross-cutting issues" in curriculum documents. Yet, their treatment tended to be superficial, commonly appearing as supplementary modules rather than as core elements embedded across subjects. Only a few documents provided examples of interdisciplinary projects or project-based learning approaches aligning with ESD principles.

The integration of Artificial Intelligence (AI) was the least developed among the three domains. Mentions of AI were sparse and predominantly framed as future goals or aspirations, rather than part of ongoing or planned instructional practice. In several policy documents, AI appeared in general terms, such as "preparing students for the digital economy" or "embracing emerging technologies," without specifying how AI literacy would be cultivated among students or teachers. No clear pedagogical guidelines or resource allocation frameworks for AI-related education were identified.

Furthermore, there was a noticeable disconnect between strategic documentation and classroom practice. While the documents indicated a vision aligned with global education trends, they often lacked concrete steps for professional development, curriculum integration, or monitoring mechanisms necessary for sustainable and system-wide implementation of STEM, ESD, and AI initiatives.

4.4. Discussion

This study aimed to investigate the current extent of integration of STEM, ESD, and AI within primary education contexts in Jakarta. The findings from the mixed-methods approach provide a convergent narrative: while the conceptual importance of these educational innovations is widely acknowledged, their actual implementation remains fragmented, superficial, and contextually inconsistent. This section discusses these findings in relation to existing literature and offers implications for policy, practice, and future research.

4.4.1. Discrepancy Between Awareness and Practice

One of the most prominent findings is the gap between teachers' awareness and practical application of STEM, ESD, and AI. Although a majority of respondents reported familiarity with these frameworks—particularly STEM (94%) and ESD (82%)—the percentage of those who had applied them in practice was significantly lower, especially for AI (26%). This aligns with previous studies Kácovský et al. (2022) & Velander et al. (2024), which noted that without proper institutional and professional support, awareness alone does not translate into pedagogical change.

The overall integration scores (STEM = 3.01; ESD = 2.69; AI = 2.43) suggest that even when integration occurs, it is often surface-level. This is consistent with Larkin & Lowrie (2023), who found that educators tend to focus on content delivery without embedding the deeper values or competencies associated with these approaches, such as sustainability thinking or ethical dimensions of AI.

4.4.2. Structural Barriers and Institutional Readiness

Interview data further revealed a set of systemic and structural challenges that inhibit deeper implementation. All five educational leaders cited institutional readiness—particularly infrastructure limitations and insufficient teacher preparation—as a primary barrier, echoing previous literature (Kulakoglu & Kondakci, 2023; UNESCO, 2020). These capacity gaps were most critical in relation to AI, where a lack of both technical tools and teacher confidence formed a major obstacle. Moreover, the analysis confirmed that top-down policy discourse is not matched by ground-level support. While documents frequently mentioned STEM and sustainability in aspirational terms, they lacked operational clarity. AI, in particular, was rarely featured in actionable terms. This disconnect is emblematic of what Hinrichs-Kinney et al. (2025) described as "implementation drift"—where strategic goals fail to translate into everyday teaching practice due to lack of systemic alignment.

4.4.3. Curriculum Rigidity and Missed Opportunities

The rigidity of the national curriculum also emerged as a significant constraint. Teachers and administrators expressed frustration at the exam-oriented and siloed nature of the curriculum, which limits opportunities for interdisciplinary and project-based learning—critical components of both STEM and ESD (Daugherty & Sahin-Topalcengiz, 2023; Lee & Lee, 2025). Although some schools attempted to introduce innovation through extracurriculars (e.g., robotics clubs, environmental campaigns), these remained peripheral and unsustainable. This finding is particularly concerning given that Gericke & Karaarslan-Semiz (2022) emphasizes the need for whole-school approaches in implementing ESD and digital literacy. When sustainability or AI is treated as an "add-on" rather than an integrated component, its educational impact is likely to be diminished. These results suggest a need to reconceptualize curriculum design, allowing for greater flexibility and cross-subject integration.

4.4.4. The Role of Teacher Professional Development

Another recurring theme was the lack of professional development tailored to integrative pedagogies. While teachers may have heard of STEM or ESD, they often lack the pedagogical strategies to implement them meaningfully. This mirrors global trends reported in OECD (OECD, 2020), where teachers express high demand for ongoing, practice-based training rather than one-off workshops. Notably, the need is not only for technical skills (e.g., coding for AI) but also for pedagogical imagination—the ability to design learning experiences that connect STEM and ESD with real-world contexts and student agency. Structured, collaborative professional development—possibly through university-school partnerships—emerges as a critical enabler.

4.4.5. Islands of Innovation and the Promise of Localized Practices

Despite the prevailing barriers, the study also uncovered examples of promising localized innovation. Initiatives such as weekend coding workshops, green classrooms, and school-university collaborations highlight the potential for grassroots change. However, these remain isolated "islands of innovation," often reliant on individual leadership or external support. Without a system-wide support framework, such practices are unlikely to scale or sustain in the long term. This suggests that policymakers must intentionally create enabling conditions—through funding, networking platforms, and capacity-building programs—that can help diffuse these innovations more widely (Bloom, 2010).

5. CONCLUSION

This study set out to examine the extent to which integrative educational frameworks—namely STEM, Education for Sustainable Development (ESD), and Artificial Intelligence (AI)—have been adopted in primary education settings in Jakarta. Employing a mixed-methods approach, the findings revealed a clear and consistent pattern: while the conceptual awareness of these frameworks is relatively widespread among educators and school leaders, their actual implementation remains limited, uneven, and frequently disconnected from broader curricular and policy structures.

Quantitative survey data demonstrated that although the majority of respondents had heard of STEM (94%), ESD (82%), and AI (76%), the proportion who had applied these concepts in classroom practice was markedly lower—particularly for AI, at only 26%. Integration, when it occurred, was generally shallow, with modest scores for frequency, depth, and contextual relevance. STEM emerged as the most advanced of the three in terms of application, albeit still falling short of a fully embedded pedagogical shift. ESD and AI, meanwhile, were typically addressed through peripheral or isolated efforts rather than as core instructional components.

Qualitative findings from interviews with educational leaders deepened these insights, highlighting four critical themes: (1) institutional readiness and capacity gaps, (2) curriculum rigidity and limited flexibility, (3) insufficient teacher professional development, and (4) promising yet isolated innovations at the local level. Participants emphasized systemic barriers such as outdated infrastructure, lack of pedagogical training, and the inflexible, exam-driven curriculum that hampers interdisciplinary teaching. While examples of good practices—such as university partnerships and sustainability programs—were shared, these remained unsystematic and highly context-dependent.

The document analysis further confirmed that although STEM and ESD were commonly referenced in school mission statements and strategic documents, they were seldom accompanied by actionable implementation plans. AI, in particular, appeared more as a future aspiration than a current reality. This disconnect between institutional vision and operational practice reflects a broader issue of "implementation drift," where policy aspirations fail to reach classroom enactment due to gaps in leadership, support, and structural alignment.

Taken together, the findings of this study suggest an urgent need for systemic reform that bridges the divide between conceptual endorsement and practical integration. Key recommendations include revising national curricula to allow for greater interdisciplinary and project-based learning, designing sustained professional development programs focused on integrative pedagogies, and establishing institutional mechanisms that can scale successful localized innovations. Without such structural and pedagogical reconfigurations, the promise of STEM, ESD, and AI as transformative educational frameworks may remain unrealized—limited to symbolic references rather than substantive change.

Future research should explore longitudinal impacts of integrative approaches and investigate how school systems in varying socio-economic contexts adapt and scale innovations in STEM, ESD, and AI. Comparative studies across regions or countries could also offer valuable insights into policy frameworks and implementation strategies that support more holistic educational transformation.

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7. REFERENCES

Akhmetova, A. I., Sovetkanova, D. M., Komekbayeva, L. K., Abdrakhmanov, A. E., Yessenuly, D., & Serikova, O. S. (2025). A systematic review of artificial intelligence in high school STEM education research. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(4), em2623. https://doi.org/10.29333/ejmste/16222

Alam, A., & Mohanty, A. (2023). Educational technology: Exploring the convergence of technology and pedagogy through mobility, interactivity, AI, and learning tools. *Cogent Engineering*, *10*(2), 2283282. https://doi.org/10.1080/23311916.2023.2283282

Balsiger, J., Förster, R., Mader, C., Nagel, U., Sironi, H., Wilhelm, S., & Zimmermann, A. B. (2017). Transformative learning and education for sustainable development. *GAIA-Ecological Perspectives for Science and Society*, *26*(4), 357–359. https://doi.org/10.14512/gaia.26.4.15

Bloom, B. S. (2010). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. Longman.

Bulathwela, S., Pérez-Ortiz, M., Holloway, C., Cukurova, M., & Shawe-Taylor, J. (2024). Artificial Intelligence Alone Will Not Democratise Education: On Educational Inequality, Techno-Solutionism and Inclusive Tools. *Sustainability*, *16*(2). https://doi.org/10.3390/su16020781

Bybee, R. (2013). The case for STEM education: Challenges and opportunities. *National Science Teachers Association*.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Daugherty, M., & Sahin-Topalcengiz, E. (2023). *21st century skills: Preparing students for the future*. 20–29.

EL-Deghaidy, H., Almasabi, Z., Elkholy, A., & Mansour, N. (2025). Mapping STEM Gender Disparities: A Scoping Review of the MENA Region. *Journal for STEM Education Research*. https://doi.org/10.1007/s41979-025-00149-0

Evans, N. (Snowy), Stevenson, R. B., Lasen, M., Ferreira, J.-A., & Davis, J. (2017). Approaches to embedding sustainability in teacher education: A synthesis of the literature. *Teaching and Teacher Education*, *63*, 405–417. https://doi.org/10.1016/j.tate.2017.01.013

Fathurohman, I., Amri, M. F., & Septiyanto, A. (2023). Integrating STEM based Education for Sustainable Development (ESD) to Promote Quality Education: A Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 1052–1059. https://doi.org/10.29303/jppipa.v9i11.4430

Gericke, N. (2022). Implementation of Education for Sustainable Development Through a Whole School Approach. In G. Karaarslan-Semiz (Ed.), *Education for Sustainable Development in Primary and Secondary*

Schools: Pedagogical and Practical Approaches for Teachers (pp. 153–166). Springer International Publishing. https://doi.org/10.1007/978-3-031-09112-4_11

Habibaturrohmah, Z., Kaniawati, I., Solihat, R., & Nirbayati, W. F. (2023). How to Integrate ESD (Education for Sustainable Development) into STEM Education?: A Systematic Literature Review. *Journal of Natural Science and Integration*, *6*(2), 270–282. http://dx.doi.org/10.24014/jnsi.v6i2.29913

Hinrichs-Kinney, L. A., Beisheim-Ryan, E. H., Butera, K. A., Braaten, M., Holtrop, J. S., & Stevens-Lapsley, J. E. (2025). Systematic development of an implementation strategy to promote high-intensity rehabilitation uptake in skilled nursing facilities. *PM&R*, *n/a*(n/a). https://doi.org/10.1002/pmrj.13389

Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education promises and implications for teaching and learning*. Center for Curriculum Redesign.

Hung, L.-C., & Pan, H.-J. (2025). Innovative Approach to ESD Integration into School-Based Curriculum Development Modules for Elementary Schools. *Sustainability*, *17*(4). https://doi.org/10.3390/su17041427

Kácovský, P., Jedličková, T., Kuba, R., Snětinová, M., Surynková, P., Vrhel, M., & Urválková, E. S. (2022). Lower secondary intended curricula of science subjects and mathematics: A comparison of the Czech Republic, Estonia, Poland and Slovenia. *Journal of Curriculum Studies*, *54*(3), 384–405. https://doi.org/10.1080/00220272.2021.1978557

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, *3*(1), 11. https://doi.org/10.1186/s40594-016-0046-z

Kulakoglu, B., & Kondakci, Y. (2023). STEM Education as a Concept Borrowing Issue: Perspectives of School Administrators in Turkey. *ECNU Review of Education*, *6*(1), 84–104. https://doi.org/10.1177/20965311221107390

Larkin, K., & Lowrie, T. (2023). Teaching Approaches for STEM Integration in Pre- and Primary School: A Systematic Qualitative Literature Review. *International Journal of Science and Mathematics Education*, *21*(1), 11–39. https://doi.org/10.1007/s10763-023-10362-1

Le, H. C., Nguyen, V. H., & Nguyen, T. L. (2023). Integrated STEM Approaches and Associated Outcomes of K-12 Student Learning: A Systematic Review. *Education Sciences*, *13*(3). https://doi.org/10.3390/educsci13030297

Lee, M. Y., & Lee, J. S. (2025). Project-Based Learning as a Catalyst for Integrated STEM Education. *Education Sciences*, *15*(7). https://doi.org/10.3390/educsci15070871

Leicht, A., & Heiss, J. (2018). *Issues and trends in education for sustainable development* (Vol. 5). UNESCO publishing.

Lohmann, J., Breithecker, J., Ohl, U., Gieß-Stüber, P., & Brandl-Bredenbeck, H. P. (2021). Teachers' Professional Action Competence in Education for Sustainable Development: A Systematic Review from the Perspective of Physical Education. *Sustainability*, *13*(23). https://doi.org/10.3390/su132313343

Luckin, R. (2018). *Machine Learning and Human Intelligence. The future of education for the 21st century*. UCL institute of education press.

Marginson, S., Tytler, R., Freeman, B., & Roberts, K. (2013). *STEM: country comparisons: International comparisons of science, technology, engineering and mathematics (STEM) education. Final report.*

Mogren, A., Gericke, N., & Scherp, H.-Å. (2019). Whole school approaches to education for sustainable development: A model that links to school improvement. *Environmental Education Research*, *25*(4), 508–531. https://doi.org/10.1080/13504622.2018.1455074

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. National Academies Press.

OECD. (2020). *Teachers and school leaders as valued professionals: OECD teaching and learning international survey (TALIS) 2018 results (Volume II)*. OECD Publishing.

Özçakır Sümen, Ö., & Çalışıcı, H. (2022). The effects of STEM activities applied in mathematics courses for elementary pre-service teachers in Turkey. *International Journal of Mathematical Education in Science and Technology*, *53*(12), 3352–3376. https://doi.org/10.1080/0020739X.2021.1944679

Pettig, F., & Ohl, U. (2023). Dealing with Uncertainty in a Transformative Education for Sustainability. In O. Muñiz Solari & G. Schrüfer (Eds.), *Understanding Sustainability with Pedagogical Practice: A Contribution from Geography Education* (pp. 29–40). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-2687-9_3

Rachmadtullah, R., Setiawan, B., Wasesa, A. J. A., & Wicaksono, J. W. (2023). The utilization of metaverse technology applications based on science, technology, engineering and mathematics (Meta-STEM) to improve critical thinking skills. *Journal of Education and E-Learning Research*, *10*(4), 778–784. Scopus. https://doi.org/10.20448/jeelr.v10i4.5203

Roehrig, G. H., Dare, E. A., Ring-Whalen, E., & Wieselmann, J. R. (2021). Understanding coherence and integration in integrated STEM curriculum. *International Journal of STEM Education*, *8*(1), 2. https://doi.org/10.1186/s40594-020-00259-8

Roll, I., & Wylie, R. (2016). Evolution and Revolution in Artificial Intelligence in Education. *International Journal of Artificial Intelligence in Education*, *26*(2), 582–599. https://doi.org/10.1007/s40593-016-0110-3

Schweingruber, H., Pearson, G., & Honey, M. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. National Academies Press.

Setiawan, B., Barokah, A., Hafifah, D. N., & Iasha, V. (2025). Enhancing Environmental Awareness through STEAM-Based Learning with ESD Principles in Elementary Education. *International Journal of Education and Learning Studies (IJELS)*, *1*(1), 1–12.

Strielkowski, W., Grebennikova, V., Lisovskiy, A., Rakhimova, G., & Vasileva, T. (2025). AI-driven adaptive learning for sustainable educational transformation. *Sustainable Development*, *33*(2), 1921–1947. https://doi.org/10.1002/sd.3221

Tapalova, O., & Zhiyenbayeva, N. (2022). Artificial intelligence in education: AIEd for personalised learning pathways. *Electronic Journal of E-Learning*, *20*(5), 639–653. https://doi.org/10.34190/ejel.20.5.2597

UNESCO. (2020). *Education for Sustainable Development: A Roadmap*.

United Nations Educational, S. and C. O. (UNESCO). (2017). *Education for sustainable development goals: Learning objectives*. UNESCO.

Velander, J., Taiye, M. A., Otero, N., & Milrad, M. (2024). Artificial Intelligence in K-12 Education: Eliciting and reflecting on Swedish teachers' understanding of AI and its implications for teaching & learning. *Education and Information Technologies*, *29*(4), 4085–4105. https://doi.org/10.1007/s10639-023-11990-4

Williamson, B., Eynon, R., & Potter, J. (2020). Pandemic politics, pedagogies and practices: Digital technologies and distance education during the coronavirus emergency. *Learning, Media and Technology*, *45*(2), 107–114. https://doi.org/10.1080/17439884.2020.1761641

Windiyani, T., Setiawan, B., Sofyan, D., Gani, R. A., & Iasha, V. (2025). *KURIKULUM CRT BERBASIS ESD: Teori dan Implementasinya di Sekolah Dasar*. PT. Pena Persada Kerta Utama.

Xu, W., & Ouyang, F. (2022). The application of AI technologies in STEM education: A systematic review from 2011 to 2021. *International Journal of STEM Education*, *9*(1), 59. https://doi.org/10.1186/s40594-022-00377-5

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – where are the educators? *International Journal of Educational Technology in Higher Education*, *16*(1), 39. https://doi.org/10.1186/s41239-019-0171-0