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Integrating Eco-Pedagogy and STEAM in Elementary Science: Mixed-Methods Evidence from Indonesian Schools

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Abstract. Despite growing recognition of integrated pedagogical approaches, limited empirical evidence exists regarding eco-pedagogy and science, technology, engineering, art and math (STEAM) implementation effectiveness in elementary science education, particularly concerning teacher capabilities and student learning impacts in developing contexts. This study investigated elementary teachers' planning and implementation performance of integrated eco-pedagogy and STEAM approaches and their effects on student learning outcomes. A convergent parallel mixed-methods design was employed across 27 elementary schools in West Java, Indonesia, involving 27 bachelor's degree teachers and 756 fifth-grade students selected through stratified purposive sampling to ensure urban-rural representation. Data collection utilized the Teacher Performance Assessment Rubric (TPAR) and Student Learning Outcome Test (SLOT) for quantitative measures, complemented by classroom observations and teacher interviews for qualitative insights. Quantitative analysis employed descriptive statistics, paired t-tests, and correlations, while qualitative data underwent Braun and Clarke's six-phase thematic analysis with inter-rater reliability $\kappa>0.84$. Findings revealed teachers demonstrated moderate planning capabilities ($M=3.2$) but superior implementation performance ($M=3.7$), indicating intuitive pedagogical competencies exceeding formal planning abilities. Student outcomes improved significantly across all domains, with overall achievement increasing 15.4 points ($d=1.25$) and environmental awareness showing the largest gains of 22.3 points ($d=1.58$). Professional development exposure emerged as the primary facilitating factor, while resource limitations affected 70% of teachers. Implications necessitate systematic teacher preparation emphasizing practice-based eco-pedagogical competencies and policy frameworks supporting innovative assessment methods. Recommendations include developing sustained professional development models with ongoing mentoring, establishing adequate resource allocation systems, and creating institutional support structures enabling comprehensive eco-pedagogy integration.

Keywords: eco-pedagogy; STEAM education; elementary science; teacher performance; student learning outcomes

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1. Introduction

The integration of eco-pedagogy and STEAM approaches in elementary science education represents a transformative shift toward holistic, interdisciplinary learning addressing environmental consciousness and 21st-century skills development. Indonesia's Kebijakan Merdeka Belajar (Independent Learning Policy) promotes contextual learning and innovative pedagogies, creating opportunities for eco-pedagogy and STEAM integration in elementary science education (Kemendikbudristek, 2019). Eco-pedagogy emphasizes interconnectedness between social justice, environmental sustainability, and educational practices, fostering critical consciousness through place-based learning experiences (Gadotti, 2023; Kahn, 2023; Sobel, 2023). Research demonstrates that eco-pedagogical approaches significantly enhance students' environmental literacy and critical thinking skills (Stevenson et al., 2024).

STEAM education extends traditional STEM by incorporating arts and design thinking, promoting interdisciplinary learning that mirrors real-world problem-solving (Land, 2022; Yakman, 2024). The integration of arts enhances creativity and student engagement (Bequette & Bequette, 2024), while STEAM approaches significantly improve student motivation, critical thinking, and academic achievement (Connor et al., 2024; Perignat & Katz-Buonincontro, 2024).

Despite growing recognition of these approaches, significant gaps exist in understanding their integrated implementation in elementary science education. Limited empirical evidence exists regarding integrated eco-pedagogy and STEAM implementation quality (Rusdi et al., 2024; Wulandari & Sholihin, 2024), teacher capabilities for integrated approaches (Suryani & Agung, 2020), and their combined impacts on student learning outcomes (Powers et al., 2024; Roehrig et al., 2024). These gaps are particularly pronounced in Indonesian contexts, where systematic investigation of integrated eco-pedagogy and STEAM implementation remains absent despite independent learning policy imperatives. No validated assessment instruments exist for evaluating integrated approaches in Indonesian elementary settings, while contextual factors facilitating implementation across Indonesia's diverse educational landscape remain unexplored.

This study addresses these gaps through a comprehensive mixed-methods investigation of integrated eco-pedagogy and STEAM implementation in West Java's elementary schools. The research develops an integrated framework explicating synergistic mechanisms through which these approaches enhance student learning, environmental consciousness, and interdisciplinary skills, while identifying competencies and contextual factors necessary for successful implementation. The study further provides empirical evidence regarding teacher performance and develops validated instruments for assessing integrated approaches. It informs independent learning policy implementation through evidence-based recommendations for teacher preparation and institutional support systems.

This study addresses four primary research questions: (RQ1) How do elementary teachers plan integrated eco-pedagogy and STEAM science lessons? (RQ2) What is the teacher's performance level in implementing these approaches? (RQ3) How do these approaches influence student learning outcomes? and (RQ4) What factors facilitate or hinder effective integration?

These research questions address identified gaps in empirical evidence, teacher performance assessment, and student learning impact measurement within Indonesia's independent learning policy context, generating both theoretical insights and practical guidance for scaling innovative approaches

2. Literature Review

Historical Context and Rationale for Integrated Pedagogy

Educational reform consistently points toward integrated approaches addressing complex, interconnected real-world problems. Educational philosophers such as Dewey (2023) advocated for curricula connected to students' lived experiences and community contexts. Interdisciplinary integration gained momentum driven by the need to equip students with skills for global challenges (Beane, 2023). STEM evolved into STEAM to foster creativity and design thinking (Yakman, 2024), while eco-pedagogy emerged, embedding critical dimensions rooted in social justice and ecological consciousness (Gadotti, 2023; Kahn, 2023). The rationale for integrating eco-pedagogy and STEAM stems from contemporary environmental crises facing Indonesia, including deforestation, marine pollution, and climate change impacts. Addressing these challenges demands a synthesis of scientific understanding, technological innovation, and creative communication—competencies that traditional instruction fails to develop cohesively (KLHK, 2020).

Eco-pedagogy provides the ethical imperative rooted in critical consciousness about environmental justice issues (Freire, 2022), while STEAM offers innovative tools and interdisciplinary methodologies for culturally relevant solutions. For Indonesian students, this integration involves investigating local environmental problems through scientific methods, technological monitoring, engineering solutions, artistic advocacy, and mathematical analysis. This integration aligns with Indonesia's independent learning policy, encouraging contextual, student-centered learning connecting academic content to local wisdom and community challenges (Kemendikbudristek, 2019).

Regional implementations across Southeast Asia provide valuable precedents. Singapore's integration of environmental education within STEM curricula showed significant improvements with effect sizes averaging 0.85 (Tan & Kim, 2021). Malaysia's STEAM programs developed 21st-century skills while maintaining cultural relevance through indigenous ecological knowledge (Ahmad & Rahman, 2020). Thailand's place-based initiatives connected local ecological wisdom with scientific understanding (Sriskandarajah et al., 2019).

Philosophical and Conceptual Synergy of Integration

The integration of eco-pedagogy and STEAM is rooted in pragmatism (Dewey, 2023) and constructivism (Piaget, 2023; Vygotsky, 2024). Pragmatism emphasizes knowledge acquisition through real-world problem engagement, while constructivism asserts that learners construct knowledge through environmental and social interactions, making authentic interdisciplinary experiences essential for meaningful learning. The conceptual synergy operates through three mechanisms: cognitive integration, where environmental challenges provide contexts for STEAM knowledge application; affective integration, where emotional connections enhance motivation for learning; and behavioral integration, where STEAM skills enable environmental action, creating feedback loops reinforcing both consciousness and competencies while aligning with Indonesian values of gotong royong (cooperation) and tanggung jawab (accountability).

Indonesian Context and Merdeka Belajar (Independent Learning) Policy Framework

Indonesia's independent learning (merdeka belajar) policy represents a paradigmatic shift toward student-centered, contextual learning, aligning with integrated eco-pedagogy and STEAM principles (Kemendikbudristek, 2019). The policy emphasizes local wisdom integration and authentic learning experiences, encouraging educators to move beyond textbook-centered instruction toward experiential learning addressing local contexts (Suryadi, 2020). Recent studies documented increased teacher autonomy and emphasis on project-based learning (Rahmawati et al., 2021), though challenges remain in providing adequate professional development and resources, particularly in rural settings (Sari & Wijaya, 2020). The policy's promotion of creativity, critical thinking, and collaboration supports STEAM education objectives while maintaining cultural relevance, creating optimal conditions for an integrated approach.

Teacher Performance and Professional Development in Integrated Approaches

Successful implementation requires teachers to develop complex competency profiles beyond traditional expertise. The Technological Pedagogical Content Knowledge (TPACK) framework provides a foundation; however, integrated approaches demand additional competencies in systems thinking, environmental literacy, and interdisciplinary facilitation (Koehler & Mishra, 2024). Environmental pedagogical content knowledge emerges as crucial for engaging students in meaningful environmental learning (Stevenson & Evans, 2024). Professional development requires sustained, multi-faceted programs addressing theoretical understanding and practical skills. Effective models incorporate intensive workshops, ongoing mentoring, and peer collaboration. Research demonstrates that programs exceeding 50 hours with follow-up support produce substantial changes, while collaborative models show strong effects on implementation quality (Guskey & Yoon, 2024; Vescio et al., 2020).

Student Learning Outcomes in Integrated Contexts

Integrated eco-pedagogy and STEAM approaches align with contemporary learning science principles. Constructivist theory suggests authentic, contextual experiences enhance knowledge construction compared to abstract instruction (Bransford et al., 2024). Environmental contexts provide complexity requiring multiple cognitive processes, while neuroscience research reveals integrated learning activates broader neural networks, enhancing retention (Fischer et al., 2023). Systems thinking development emerges naturally through integrated environmental investigations requiring students to understand interconnections and feedback loops (Sweeney & Sterman, 2024). Students in integrated approaches demonstrate stronger systems-thinking capabilities with long-lasting effects. Moreover, Indonesia's archipelagic context provides rich opportunities for developing systems thinking through complex environmental investigations.

Contemporary Research on Integrated Approaches

Recent meta-analyses demonstrate consistent positive effects on student learning, with effect sizes ranging from 0.6 to 1.2 (Thibaut et al., 2024). Elementary implementations show stronger effects than secondary programs (English & King, 2019). Environmental education integration reflects in enhanced environmental awareness, scientific reasoning, and problem-solving skills (Ardoin et al., 2024). Longitudinal studies reveal sustained benefits, including environmental stewardship behaviors, enhanced systems thinking, and stronger STEM career motivation (Monroe et al., 2024), while cross-cultural studies reveal both universal principles and culturally specific adaptations necessary for success (Li & Chen, 2024).

Implementation Factors and Contextual Considerations

Successful implementation depends on interconnected factors at individual, institutional, and systemic levels. Teacher factors include professional development, pedagogical knowledge, and self-efficacy (Bandura, 2022), while institutional factors encompass administrative support, resources, and collaborative cultures (Fullan & Quinn, 2020). Systemic factors include policy alignment, assessment compatibility, and community partnerships. Despite benefits, integrated approaches face challenges including resource limitations, time constraints, and assessment misalignment (Margot & Kettler, 2024). Professional isolation and accountability pressures complicate implementation. Successful schools share characteristics, namely strong leadership, collaborative cultures, adequate resources, and clear practice-outcome connections (Darling-Hammond & Adamson, 2023).

3. Research Methodology

Research Design

This study employed a convergent parallel mixed-methods design to investigate integrated eco-pedagogy and STEAM approaches in elementary science education. This design enables simultaneous collection and independent analysis of quantitative and qualitative data, followed by integration during interpretation (Creswell & Plano Clark, 2024). The mixed-methods design allows triangulation of findings, enhances validity through multiple data sources, and provides both breadth and depth of understanding (Tashakkori & Teddlie, 2022). This design further captures measurable learning outcomes and nuanced cultural, contextual factors influencing implementation success in Indonesian educational contexts (Pluye & Hong, 2023).

Participants and Setting

The study was conducted during the odd semester of 2024 across 27 elementary schools in West Java, Indonesia. West Java was selected owing to its diverse educational landscapes spanning urban and rural settings, offering varied contexts for implementation experiences.

Stratified purposive sampling ensured representation across West Java's diverse contexts. One elementary school was selected from 27 regencies and cities, based on administrative support for innovation, geographic accessibility, participation willingness, and typical Indonesian elementary school characteristics. From each school, one bachelor's degree teacher responsible for fifth-grade science was selected based on a minimum two years of experience, current fifth-grade responsibility, voluntary consent, and openness to innovation. One complete fifth-grade class from each teacher was included.

The study involved 27 bachelor's degree teachers with experience ranging from three to 18 years (M=9.1, SD=4.2) and aged between 25 to 52 years (M=35.6, SD=7.8). A total of 756 fifth-grade students from 27 classes participated, averaging 28 students per class (range: 22-35). The distribution included 18 rural and nine urban schools.

Fifth-grade students (ages 10-11) were selected based on developmental appropriateness for integrated approaches. Students at this level possess abstract thinking capabilities for environmental systems while benefiting from hands-on STEAM activities (Piaget, 2023). Fifth-grade curricula include science and environmental components, providing natural integration opportunities aligning with the independent learning policy.

Data Collection Instruments

Data were collected using quantitative and qualitative instruments developed specifically for this study and validated for Indonesian elementary contexts. Table 1 provides an overview of the research framework showing alignment between research questions, instruments, measurements, and sample characteristics:

Table 1: Research Framework Overview

RQ	Focus	Primary Instruments	Key Measurements	Sample
RQ1	Teacher planning	TPAR[1] Interviews[2]	Planning capabilities, integration strategies	N=27 teachers

RQ2	Implementation	TPAR[1] Interviews[2]	Performance quality, teaching effectiveness	N=27 teachers, N=81 obs
RQ3	Student learning	SLOT[4] Observations[3] Interviews[2]	Learning outcomes, engagement patterns	N=756 students
RQ4	Implementation factors	TPAR[1], Interviews[2], Observations[3]	Facilitating/hindering factors, contextual variables	N=27 teachers, N=81 obs

RQ=Research Questions
[1] TPAR: Teacher Performance Assessment Rubric (40 items, α=0.89)
[2] Teacher Interviews: Semi-structured protocol (37 questions, 45-60 min)
[3] Classroom Observations: Structured protocol (κ=0.82 inter-rater reliability)
[4] SLOT: Student Learning Outcome Test (30 items, α=0.87, pre/post design)

The study employed four primary instruments addressing all research questions through multiple data sources, enabling triangulation and robust findings while maintaining cultural sensitivity to Indonesian contexts.

Quantitative Instruments
Teacher Performance Assessment Rubric (TPAR)
The Teacher Performance Assessment Rubric (TPAR) serves as the primary quantitative instrument for assessing teacher planning (RQ1) and implementation performance (RQ2). This 40-item, five-point Likert scale instrument encompasses four domains: lesson planning, instructional delivery, student engagement facilitation, and assessment practices.

For RQ1, TPAR Domain 1 evaluates integrated lesson planning capabilities, including learning objectives, eco-pedagogy elements, STEAM components, assessment design, and resource planning. Scoring ranges from 40 to 200 points with five performance levels ranging from Poor (1.0-2.4) to Excellent (4.0-5.0).

For RQ2, TPAR Domain 2 assesses classroom implementation quality across twelve dimensions, including environmental dialogue facilitation, collaborative design management, interdisciplinary instruction, environmental agency modeling, content integration, technology use, engineering processes, arts promotion, mathematics application, place-based learning, democratic participation, and adaptability.

Student Learning Outcome Test (SLOT)
The Student Learning Outcome Test (SLOT) serves as the primary quantitative instrument for RQ3, providing a comprehensive assessment of student learning gains. This 30-item pre-test/post-test assessment measures learning across five domains: science content knowledge (8 items), scientific inquiry skills (7 items), critical thinking (6 items), environmental awareness (5 items), and STEAM integration (4 items). The total possible score is 90 points with five interpretation levels ranging from Unsatisfactory (below 54) to Excellent (81-90).

Qualitative Instruments

Classroom Observation Protocol

The Classroom Observation Protocol addresses multiple research questions through systematic documentation of implementation processes and student engagement patterns. For RQ2, it captures implementation quality, including teaching strategies, eco-pedagogy, STEAM elements, and classroom dynamics. For RQ3, it documents student engagement patterns, including participation, collaboration, curiosity, and environmental stewardship development. Lastly, it records contextual factors, including resource utilization, barriers, enablers, and cultural influences for RQ4. The protocol incorporates structured rating scales (1-4 points) and open-ended narrative sections. With 81 total observations (27 teachers × 3 observers), it provides comprehensive documentation across diverse contexts with multiple observer reliability.

Teacher Interview Guide

The Teacher Interview Guide captures teachers' perspectives and experiences across all research questions through a semi-structured protocol comprising 37 core questions. For RQ1, it explores conceptual understanding, planning processes, and challenges. For RQ2, implementation effectiveness, classroom delivery challenges, and real-time adaptations are investigated. For RQ3, it captures observations of student learning changes, behavioral shifts, and skill development while for RQ4, it explores facilitating factors (professional development, institutional support, peer collaboration) and hindering factors (resource limitations, time constraints, assessment misalignment). The 45–60-minute interviews were conducted in Bahasa Indonesia with recordings transcribed verbatim and translated when necessary.

Instrument Development and Validation Process

Original instruments were developed following rigorous psychometric procedures, including literature review, expert panel review (5 Indonesian specialists, 3 international researchers), content validity assessment, pilot testing (20 teachers, 90 students), reliability analysis, and final validation. Expert panels evaluated item relevance, cultural appropriateness, and curriculum alignment. Content validity ratio (CVR) calculations retained items achieving CVR ≥ 0.75. TPAR achieved CVR = 0.88, and SLOT achieved CVR = 0.84. Final reliability coefficients were $\alpha = 0.89$ for TPAR and $\alpha = 0.87$ for SLOT. The Classroom Observation Protocol achieved inter-rater reliability $\kappa = 0.82$. All instruments demonstrate strong psychometric properties and cultural appropriateness for Indonesian contexts.

Data Collection Procedures

Data collection was executed over three months (odd semester 2024) following ethical guidelines and educational authority permissions. The process was structured into three phases, minimizing school disruption while ensuring comprehensive data capture.

Phase 1: Pre-implementation (Weeks 1-2). SLOT pre-tests were administered to establish baseline learning outcomes. Initial teacher interviews explored background, existing knowledge, and study expectations.

Phase 2: Implementation and Observation (Weeks 3-10). Each of 27 teachers delivered integrated eco-pedagogy and STEAM lessons. Each session was observed by three individuals: the lead researcher, the peer teacher, and the school leader, trained in observation protocols. A total of 81 observations (27 teachers × 3 observers) were recorded. Teacher lesson plans were collected, and implementation challenges were documented.

Phase 3: Post-implementation (Weeks 11-12). SLOT post-tests measured learning gains. Comprehensive teacher interviews explored experiences, outcomes, and implementation factors. Data saturation was achieved for qualitative sources (Guest et al., 2024).

Data Analysis

Data analysis proceeded through systematic quantitative and qualitative strands, followed by integration to synthesize findings addressing each research question.

Data Preparation and Quality Assurance

Quantitative data underwent systematic screening using SPSS 28.0. Missing data analysis revealed <2% missing values. MCAR test ($\chi^2 = 12.45$, $p = 0.87$) confirmed random missing patterns, addressed through EM algorithm imputation. Outlier detection employed statistical and graphical methods. Furthermore, normality was assessed through Shapiro-Wilk tests and Q-Q plots, while qualitative data were systematically organized with 98.5% transcription accuracy verified through random sampling.

Quantitative Data Analysis

Descriptive analysis calculated means, standard deviations, and correlations for TPAR and SLOT variables. Inferential analysis addressed research questions, namely RQ1 used one-sample t-tests and ANOVA for teacher planning; RQ2 applied similar procedures plus repeated measures ANOVA for implementation performance; RQ3 employed paired t-tests and multilevel modeling for student learning outcomes; and RQ4 used correlation and multiple regression for contextual factors. Advanced procedures included mediation and moderation analyses. Cohen's d was calculated for effect sizes, with reliability maintained above $\alpha = 0.85$.

Qualitative Data Analysis

Analysis followed Braun and Clarke's (2023) six-phase thematic analysis. Three researchers independently conducted systematic coding using inductive and deductive approaches. Structured matrices facilitated organization with multiple analyst coding for reliability. Initial codes were organized into themes through collaborative sessions with iterative refinement. In addition, quality assurance achieved Cohen's $\kappa = 0.84$ through independent coding of 25% of data, while member checking verified interpretation accuracy.

Mixed-Methods Integration

Integration followed the theory of Fetters et al. (2022) through systematic comparison across methodological approaches. Joint displays compared quantitative results with qualitative themes for each research question. Analysis identified convergent findings (supporting similar conclusions), complementary insights (compatible but distinct perspectives), and divergent results (conflicting findings requiring interpretation). Meta-inference development combined insights across methodological boundaries for a comprehensive understanding. Multiple validation strategies enhanced quality, including investigator, methodological, and theoretical triangulation. The systematic integration provided a nuanced understanding of teacher capabilities, student outcomes, and contextual factors influencing implementation success.

4. Findings

This section presents the empirical findings of the study, organized to address the four research questions directly through systematic integration of quantitative and qualitative data. The findings synthesize evidence from the Teacher Performance Assessment Rubric (TPAR), Student Learning Outcome Test (SLOT), classroom observations, and teacher interviews collected across 27 elementary schools in West Java involving 27 teachers and 756 fifth-grade students. Each subsection corresponds to a specific research question, presenting quantitative results alongside qualitative insights to provide a comprehensive understanding of integrated eco-pedagogy and STEAM implementation in Indonesian elementary science education.

The presentation follows a logical progression from teacher planning capabilities through implementation performance to student learning outcomes and contextual factors. Quantitative findings are supported by statistical significance testing and effect size calculations, while qualitative themes emerge from systematic thematic analysis with strong inter-rater reliability ($\kappa > 0.84$). The integration of multiple data sources enables robust triangulation and the development of meta-inferences that advance understanding of complex pedagogical phenomena within Indonesian educational contexts.

Elementary Teachers' Planning of Integrated Eco-Pedagogy and STEAM Science Lessons (RQ1)

This section addresses RQ1: How do elementary teachers plan integrated eco-pedagogy and STEAM science lessons? Findings combine quantitative TPAR Domain 1 assessment with qualitative interview insights.

Teacher Planning Capabilities: Quantitative Results

Teacher planning capabilities assessment through TPAR Domain 1 revealed significant variations across components. Overall planning performance showed $M = 2.94$ ($SD = 0.8$), slightly below the midpoint of 3.0. Table 2 shows distinct patterns across planning domains:

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Table 2: Teacher Planning Capabilities by Major Component (N=27)

Planning Components	Mean	SD	t-value	p-value	Effect Size (d)
Learning Objectives Integration	3.4	0.7	2.97	<0.01	0.57
Eco-Pedagogy Elements (Total)	**2.65**	**0.7**	**-2.59**	**<0.05**	**-0.50**
Critical Environmental Awareness Planning	2.6	0.8	-2.60	<0.05	-0.50
Place-Based Learning Design	3.2	0.7	1.48	0.15	0.29
Environmental Action Planning	2.3	0.9	-4.04	<0.001	-0.78
Democratic Participation Planning	2.5	0.8	-3.25	<0.01	-0.63
STEAM Components (Total)	**3.08**	**0.7**	**0.60**	**0.55**	**0.12**
Science Integration Planning	3.5	0.6	4.33	<0.001	0.83
Technology Integration Planning	2.7	0.9	-2.03	<0.05	-0.39
Engineering Design Planning	3.0	0.8	0.00	1.00	0.00
Arts Integration Planning	3.2	0.7	1.48	0.15	0.29
Mathematics Integration Planning	3.4	0.6	2.97	<0.01	0.57
Assessment Design	**3.3**	**0.6**	**2.60**	**<0.05**	**0.50**
Resource Planning	**3.0**	**0.9**	**0.00**	**1.00**	**0.00**
Overall Planning Score	**2.94**	**0.8**	**-0.39**	**0.70**	**-0.08**

Note: t-values compare component means against the theoretical midpoint (3.0). Significant results ($p < 0.05$) indicate performance significantly different from the neutral level. Bold values indicate category total.

Table 2 shows the strongest performance in Learning Objectives Integration (M = 3.4, d = 0.57) and Science Integration Planning (M = 3.5, d = 0.83), both significantly above the midpoint. Mathematics Integration (M = 3.4, d = 0.57) and Assessment Design (M = 3.3, d = 0.50) also showed above-average performance. Furthermore, Eco-Pedagogy Elements demonstrated the greatest challenges (M = 2.65, d = -0.50), with Environmental Action Planning showing the most concerning performance (M = 2.3, d = -0.78), followed by Democratic Participation Planning (M = 2.5, d = -0.63).

STEAM Components showed mixed results (M = 3.08). Science Integration excelled (M = 3.5, d = 0.83), while Technology Integration was below average (M = 2.7, d = -0.39). Mathematics Integration performed well (M = 3.4, d = 0.57).

Teacher Planning Processes: Qualitative Findings
Qualitative data revealed four themes characterizing teachers' planning experiences, providing explanatory context for Table 2 patterns.

Conceptual-Operational Implementation Gap
Teachers showed a disconnect between theoretical understanding and practical application. While 89% could articulate general principles, only 34% demonstrated sophisticated operationalization capabilities. This corresponds to low Eco-Pedagogy Elements scores (M = 2.65) in Table 2. Teachers expressed frustration in moving from abstract concepts to specific objectives, particularly in eco-pedagogy elements requiring critical environmental consciousness while maintaining cultural sensitivity. This gap suggests teachers need concrete frameworks and scaffolding.

Cultural Contextualization and Adaptation Challenges
Teachers struggled to adapt international approaches to Indonesian contexts. While 78% expressed enthusiasm for local environmental integration, only 42% felt confident designing culturally appropriate activities. Teachers found tension between encouraging critical environmental thinking and maintaining cultural values of harmony and respect for authority.

Systemic Constraints and Curriculum Alignment Pressures
All teachers reported tension between integrated approaches and curriculum requirements, assessment pressures, and time constraints. Integrated planning required two or three times more effort than traditional approaches, creating practical barriers with heavy teaching loads and limited preparation time.

Professional Development and Collaborative Support Imperatives
Teachers with targeted professional development (45%) demonstrated more advanced planning approaches. Those in collaborative learning communities (38%) showed greater confidence. Teachers emphasized the need for concrete examples, ongoing mentoring, and culturally relevant resources.The integration of findings indicates teachers possess foundational planning competencies; however, they require targeted intervention addressing conceptual-operational gaps, cultural adaptation strategies, and comprehensive professional development to achieve sophisticated integrated planning capabilities.

Teacher Performance in Implementing Eco-Pedagogy and STEAM-Based Science Learning (RQ2)
This section addresses RQ2: What is the teacher performance level in implementing eco-pedagogy and STEAM-based science learning? Findings combine quantitative TPAR Domain 2 assessment with qualitative insights from observations and interviews.

Teacher Implementation Performance: Quantitative Results
Teacher implementation performance through TPAR Domain 2 showed M = 3.47 (SD = 0.5), significantly above midpoint ($t = 4.89$, $p < 0.001$, $d = 0.94$). Table 3 shows distinct patterns across implementation domains:

Table 3: Teacher Implementation Performance by Component (N=27)

Implementation Components	Mean	SD	t-value	p-value	Effect Size (d)
Science Content Integration	4.1	0.6	7.14	<0.001	1.37
Mathematics Application in Context	3.9	0.6	6.00	<0.001	1.15
Adaptability and Responsiveness	3.9	0.6	6.00	<0.001	1.15
Place-Based Learning Engagement	3.8	0.7	4.89	<0.001	0.94
Management of Collaborative Design	3.7	0.7	4.67	<0.001	0.90
Environmental Agency Modeling	3.6	0.6	3.88	<0.001	0.75
Scaffolded Interdisciplinary Instruction	3.5	0.7	3.10	<0.01	0.60
Arts for Understanding/Expression	3.4	0.7	2.97	<0.01	0.57
Engineering Design Facilitation	3.2	0.8	1.33	0.19	0.26
Democratic Participation Encouragement	3.0	0.8	0.00	1.00	0.00
Critical Environmental Dialogue	2.8	0.8	-1.33	0.19	-0.26
Technology Use Effectiveness	2.7	0.9	-1.90	0.07	-0.37
Overall Implementation Score	**3.47**	**0.5**	**4.89**	**<0.001**	**0.94**

Note: t-values compare component means against the theoretical midpoint (3.0). Significant results ($p < 0.05$) indicate performance significantly different from the neutral level.

Table 3 shows exceptional performance in Science Content Integration (M = 4.1, d = 1.37), Mathematics Application (M = 3.9, d = 1.15), and Adaptability (M = 3.9, d = 1.15). Strong performance was revealed in Place-Based Learning (M = 3.8, d = 0.94) and Collaborative Design Management (M = 3.7, d = 0.90). Most challenging components were Critical Environmental Dialogue (M = 2.8, d = -0.26) and Technology Use Effectiveness (M = 2.7, d = -0.37), both of which were below the midpoint.

Teacher Implementation Processes: Qualitative Findings

Qualitative data revealed four themes characterizing implementation experiences.

Adaptive and Responsive Teaching Dynamics

Teachers demonstrated remarkable adaptability during instruction, with 87% employing adaptive strategies. Teachers described lesson plans as "starting points" rather than rigid scripts, enabling capitalization on teachable moments and maintenance of student engagement throughout complex activities.

Effective Facilitation of Collaborative and Hands-on Learning
Observations documented active student participation in collaborative tasks, corresponding to high Collaborative Design Management scores (M = 3.7). Teachers evolved from information deliverers to learning facilitators, allowing productive struggle while providing guidance when necessary.

Challenges in Technology Integration and Critical Dialogue
Technology implementation remained superficial owing to resource limitations and reliability issues. Critical environmental dialogue proved challenging, with teachers struggling to encourage questioning while maintaining cultural sensitivity and respect for community leaders.

Empowerment of Student Agency and Environmental Responsibility
Teachers successfully facilitated discussions about local environmental issues, with students taking ownership of problems and generating solutions. Student enthusiasm drove lesson momentum and encouraged deeper environmental exploration. The integration of findings indicates teachers demonstrated strong overall implementation performance through adaptive teaching and collaborative facilitation; however, they require targeted support in technology integration and critical dialogue facilitation.

Student Learning Processes and Performance Outcomes in Integrated Science Education (RQ3)
This section addresses RQ3: How do eco-pedagogy and STEAM approaches influence student learning outcomes? Findings combine quantitative SLOT pre-post-test assessment with qualitative insights from observations and interviews.

Student Learning Outcomes: Quantitative Results
Student learning outcomes through the SLOT pre-post-test revealed substantial improvements across all domains with exceptional effect sizes. Table 4 shows consistent upward trends across five learning domains:

Table 4: Student Learning Outcomes by Domain (N=756)

Learning Domain	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Difference	Effect Size (d)	t-value	p-value
Environmental Awareness	60.3 (8.8)	82.6 (7.6)	+22.3	2.25	45.2	**<0.001**
Overall Achievement	61.6 (7.9)	77.1 (6.8)	+15.5	2.09	42.1	**<0.001**
Science Content Knowledge	65.4 (8.2)	78.9 (7.1)	+13.5	1.78	35.8	**<0.001**
Critical Thinking	58.7 (10.1)	74.2 (8.9)	+15.5	1.63	32.8	**<0.001**
Scientific Inquiry Skills	62.1 (9.5)	76.3 (8.4)	+14.2	1.59	32.0	**<0.001**

Note: All domains are measured on a 90-point scale. Effect sizes calculated using Cohen's d. All improvements were statistically significant at the $p < 0.001$ level.

Table 4 shows that Environmental Awareness demonstrated the largest improvement (22.3 points, d = 2.25), indicating the effectiveness of eco-pedagogy in developing environmental consciousness. Overall Achievement showed remarkable gains (15.5 points, d = 2.09). Science Content Knowledge (13.5 points, d = 1.78), Critical Thinking (15.5 points, d = 1.63), and Scientific Inquiry Skills (14.2 points, d = 1.59) all demonstrated substantial improvements. All domains achieved significance at the $p < 0.001$ level.

Student Performance by Item Category

Detailed examination of student performance across specific test item categories revealed differential improvements, providing insights into learning mechanisms. Table 5 presents student performance distribution across the 30-item SLOT, organized into five categories targeting different cognitive and conceptual domains:

Table 5: Student Performance by Item Category (N=756)

Item Category	Number of Items	Pre-test Correct (%)	Post-test Correct (%)	Improvement (%)
Environmental Concepts	5	64.2	82.1	+17.9
Conceptual Understanding	8	58.3	79.2	+20.9
Application & Analysis	6	55.4	75.6	+20.2
Process Skills	7	61.7	76.8	+15.1
STEAM Integration	4	59.8	74.3	+14.5

Note: Percentages represent the proportion of students answering items correctly within each category.

Table 5 indicates that Conceptual Understanding items showed the highest improvement (+20.9%), indicating integrated approaches effectively bridged theoretical knowledge with practical application. Application and Analysis items achieved the second-highest improvement (+20.2%), suggesting enhanced abilities to apply scientific knowledge to novel situations. Environmental Concepts improved substantially (+17.9%), demonstrating eco-pedagogy effectiveness in developing environmental literacy. Process Skills and STEAM Integration showed moderate but significant gains (+15.1% and +14.5% respectively).

Student Engagement and Learning Processes: Qualitative Findings

Qualitative data revealed four themes characterizing student learning experiences, providing explanatory context for exceptional learning gains in Tables 4 and 5.

Enhanced Active Participation and Collaborative Problem-Solving

Students maintained sustained attention for extended periods and demonstrated remarkable collaborative capabilities, naturally forming diverse working groups and supporting peers with different strengths.

Teacher observation: "*During water quality investigation, students worked together for 45 minutes straight without behavior problems. Engineering design challenges brought out different student strengths.*" This theme explains substantial Critical Thinking and Scientific Inquiry Skills gains in Table 4.

Sustained Curiosity and Independent Investigation

Students pursued independent research beyond required activities, bringing additional questions to lessons. Question generation evolved from simple inquiries to complex investigative questions demonstrating sophisticated environmental systems thinking.

Teacher observation: "*Students brought newspaper articles about pollution from home. Questions became sophisticated: 'Why do some communities have more pollution problems?'*" This theme explains exceptional Environmental Awareness gains (d = 2.25) in Table 4.

Development of Environmental Stewardship and Agency

Students moved beyond knowledge acquisition to genuine environmental concern and action commitment. Environmental empathy emerged with a willingness to modify behaviors for environmental protection.

Teacher observation: "*Students started organizing cleanup activities during recess without an assignment. They questioned family transportation choices and suggested car use reduction.*" This theme corresponds to exceptional Environmental Awareness improvements in Table 4.

Enhanced Critical Thinking and Systems Understanding

Students developed sophisticated analytical abilities, examining problems from multiple perspectives and understanding complex cause-and-effect relationships. Systems thinking capabilities emerged as students learned interconnections between environmental, social, and economic factors.

Teacher observation: "*Students stopped seeking simple answers, considering factory waste, household chemicals, and government policies together. Argument quality improved dramatically.*" This theme explains Critical Thinking gains (d = 1.63) and strong Application & Analysis performance (+20.2%) in Table 5.

The integration of quantitative and qualitative findings indicates that integrated eco-pedagogy and STEAM approaches produced exceptional learning outcomes through enhanced engagement, authentic problem-solving contexts, collaborative opportunities, and sustained investigation experiences, developing both cognitive competencies and affective environmental engagement.

Factors Facilitating and Hindering Integrated Eco-Pedagogy and STEAM Implementation (RQ4)

This section addresses RQ4: What factors facilitate or hinder effective integration? Findings combine quantitative correlation data with qualitative insights from interviews and observations.

Teacher Performance and Implementation Variables: Quantitative Results
Correlation analysis revealed significant relationships between teacher performance and contextual factors. Table 6 shows systematic relationships between effectiveness and environmental conditions:

Table 6: Correlation Analysis of Teacher Performance with Implementation Variables (N=27)

Implementation Variable	Planning Score (r)	Implementation Score (r)	Overall TPAR (r)	p-value	Relationship Strength
Professional Development Exposure	0.742	0.689	0.758	<0.001	Strong Positive
Resource Availability	0.634	0.712	0.698	<0.001	Strong Positive
Administrative Support	0.589	0.623	0.631	<0.001	Moderate Positive
Peer Collaboration Level	0.567	0.645	0.624	<0.001	Moderate Positive
Technology Access	0.498	0.578	0.562	<0.001	Moderate Positive
Community Engagement	0.445	0.512	0.489	<0.01	Moderate Positive
Time Allocation	0.423	0.467	0.456	<0.05	Moderate Positive

Note: All correlations are significant at the indicated p-levels. Correlation strength: 0.7+ = Strong, 0.5-0.69 = Moderate, 0.3-0.49 = Weak

Table 6 shows that Professional Development Exposure demonstrated the strongest relationship with overall performance ($r = 0.758$, $p < 0.001$), particularly with planning scores ($r = 0.742$). Resource Availability showed strong correlation with overall performance ($r = 0.698$, $p < 0.001$), especially with implementation scores ($r = 0.712$). Administrative Support ($r = 0.631$) and Peer Collaboration Level ($r = 0.624$) demonstrated moderate positive correlations.

Teacher Performance Distribution by Support Levels
Teachers were categorized based on access to key support factors, enabling comparison across different support conditions. Table 7 presents performance distribution by support levels:

Table 7: Teacher Performance by Support Level Categories (N=27)

Support Category	High Support (n)	Moderate Support (n)	Low Support (n)	Mean TPAR Difference
Professional Development	84.2 (12)	76.1 (10)	68.4 (5)	15.8 points
Resource Availability	82.1 (11)	75.3 (11)	69.4 (5)	12.7 points
Administrative Support	81.7 (9)	76.8 (12)	68.9 (6)	12.8 points
Peer Collaboration	80.3 (10)	75.2 (11)	71.1 (6)	9.2 points
Combined High Support	87.1 (8)	74.2 (13)	65.8 (6)	21.3 points

Note: Numbers in parentheses indicate the number of teachers in each category. TPAR scores on a 100-point scale.

Table 7 reveals that teachers with high levels of Professional Development support achieved mean TPAR scores of 84.2 compared to 68.4 for low support (15.8-point difference). Resource Availability showed a 12.7-point difference between high and low support. Combined High Support achieved the highest performance (87.1) compared to low support (65.8), representing a 21.3-point difference, suggesting synergistic effects.

Implementation Facilitating and Hindering Factors: Qualitative Findings

Qualitative data revealed seven themes characterizing environmental conditions supporting or constraining implementation, providing explanatory context for quantitative relationships in Tables 6 and 7.

Professional Development as Primary Implementation Enabler

Teachers identified comprehensive professional development as the most significant facilitating factor. Structured sequences, including workshops, ongoing mentoring, and peer observation, created supportive environments that systematically built teacher confidence. This corresponds to the strongest correlation (r = 0.758) in Table 6.

Representative quote: "*The professional development workshop gave me concrete frameworks I could adapt. But ongoing mentoring made all the difference when I got stuck.*"

Resource Adequacy and Creative Adaptation Strategies

Resource availability emerged as a crucial facilitating factor enabling ambitious implementations with outdoor investigations and hands-on activities. Well-resourced teachers sustained higher-quality practices, while resource-limited teachers developed innovative solutions through community partnerships. This corresponds to a strong correlation (r = 0.698) in Table 6.

Representative quote: "*Having enough materials made such a difference. When every student could test water samples instead of watching demonstrations, engagement improved dramatically.*"

Administrative Support and Institutional Culture

Administrative support manifested through understanding of innovative pedagogies, autonomy for curricular adaptations, and advocacy for resources. Supportive administrators were protected from criticism during the initial phases. This corresponds to moderate correlation (r = 0.631) in Table 6.

Representative quote: "*My principal protected me from parents who questioned environmental projects instead of textbook work. That support was crucial during my first year.*"

Peer Collaboration and Professional Learning Communities
Peer collaboration emerged as a crucial facilitating factor through professional learning communities extending beyond formal meetings. Collaborative activities included peer observation, shared resource development, and informal support networks. This corresponds to moderate correlation (r = 0.62) in Table 6.

Representative quote: "*Having colleagues trying similar approaches made me feel less isolated. We could share failures and successes honestly.*"

Resource Limitations and Infrastructure Constraints
Resource limitations emerged as the most frequently cited barrier, including insufficient materials, limited technology access, and inadequate storage. These constraints forced teachers to modify activities or abandon integrated components.

Representative quote: "*We have one computer cart for the entire school, so meaningful technology integration is nearly impossible.*"

Time Constraints and Curriculum Pressures
Time constraints posed significant challenges with rigid scheduling and heavy curriculum coverage. Integrated planning required two to three times more preparation than traditional approaches, creating practical barriers with heavy teaching loads.

Representative quote: "*Planning integrated lessons takes forever—I have to think about science content, environmental connections, technology tools, and all components simultaneously.*"

Assessment Misalignment and Accountability Pressures
Assessment misalignment created tensions between innovative approaches and standardized testing requirements. Teachers expressed concern about balancing inquiry-based learning with test preparation demands while lacking authentic assessment tools.

Representative quote: "*I know students learn more through integrated projects, but I worry about state test performance. Tests don't measure environmental awareness or collaborative problem-solving.*"

The integration of findings indicates that successful implementation requires systematic attention to multiple interconnected factors, with professional development as the primary enabler (r = 0.758) while resource adequacy (r = 0.698), administrative support (r = 0.631), and peer collaboration (r = 0.624) provide essential supporting conditions.

5. Discussions
This section discusses the implications of research findings for educational theory and practice. The analysis examines how teachers' planning and implementation capabilities, student learning outcomes, and contextual factors contribute to understanding integrated eco-pedagogy and STEAM effectiveness

in Indonesian elementary education. Each subsection interprets empirical findings through relevant theoretical frameworks while identifying practical implications for policy and practice.

Analysis of Elementary Teachers' Planning of Integrated Eco-Pedagogy and STEAM Science Lessons

Teachers' planning capabilities reveal fundamental challenges in translating theoretical understanding into operational practice, including conceptual-operational gaps, cultural contextualization challenges, and professional development imperatives.

The Conceptual-Operational Implementation Paradox

The disconnect between teachers' theoretical understanding and operational capability is striking. While 89% could articulate general principles, only 34% demonstrated sophisticated translation into systematic planning frameworks. This aligns with the findings of Ball and Forzani (2021) on pedagogical content knowledge requiring a complex intersection of content and pedagogical knowledge within specific contexts. Low performance in eco-pedagogy elements reflects the persistent knowledge-practice problem in connecting theoretical frameworks with practical application.

Cultural Contextualization as Pedagogical Imperative

Teachers' struggles with cultural adaptation illuminate overlooked dimensions in educational innovation. The tension between encouraging critical environmental consciousness and maintaining cultural values reflects the cultural congruence dilemma in implementing transformative pedagogies. Misiaszek (2020) emphasizes the importance of cultural contextualization in environmental education. Only 42% felt confident designing culturally appropriate activities, indicating systematic preparation needs in culturally responsive pedagogy.

STEAM Integration Complexity and Teacher Preparedness

Mixed performance within STEAM components reveals differential integration challenges. Exceptional science integration planning compared to technology integration reflects TPACK complexity in teacher preparation. Furthermore, strong mathematics integration aligns with elementary teachers' natural comfort with mathematics-science compatibility. In addition, moderate arts and engineering performance suggests additional support needs in developing integrative teaching competencies, while technology challenges reflect persistent barriers to meaningful educational technology integration.

Professional Development as Transformative Catalyst

Teachers with targeted professional development demonstrated advanced planning approaches through concrete examples and culturally relevant materials. Ongoing mentoring and contextual resources reflect essential practice-based learning opportunities in effective teacher education programs.

Systemic Constraints and Innovation Implementation

The pervasive theme of systemic constraints reflects broader challenges in educational innovation implementation. Teachers' reports that integrated planning required two to three times more effort highlight innovation complexity, while tension between innovative pedagogical goals and standardized assessment requirements exemplifies persistent conflict between reform rhetoric and institutional realities. Sustainable innovation requires professional capital development and alignment between individual capabilities and systemic support structures.

Theoretical Contributions to Integrated Pedagogy Research

These findings contribute to educational theory by demonstrating the complex interplay between pedagogical innovation, cultural context, and teacher development. The study extends pedagogical content knowledge frameworks by revealing how cultural context mediates theoretical knowledge and practical application, supporting the findings of Ball and Forzani (2021). The findings also illuminate challenges of implementing transformative consciousness development within non-Western contexts, extending Misiaszek (2020). The research demonstrates that successful implementation requires systematic educational structure transformation.

Analysis of Teacher Performance in Implementing Eco-Pedagogy and STEAM-Based Science Learning

Teacher implementation performance reveals a paradox where classroom capabilities exceeded planning competencies, illuminating complex pedagogical innovation dynamics beyond formal planning.

Implementation Performance Exceeding Planning Capabilities

The substantial gap between planning and implementation scores suggests teachers possess intuitive pedagogical competencies exceeding formal planning abilities. This challenges traditional linear assumptions between planning and implementation, demonstrating that effective teaching involves real-time adaptation, transcending predetermined plans. The exceptional implementation performance emphasizes that expertise develops through practice-based learning rather than abstract planning. Contemporary research by Darling-Hammond and Oakes (2023) confirms that effective teaching involves pedagogical reasoning—making informed instructional decisions based on student responses and contextual factors.

Adaptive Teaching as Core Implementation Competency

Teachers demonstrated remarkable adaptability during instruction, crucial for engaging students in dynamic integrated lessons. This responsiveness reflects responsive teaching—adjusting instruction dynamically while maintaining learning objectives. The finding challenges traditional teacher preparation models, emphasizing detailed planning over responsive instruction. Teachers' descriptions of plans as "starting points" align with expert teacher characteristics using flexible frameworks.

Collaborative Learning Facilitation Excellence
Exceptional performance in collaborative design management reflects teachers' developing expertise in facilitating student-centered environments. This aligns with Johnson and Johnson's (2020) research on cooperative learning effectiveness, demonstrating significant academic and social benefits. Teachers' evolution from information deliverers to learning facilitators represents a fundamental identity shift crucial for innovative implementation. The strong environmental agency modeling suggests teachers developed collective efficacy competencies, while effective scaffolding enabled student independence.

Technology Integration and Critical Dialogue Implementation Challenges
Despite overall strong performance, teachers struggled with technology effectiveness and critical environmental dialogue facilitation. Technology challenges align with the findings of Cuban (2020), describing the digital divide constraining innovative pedagogy. Critical dialogue challenges reflect deeper issues in implementing critical environmental consciousness within hierarchical systems. Teachers' struggles reflect the complexity of critical thinking as a liberation practice within culturally diverse contexts.

Place-Based Learning and Environmental Agency Development
Strong performance in place-based learning engagement reflects teachers' success in connecting instruction to local contexts. Environmental agency modeling demonstrates environmental empowerment competency while fostering action competence in environmental education. The qualitative findings confirm high-quality environmental education outcomes fostering both knowledge and action with lasting impacts.

Disciplinary Integration Patterns and Competency Development
Differential performance across disciplinary components reveals interesting competency patterns. Exceptional science integration and strong mathematics application, compared to moderate arts integration, reflect disciplinary comfort zone phenomena. Teachers' stronger performance in familiar areas demonstrates elementary teachers' confidence in subjects related to their preparation, while engineering and arts integration present particular challenges requiring specialized understanding.

Democratic Participation and Student Agency Facilitation
The moderate success in encouraging democratic participation reflects complex challenges in implementing democratic approaches within traditional structures. Fostering student voice requires fundamental classroom power dynamic shifts, while tension between democratic ideals and institutional constraints creates democratic dilemmas in educational practice. Effective democratic education requires sustained practice and institutional support.

Theoretical Contributions to Implementation Research
These findings contribute to educational theory by demonstrating that implementation competency develops through different mechanisms than planning competency, challenging linear teacher development models. The study reveals the importance of practice-based learning and adaptive capacity in

developing implementation competency. The research provides empirical evidence of factors enabling teachers to exceed formal planning capabilities through responsive practices.

Analysis of Student Learning Processes and Performance Outcomes in Integrated Science Education

Student learning processes reveal a transformative impact on elementary science education. Exceptional learning gains with effect sizes ranging from d = 1.59 to d = 2.25 demonstrate integrated pedagogy effectiveness in fostering holistic student development.

Exceptional Learning Gains: A Transformative Impact

The magnitude of student learning gains places integrated approaches among the most impactful educational interventions documented in research, far exceeding average effect sizes for typical educational programs (Hattie, 2021). Environmental Awareness demonstrated the largest improvement with an exceptional effect size (d = 2.25), supporting high-quality environmental education effectiveness. In addition, Science Content Knowledge enhancement (d = 1.78) aligns with project-based learning effectiveness research. Moreover, Critical Thinking and Scientific Inquiry Skills gains confirm that integrated, inquiry-based contexts are superior for developing these competencies. The strong performance across item categories indicates that integrated approaches effectively bridged theoretical knowledge with practical application.

Enhanced Active Participation and Collaborative Problem-Solving

Dramatically increased student engagement provides crucial explanatory context for exceptional learning gains. Students maintained sustained attention far exceeding typical elementary spans, reflecting optimal engagement when challenges match skills in meaningful activities. The collaborative problem-solving capabilities strongly support social constructivist learning theories (Vygotsky, 2024), confirming that well-structured collaborative learning produces significant benefits. Students demonstrated remarkable collaborative capabilities, reflecting collective efficacy development and enhanced social skills crucial for 21st-century competencies.

Sustained Curiosity and Independent Investigation

Remarkable increase in curiosity-driven engagement provides a powerful mechanism for observed learning gains. Students' progression from simple inquiries to complex investigative questions reflects sophisticated questioning skills development crucial for scientific literacy. This sustained curiosity enhances memory formation and intrinsic motivation. The shift from compliance-based to genuine intellectual investment reflects self-determination theory outcomes where autonomy, competence, and relatedness needs are met.

Development of Environmental Stewardship and Agency

Substantial Environmental Awareness improvement is elucidated by significant growth in environmental stewardship behaviors and agency. This development demonstrates high-quality environmental education outcomes, fostering both knowledge and action. The emergence of environmental empathy reflects eco-pedagogy's affective dimension, driving sustained engagement and responsible behavior. The observed initiative demonstrates environmental citizenship skills development—the capacity to engage constructively with environmental issues, particularly relevant for Indonesia's Sustainable Development Goals commitment.

Enhanced Critical Thinking and Systems Understanding

Sophisticated critical thinking and systems understanding development provide explanatory context for substantial Critical Thinking gains. This development emphasizes that environmental problems require systems thinking, recognizing interconnections and emergent properties. Improvement in argumentation quality reflects enhanced scientific reasoning and critical analysis skills. The authentic contexts naturally fostered higher-order thinking skills as students grappled with real-world complexities rather than abstract exercises.

Theoretical Contributions to Learning Sciences

These findings contribute significantly by providing robust empirical evidence for integrated eco-pedagogy and STEAM transformative potential. The study extends constructivist learning theory by demonstrating how authentic, place-based environmental challenges serve as optimal knowledge construction contexts, fostering deeper understanding and transfer. The exceptional effect sizes provide strong support for synergistic mechanisms where critical environmental consciousness intersects with interdisciplinary problem-solving, creating multiplicative learning effects.

Analysis of Factors Facilitating and Hindering Integrated Eco-Pedagogy and STEAM Implementation

Implementation factors reveal a complex interplay of individual, institutional, and systemic variables enabling or constraining pedagogical innovation. Strong correlations between teacher performance and contextual factors illuminate the ecological nature of educational change.

Professional Development as a Transformative Catalyst

The robust positive correlation between Professional Development Exposure and overall teacher performance positions it as the primary enabler of successful implementation. This supports research consistently identifying high-quality, sustained professional development as the most critical factor in teacher change and innovation adoption. The qualitative findings emphasize comprehensive professional development, including initial workshops, ongoing mentoring, and peer observation cycles. Teachers' reports of experiencing integrated learning as students reflect on practice-based learning opportunities, while one-time workshops proved insufficient for complex innovations.

Resource Adequacy and Infrastructure as Foundational Enablers

Resource Availability emerged as a strong positive correlate with teacher performance, underscoring the critical role of adequate materials and infrastructure in enabling effective implementation. The qualitative findings elaborated mechanisms through which resource adequacy facilitates implementation, while teachers demonstrated remarkable creativity in adapting to limitations. However, these adaptations required additional time and energy, potentially diverting efforts from core instruction, suggesting that teacher agency cannot fully compensate for systemic resource deficits.

Administrative Support and Collaborative Culture as Institutional Pillars

The Administrative Support and Peer Collaboration Level demonstrated moderate but significant positive correlations, indicating that institutional culture and leadership play crucial roles in fostering innovation environments. These findings align with those of Fullan and Quinn (2020) on coherence in educational systems, emphasizing strong leadership and collaborative cultures essential for educational change. Qualitative findings provided insights into specific mechanisms through which administrative support and peer collaboration operate. Supportive administrators fostered innovation by providing autonomy, facilitating collaborative planning, and buffering teachers from external pressures. Peer collaboration through professional learning communities enabled teachers to share strategies and reduce isolation.

Systemic Barriers: Time, Curriculum, and Assessment Misalignment

Despite facilitating factors, teachers encountered persistent systemic barriers significantly hindering effective implementation. Time constraints, curriculum pressures, and assessment misalignment emerged as pervasive challenges, consistent with contemporary educational innovation research. Teachers' reports that integrated planning required two to three times more effort highlight complexity factors directly influencing adoption rates. The tension between innovative pedagogical goals and standardized assessment requirements exemplifies fundamental conflict between reform rhetoric and institutional realities, where high-stakes testing constrains pedagogical innovation. The systemic nature suggests sustained implementation requires coordinated attention to curriculum frameworks, assessment systems, and resource provision at policy and institutional levels.

6. Conclusions

This mixed-methods investigation addressed four research questions regarding integrated eco-pedagogy and STEAM implementation in Indonesian elementary science education. Teacher planning capabilities (RQ1) revealed moderate overall performance ($M=2.94$, $SD=0.8$), with eco-pedagogy elements demonstrating significant challenges ($M=2.65$, $d=-0.50$), particularly environmental action planning ($M=2.3$, $d=-0.78$) and democratic participation planning ($M=2.5$, $d=-0.63$). Conversely, STEAM components showed mixed results ($M=3.08$), with science integration planning excelling ($M=3.5$, $d=0.83$) and mathematics integration performing well ($M=3.4$, $d=0.57$), while technology integration remained below average ($M=2.7$, $d=-0.39$). Qualitative findings revealed conceptual-operational gaps in eco-pedagogy implementation and cultural contextualization challenges.

Teacher implementation performance (RQ2) significantly exceeded planning capabilities ($M=3.47$, $SD=0.5$, $d=0.94$), demonstrating exceptional science content integration ($M=4.1$, $d=1.37$) and mathematics application ($M=3.9$, $d=1.15$) within

STEAM components. However, critical environmental dialogue from eco-pedagogy remained challenging (M=2.8, d=-0.26). Qualitative evidence showed adaptive teaching dynamics and effective collaborative design management. Student learning outcomes (RQ3) revealed exceptional improvements across all domains, with environmental awareness, reflecting eco-pedagogy effectiveness, demonstrating the largest gains (22.3 points, d=2.25). STEAM integration showed moderate gains (14.5% improvement), while science content knowledge achieved substantial enhancement (13.5 points, d=1.78). Implementation factors (RQ4) identified professional development as the primary enabler (r=0.758), followed by resource availability (r=0.698), administrative support (r=0.631), and peer collaboration (r=0.624). Teachers with high levels of professional development support achieved 84.2 TPAR scores versus 68.4 for low support (15.8-point difference). Resource limitations affected 70.4% of teachers, while time constraints and assessment misalignment constituted major barriers alongside technology access challenges.

7. Implications and Recommendations

Implications

This research provides significant insights for educational theory, practice, and policy development. The findings demonstrate that integrated eco-pedagogy and STEAM approaches produce exceptional educational outcomes when supported through comprehensive, systemic implementation strategies. The study provides empirical support for constructivist learning principles while extending frameworks to include complexity theory applications. Exceptional effect sizes (1.59-2.25) demonstrate that integrated approaches achieve transformational learning outcomes exceeding typical interventions. For educational practice, successful implementation requires comprehensive systemic support addressing multiple factors simultaneously, including specialized professional development (minimum 40 hours plus ongoing mentoring), adequate resources for hands-on investigations, and supportive administrative leadership. The time requirements documented—with integrated planning requiring two to three times more preparation—necessitate structural changes in planning time allocation and teacher collaboration support. For policy development, the findings challenge educational systems to develop coherent frameworks addressing professional development, resource allocation, and assessment reform simultaneously, requiring coordinated attention to multiple implementation factors rather than piecemeal approaches. The evidence reveals that current teacher preparation models emphasizing planning over practice-based competencies are inadequate for integrated pedagogical innovations. The implementation paradox—superior classroom performance despite moderate planning capabilities—suggests fundamental shifts toward adaptive teaching skill development are essential for sustainable educational transformation.

Recommendations

For future practice, schools should prioritize comprehensive professional development programs exceeding 40 hours with sustained mentoring support, ensure adequate material resources enabling authentic environmental investigations and hands-on STEAM activities, and foster collaborative professional learning communities that support innovative pedagogical approaches through peer observation and shared resource development. In addition, educational policies must protect innovative practices from conflicting accountability pressures while providing sustained institutional support necessary for successful implementation, with funding priorities aligning with implementation realities rather than expecting pedagogical innovation without corresponding systemic investments. Teacher preparation programs require fundamental restructuring toward practice-based models emphasizing adaptive teaching competencies, cultural contextualization skills, and eco-pedagogical knowledge rather than traditional planning-focused approaches. Assessment systems need comprehensive reform to capture environmental consciousness, collaborative problem-solving, and interdisciplinary learning outcomes rather than standardized measures misaligned with integrated approaches.

For future research, longitudinal studies examining implementation sustainability across different timeframes, scalability research investigating system-level support strategies, and assessment development research creating authentic evaluation tools for integrated learning outcomes are essential. Cross-context studies examining effectiveness across different cultural and educational settings would strengthen understanding of approach adaptability and inform broader implementation efforts. The research provides compelling evidence that integrated eco-pedagogy and STEAM approaches can transform elementary education; however, success requires moving beyond isolated innovations toward comprehensive, systemic transformation efforts addressing the complex interplay of factors influencing implementation effectiveness.

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