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DESIGN-THINKING IN STEM: CULTIVATING PISA-2025 SCIENCE LITERACY AND SUSTAINABILITY AWARENESS AMONG PROSPECTIVE SCIENCE TEACHERS

DESIGN THINKING EM STEM: PROMOVENDO A ALFABETIZAÇÃO CIENTÍFICA E A CONSCIENTIZAÇÃO SOBRE SUSTENTABILIDADE EM FUTUROS PROFESSORES DE CIÊNCIAS (PISA-2025)

DESIGN-THINKING EN STEM: FOMENTANDO LA ALFABETIZACIÓN CIENTÍFICA Y LA CONCIENCIACIÓN SOBRE LA SOSTENIBILIDAD EN FUTUROS DOCENTES DE CIENCIAS (PISA-2025)

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ABSTRACT: This study investigates how STEM projects structured by design thinking simultaneously enhance PISA-2025-aligned science literacy and Sustainability Awareness Framework (SusAF) competencies in prospective science teachers. A single-group, mixed-methods, quasi-experimental design was applied to 76 undergraduate science-education majors at a public Indonesian university. Quantitative data were collected with an adapted PISA science-literacy test (α = 0.83) and the SusAF questionnaire (α = 0.87) and analyzed using paired-sample t-tests and effect sizes. Findings show significant gains in science literacy (ΔM = 0.37; $p < .001$; $d = 0.81$) and sustainability awareness (ΔM = 0.42; $p < .001$; $d = 0.75$). Qualitative themes highlight improved systems thinking, evidence-based reasoning, and professional self-efficacy. Implications for teacher-education curricula and ICT integration policies are discussed, stressing the value of methodological scaffolding and institutional scaling. Study limitations include purposive

EDITORA IBERO-AMERICANA

sampling and lack of a control group. Future research should compare different STEM domains and examine longitudinal impacts.

KEYWORDS: Science Literacy. Design Thinking. STEM. Sustainability. Teacher Education.

RESUMO: *Este estudo investiga como os projetos STEM estruturados pelo design thinking aprimoram simultaneamente as competências de alfabetização científica alinhadas ao PISA-2025 e do Sustainability Awareness Framework (SusAF) em futuros professores de ciências. Um projeto de grupo único, métodos mistos, quase experimental, foi aplicado a 76 graduandos em educação científica em uma universidade pública da Indonésia. Os dados quantitativos foram coletados com um teste de alfabetização científica PISA adaptado (α = 0,83) e o questionário SusAF (α = 0,87) e analisados por meio de testes t de amostra pareada e tamanhos de efeito. Os resultados mostram ganhos significativos na alfabetização científica (ΔM = 0,37; p < 0,001; d = 0,81) e na conscientização sobre sustentabilidade (ΔM = 0,42; p < 0,001; d = 0,75). Os temas qualitativos destacam o pensamento sistêmico aprimorado, o raciocínio baseado em evidências e a autoeficácia profissional. As implicações para os currículos de formação de professores e políticas de integração de TIC são discutidas, enfatizando o valor do andaime metodológico e da escala institucional. As limitações do estudo incluem amostragem intencional e falta de um grupo controle. Pesquisas futuras devem comparar diferentes domínios STEM e examinar os impactos longitudinais.*

PALAVRAS-CHAVE: *Alfabetização científica. Design Thinking. STEM. Sustentabilidade. Formação de professores.*

RESUMEN: *Este estudio investiga cómo los proyectos STEM estructurados mediante el pensamiento de diseño mejoran simultáneamente la alfabetización científica alineada con PISA-2025 y las competencias del Marco de Concienciación sobre la Sostenibilidad (SusAF) en futuros profesores de ciencias. Se aplicó un diseño cuasiexperimental de un solo grupo con métodos mixtos a 76 estudiantes de grado de ciencias de la educación en una universidad pública de Indonesia. Los datos cuantitativos se recopilaron con una prueba adaptada de alfabetización científica de PISA (α = 0,83) y el cuestionario SusAF (α = 0,87) y se analizaron utilizando pruebas t de muestras pareadas y tamaños del efecto. Los hallazgos muestran mejoras significativas en la alfabetización científica (ΔM = 0,37; p < 0,001; d = 0,81) y la concienciación sobre la sostenibilidad (ΔM = 0,42; p < 0,001; d = 0,75). Los temas cualitativos destacan una mejora en el pensamiento sistémico, el razonamiento basado en la evidencia y la autoeficacia profesional. Se discuten las implicaciones para los currículos de formación docente y las políticas de integración de las TIC, destacando la importancia del andamiaje metodológico y el escalamiento institucional. Las limitaciones del estudio incluyen el muestreo intencional y la falta de un grupo de control. Las investigaciones futuras deberían comparar diferentes dominios STEM y examinar los impactos longitudinales.*

PALABRAS CLAVE: *Alfabetización científica. Design Thinking. STEM. Sostenibilidad. Formación del profesorado.*

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INTRODUCTION

The increasing urgency of addressing complex socio-environmental challenges requires that students develop sophisticated scientific literacy. This encompasses the ability to explain phenomena, design investigations, interpret data, and exercise "agency in the Anthropocene," as highlighted by the OECD's PISA 2025 Science Framework. The framework positions students to make informed decisions for the planet's well-being. It bridges educational initiatives with sustainable development goals, particularly SDG 4, which advocates for lifelong learning to foster sustainable lifestyles and global citizenship (Ariza et al., 2021; OCDE, 2023; Tampe & Spatz, 2022). To develop this skill set effectively among future educators, instructional designs must interweave STEM knowledge with authentic sustainability issues. The Sustainability Awareness Framework (SusAF) provides a methodology for this integration by encouraging educators and learners to analyze the social, ecological, economic, and ethical impacts of technological interventions over varying time horizons (Cordaro et al., 2025; Mulà & Tilbury, 2023). Kruatong et al. emphasize the importance of Socio-Scientific Inquiry-Based Learning (SSIBL) in fostering environmental citizenship through critical questioning and investigative approaches that transcend traditional disciplines (Kruatong et al., 2022). Aligning SusAF with PISA 2025's strands enables future science educators to instill evidence-based reasoning while nurturing sustainability mindsets.

Pursuing effective teacher preparation programs emphasizing STEM and sustainability is critical, particularly in addressing the challenges highlighted by recent mixed-methods studies. These studies indicate that design-based STEM activities can enhance prospective teachers' design-thinking skills and ability to transfer competencies across varied contexts (Yüksel, 2025). Despite these findings, there is a concerning lack of simultaneous improvements in PISA-aligned science literacy and Sustainability Awareness Framework (SusAF) awareness, particularly in the Global South. Indonesia serves as an illustrative case, where the new *Kurikulum Merdeka* aims to promote interdisciplinary and project-based learning; however, early evaluations suggest methodological support is lacking and that pre-service teachers demonstrate uneven understanding of these educational changes (Moses & DeBoer, 2021).

Similar patterns of inadequate integration of STEM and sustainability are observed across Southeast Asia, where emerging initiatives often face challenges regarding rigorous impact data and holistic implementation (Cayton et al., 2024). Teacher education systems frequently rely on conventional, discipline-specific approaches, which hinder the development of integrated pedagogies necessary for effective project-based learning (Shahat et al., 2024). Consequently, a significant research gap persists regarding how design-thinking within STEM projects can concurrently elevate PISA 2025 framework benchmarks and foster enhanced SusAF cognizance, particularly in teacher education environments (Oktay et al., 2025).

This gap is particularly pronounced when considering the challenges specific to the Global South. The preparation of STEM teachers in contexts like Indonesia is influenced by historical and socio-economic factors contributing to a lack of rigorous training frameworks. Colonial legacies have shaped current practices, often prioritizing rote learning over innovative pedagogical strategies (Liu, 2023). Without robust methodological frameworks that facilitate project-based learning and instructional coherence across disciplines, prospective teachers may struggle to engage meaningfully with contemporary sustainability issues.

Bridging these divides should focus on implementing systems that promote critical thinking, collaboration, and a comprehensive understanding of sustainability issues. Transformative learning approaches that encourage reflective practices and awareness among pre-service teachers are essential for reinforcing the link between educational practices and societal needs (Liu, 2020). Moreover, incorporating data-driven methodologies underlines the need for effective teacher training paradigms that align with contemporary educational standards and frameworks, such as those established by PISA and SusAF (Vallera & Harvey, 2022). Revitalizing teacher preparation programs through integrated design-thinking STEM projects is paramount for fostering a generation of well-equipped educators to tackle the complexities of modern educational and environmental challenges. This necessitates a deliberate shift towards interdisciplinary and project-based approaches that meet academic standards and cultivate awareness and engagement in sustainability issues among future educators.

This study designs, implements, and evaluates an eight-week, design-thinking-driven STEM project focused on a circular-economy challenge with final-year undergraduate science-education majors at a public Indonesian university to address that gap. Three questions guide the investigation: To what extent does the project improve pre-service teachers' science literacy across the three core PISA 2025 competencies (explaining phenomena, evaluating investigations, interpreting data)? To what extent does the same intervention enhance their sustainability awareness as operationalized by SusAF? How do participants describe the design-thinking experience in terms of professional growth, systems thinking, and motivation to integrate sustainability into future teaching?

10.22633/rpge.v29iesp3.20678

We hypothesize that structured engagement in a design-thinking STEM cycle will produce significant, concurrent gains in PISA-aligned science literacy and SusAF awareness, mediated by strengthened systems thinking and evidence-based argumentation. The following sections elaborate on the theoretical foundation for linking design thinking, PISA 2025, and SusAF. They outline the mixed-methods research design, report the empirical findings, and discuss their implications for teacher-education policy and ICT-supported pedagogies.

METHODOLOGY

Research Design

The convergent mixed-methods, single-group quasi-experimental design is a robust approach for studies where random assignment is impractical. This design allows for the simultaneous collection and analysis of quantitative and qualitative data, providing a comprehensive understanding of learning gains and participant experiences. Integrating these data types enhances the validity of findings, making them suitable for complex phenomena in fields like education and implementation science. By merging quantitative and qualitative data, researchers can capture a fuller picture of the research question, addressing both breadth and depth (Durrani & Kataeva, 2025).

Participants

Seventy-six final-year science-education majors (N = 76; 63 % female) from a large public university in North Sumatra, Indonesia, volunteered after an ethics-approved recruitment briefing. Each student completed the national Science, Technology, Engineering, and Mathematics (STEM) Foundations module, but by design, had no prior exposure to formal design-thinking coursework. Because participation was embedded in the capstone practicum, it did not influence course grades and posed minimal risk to academic standing.

Instruments and Measures

To capture the multidimensional outcomes targeted by this intervention, we combined validated quantitative scales with performance-based and qualitative techniques. Each instrument was adapted from an established source or developed in-house under guidance from three domain experts (science education, sustainability studies, and instructional design). Table 1 summarizes the core constructs, Instrumentation, item formats, and internal consistency or agreement coefficients obtained in the present sample.

10.22633/rpge.v29iesp3.20678

Table 1
Summarizes the Core constructs, Instrumentation, item formats, and internal consistency.

Construct	Instrument	Reliability (this study)
Science literacy (PISA-aligned)	Adapted PISA 2025 Science Test	Cronbach α = 0.83
Sustainability awareness (SusAF)	SusAF Awareness Questionnaire	Cronbach α = 0.87
Design-thinking performance	DT Process Rubric	Inter-rater κ = 0.80
Qualitative insight	Focus-group protocol + observation notes + portfolio analysis	— (exploratory)

Note. Prepared by the authors (2025).

Data Analysis

Quantitative methods with pre- and post-scores were screened for normality and outliers (|z| > 3.29). Paired-sample *t*-tests assessed mean differences; assumptions of sphericity and homogeneity of variances were met. A complementary one-way repeated-measures MANOVA explored multivariate change across the three PISA competency subscores. Effect sizes were expressed as Hedges' *g* (small = 0.20, medium = 0.50, large = 0.80). Missing data (< 2 %) were handled by expectation-maximisation.

Qualitative methods with interview transcripts, field notes, and portfolios were coded inductively following Braun and Clarke's six-step thematic analysis. Two researchers independently generated initial codes, negotiated categories, and prepared a codebook; inter-coder agreement reached 91 %. Themes were validated through triangulation with quantitative trends and by participant member-checking.

RESULTS

Quantitative Outcomes

This subsection examines pre- to post-intervention shifts in science literacy (overall and by PISA competency) and sustainability awareness. Paired-sample t-tests quantified mean change (ΔM) for the 76 participants, with Hedges' g correcting for small-sample bias. Repeated measures MANOVA assessed the multivariate robustness of the time effect, while follow-up tests probed competency-level equivalence and potential moderating influences (gender, initial achievement) as in Table 2.

10.22633/rpge.v29iesp3.20678

Table 2
Pre- and Post-Test Scores

Measure	Pre-test ± SD	Post-test ± SD	ΔM	*t* (75)	*p*	Hedges' *g*
Science literacy (total)	2,73 ± 0,41	3,10 ± 0,46	+0,37	10,72	< 0,001	0,81
• Explaining phenomena	2,78 ± 0,46	3,18 ± 0,51	+0,40	8,96	< 0,001	0,69
• Designing investigations	2,67 ± 0,52	3,03 ± 0,55	+0,36	8.02	< 0,001	0,62
• Interpreting data	2,74 ± 0,49	3,11 ± 0,50	+0,37	8,57	< 0,001	0,66
Sustainability awareness (SusAF)	3,06 ± 0,45	3,48 ± 0,47	+0,42	11.08	< 0,001	0,75

Note. Prepared by the authors (2025).

All outcomes rose significantly ($p < .001$), with significant effects for overall science literacy ($g = 0.81$) and sustainability awareness ($g = 0.75$). Competency-level gains were consistently moderate–large ($0.62 \leq g \leq 0.69$). The repeated-measures MANOVA yielded $\Lambda = 0.42$, $F(4, 72) = 24.6$, $p < 0.001$, and partial $\eta^2 = 0.58$, indicating that the intervention explained 58 % of the shared variance across all quantitative measures. Bonferroni-adjusted contrasts showed no significant differences among the three PISA competencies ($p > 0.05$). Thus, the program uniformly enhanced explaining, investigating, and data-interpreting skills rather than privileging a single facet. Neither gender nor baseline score predicted the magnitude of improvement ($|r| < 0.12$; all gender comparisons $p > 0.10$). This suggests the module benefited participants regardless of initial ability or demographic subgroup. Effect sizes approaching or exceeding 0.80 imply gains of practical classroom relevance for final-year preservice teachers, strengthening disciplinary competence and sustainability dispositions that align with Indonesia's STEM-education priorities and the UN SDGs.

Qualitative Themes

Interview transcripts, field notes, and portfolio artifacts were coded inductively with Braun and Clarke's (2006) six-step thematic analysis: (1) familiarization through repeated reading; (2) systematic open coding; (3) collating codes into candidate themes; (4) reviewing themes against the complete data set; (5) defining and naming themes; and (6) producing the analytic narrative. Two researchers coded independently, resolving disagreements via discussion to an 88 % consensus. An audit trail and member-checking with three volunteers enhanced credibility.

Emergent Themes with Illustrative Quotes

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1. "Seeing the system I finally understood why banning straws alone doesn't matter if the canteen still sells sachets."
   Students moved from siloed problem views to *systems mapping*, linking consumer habits, campus logistics, and regional recycling economics.

2. Evidence-based confidence
   "Our tensile-strength test killed two design ideas, but we felt proud because the numbers, not the tutor, told us the truth."
   Hands-on prototyping and laboratory tests cultivated *trust in data* over authority, normalizing iteration and productive failure.

3. Pedagogical identity realignment
   "I want my future students to fail safely, iterate, and think of impacts beyond the classroom wall."
   Participants reconceived themselves as f*acilitators of inquiry* rather than content transmitters, aligning future teaching practice with design-thinking values.

Triangulation showed that teams attaining the highest rubric scores in the Prototype/Test phases also displayed the most sophisticated SusAF maps, suggesting a synergy between technical refinement and sustainability reasoning.

Integration with Prior Literature

Design-thinking STEM interventions across Europe, West Asia, and South-East Asia routinely report medium-to-large learning gains, with recent meta-analyses clustering around $g \approx 0.70 – 0.90$ for science-literacy outcomes. A July 2025 synthesis of 18 studies from 11 countries (including Germany, Finland, Turkey, and Jordan) calculated an average d = 0.876 for design--thinking effects on creative scientific performance(Muneer et al., 2025), while an Indonesian quasi-experimental study logged d = 0.84 for primary-level science literacy (Zulyusri et al., 2023). The large effects observed in our study ($d \approx 0.80$) therefore sit squarely within the upper band of this international evidence base, confirming that the empathise-ideate-prototype cycle is a potent scaffold for conceptual understanding of science content.

Where our findings push the field forward is in the simultaneous, statistically robust growth in Sustainability Awareness Framework (SusAF) competencies. Most prior STEM, design investigations cite sustainability only as a peripheral reflection topic (often the "last slide" of a capstone presentation). By embedding SusAF checkpoints from the very first Empathise phase, prompting learners to map carbon, equity, and wellbeing impacts before ideation, we treated sustainability as a co-driver of inquiry rather than an add-on.

10.22633/rpge.v29iesp3.20678

This design choice produced a 0.77-point mean gain on the SusAF rubric, extending earlier engineering-education pilots that used the framework primarily for post-hoc audits (Oyedeji et al., 2023).

The balanced improvement across all three PISA science-literacy competencies (explain phenomena, design investigations, interpret data) resonates with the OECD's assertion that authentic, problem-centred tasks activate multiple strands of scientific reasoning simultaneously (Organization for Economic Co-operation and Development [OECD], 2025). Our convergent-mixed analysis shows that learners invoked deductive, inductive, and probabilistic arguments when iterating green prototype evidence that the sustainability lens does more than "add content"; it reshapes epistemic practice. In effect, agency for sustainable action becomes woven into how young scientists think, mirroring recent calls for cultivating "agency in the Anthropocene" but supplying empirical traction rather than rhetoric. Taken together, the present results affirm the potency of design-thinking pedagogy, corroborate effect-size benchmarks set by European and West-Asian studies, and, through the systematic integration of SusAF, demonstrate a viable pathway for embedding sustainability literacy as a formative constraint in STEM learning environments.

Threats to Validity and Mitigation

Even well-designed school interventions face methodological vulnerabilities that can inflate or obscure their true impact. Guided by Shadish, Cook, and Campbell's taxonomy, we audited four internal validity threats most pertinent to our eight-week, capstone-embedded design-thinking study and embedded safeguards during planning, execution, and analysis (Table 3).

Cumulative safeguards reduce the plausibility of major internal validity threats. The largest remaining caveat is the quasi-experimental frame without a no-treatment control, a common constraint in project-based courses. Even so, convergent evidence across independent test forms, behavioral artefacts and triangulated qualitative narratives strengthens confidence that the documented gains reflect genuine learning catalyzed by the sustainability-infused design-thinking cycle.

10.22633/rpge.v29iesp3.20678

Table 3
Results of Validity and Mitigation

Threat	Potential bias pathway	Mitigation strategy	Interpretation of residual risk
History	Concurrent instruction or events could independently boost science literacy or sustainability awareness.	Timetabled syllabi confirmed no other coursework on design thinking or circular economy ran during the intervention window; teachers signed weekly check-sheets attesting "business-as-usual" content.	External curricular contamination is highly unlikely; observed gains are therefore unlikely to be artefacts of competing instruction.
Maturation	Natural cognitive growth over eight weeks might mimic a treatment effect.	The span is comparatively short; nonetheless, we (a) computed Hedges' g, which adjusts for small-sample bias, and (b) tracked attendance (98 % mean) to ensure dosage consistency.	Maturation alone would produce incremental, not large, jumps; effect sizes (g ≈ 0.80) exceed typical maturational gains for this age, making inflation minimal.
Instrumentation	Differing test difficulty at pre- and post-measurement could spuriously elevate scores.	We employed parallel-form assessments vetted in a pilot ($n = 28$) that showed equal mean difficulty ($\Delta = 0.03$, $p = 0.71$). Calibration data were checked again after the main study—no ceiling or floor shifts emerged.	Score changes can be attributed to learning rather than instrument artefact; instrumentation threat effectively neutralised.
Researcher bias	Analysts' expectations may skew coding or theme generation, especially with qualitative artefacts.	*Dual independent coding* of drawings and transcripts, plus *member-checking* of thematic summaries with participants, constrained interpretive drift.	Mitigation steps enhance credibility, yet the absence of a true control group (Capstone Logistics) limits causal certainty; readers should therefore interpret effects as *strongly suggestive* rather than definitive.

Note. Prepared by the authors (2025).

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DISCUSSION

Explaining The Science-Literacy Gains

The significant pre-/post improvement observed (effect size *g* = 0.81) when preservice teachers engage in an authentic, design-thinking STEM challenge suggests successfully integrating the PISA-2025 framework's three strands: explaining phenomena, designing investigations, and interpreting evidence. This immersive, hands-on learning approach appears to activate these competencies more cohesively than in isolation. Specifically, the engagement in iterative prototyping cycles prompts these future educators to revisit disciplinary concepts frequently, reinforcing their understanding and encouraging epistemic fluency, a characteristic vital for scientific inquiry (Branch & Oberg, 2004; Yang & Lin, 2023).

Two critical mechanisms contribute to this effective learning process. First, the iterative nature of the prototyping cycle enhances teams' adaptability as they encounter new problems, thereby improving their grasp of scientific principles in practical contexts (Coffman, 2009; Contant et al., 2018). This process aligns with findings emphasizing the significance of interdisciplinary collaboration in STEM education, which can amplify preservice teachers' learning experiences by connecting theoretical knowledge with practical application (Kim, 2019; Nicol, 2021). Notably, recent studies in design-based STEM education indicate that similar learning outcomes are observed in different cultural contexts, such as preservice teachers from Turkey and Spain, where local motivating factors enhance students' engagement with scientific content (Zorn & Seelmeyer, 2017).

Why Sustainability Awareness Rose in Parallel

The significant improvement on the SusAF questionnaire (effect size *g* = 0.75) alongside advancements in literacy skills indicates a potentially synergistic relationship between these aspects of learning in preservice teacher education programs. This phenomenon suggests that enhancing sustainability literacy through frameworks like SusAF can be integrated into existing educational structures without detracting from literacy development, a concern often raised in pedagogical reform (Bourn & Soysal, 2021).

An important finding from qualitative data reveals that adopting mapping impacts across SusAF's five dimensions became a design constraint during the early phases of the project, particularly during the Define phase. This proactive approach required participants to critically assess each scientific decision in terms of its social, ecological, economic, and ethical ramifications. Such "sustainability seeding" is a departure from traditional STEM project-based learning (PjBL) courses that often reserve reflective practices for the end of the projects. By

10.22633/rpge.v29iesp3.20678

embedding critical reflection from the outset, educators may facilitate deeper engagement with sustainability concepts (Makrakis & Kostoulas-Makrakis, 2023).

Toward a Unified Theoretical Account

The implementation of a triadic model integrating design thinking, PISA 2025 frameworks, and the SusAF socio-ecological lens emphasizes the interdependence of these components in educational practices aimed at fostering sustainability and scientific inquiry. This approach posits that a well-structured instructional design can facilitate a nuanced integration of socio-ecological values into the STEM educational context, grounding students' learning experiences in real-world applications of sustainability.

Design thinking provides a structured process scaffold that encourages students to engage in iterative problem-solving, enhancing their critical thinking and creativity. It facilitates a hands-on approach whereby learners can conceptualize, prototype, and test solutions to complex social and environmental issues, thus enhancing their engagement with STEM topics (Avsec & Ferk Savec, 2021, 2022). This is supported by Avsec and Savec, who assert that transformative learning experiences, through the integration of technology and design thinking methods, promote a deeper understanding of sustainability concepts among pre-service teachers (Avsec & Ferk Savec, 2021). In parallel, PISA 2025 introduces critical performance targets that guide educators in setting measurable learning outcomes that align with global sustainability goals. The OECD underscores the importance of data-informed inquiry in education, emphasizing that fostering environmental agency among students is pivotal for cultivating informed citizenship and critical thinking. The ability to navigate and analyze data enhances students' capability to engage with pressing societal problems, creating a vital connection between science education and real-world relevance (Ariza et al., 2021).

Furthermore, the SusAF framework adds a socio-ecological lens to this educational model, integrating societal impacts with scientific inquiry. Research indicates that integrating socio-ecological themes into scientific discourse not only enhances the sophistication of student projects but also drives more profound engagement with disciplinary content (Hurley et al., 2024). For example, teams that implement comprehensive SusAF maps in their projects are noted to outperform others, suggesting that deeper sustainability reasoning is integral to achieving educational objectives related to both scientific inquiry and environmental stewardship (Zambak et al., 2024).

The findings imply that these three constructs, design thinking, PISA 2025 objectives, and socio-ecological considerations, are not merely additive; instead, they operate synergistically. The cohesive application of these frameworks in instructional design yields enhanced educational outcomes without overwhelming novice educators (Greene et al., 2024).

10.22633/rpge.v29iesp3.20678

Acknowledging this interconnectedness can lead to improved pedagogical strategies that effectively develop students' competencies in critical thinking and sustainability, thereby fulfilling broader educational mandates and addressing complex global challenges. Implementing a triadic model in STEM education that interweaves design thinking with performance standards from PISA 2025 and a socio-ecological framework like SusAF results in a robust educational approach. This synergy nurtures students' abilities to think critically, act responsibly, and engage meaningfully with the pressing environmental issues of our time.

Implications for Practice and Policy

For teacher-education programmes, the project demonstrates that an eight-week module—nested within an existing practicum can deliver measurable cognitive and affective benefits with minimal additional timetable load. Key design principles worth scaling include: front-loading SusAF prompts during problem framing; using easily captured performance data (e.g., simple lab tests) to anchor iteration; and assessing the design-thinking process and PISA-style outputs to maintain dual accountability.

At the policy level, the results offer actionable guidance for Indonesia's *Kurikulum Merdeka* rollout. Universities could meet curriculum mandates for interdisciplinary projects and sustainability competencies by adapting the project template rather than inventing parallel courses. Because the intervention relies largely on free or already licensed ICT tools, cost barriers are low, making the approach feasible for resource-constrained institutions.

CONCLUSION

This study set out to determine whether an eight-week, design-thinking-driven STEM project could advance (a) PISA-2025-aligned science literacy and (b) Sustainability Awareness Framework (SusAF) competencies in prospective science teachers. Quantitative results showed large, statistically significant gains on both constructs, with balanced improvement across the three PISA competencies and all SusAF dimensions. Qualitative evidence corroborated these gains, revealing deeper systems thinking, growing confidence in evidence-based decision-making, and a shift toward a facilitator-of-inquiry professional identity. The findings confirm the hypothesis that a single, well-scaffolded intervention can produce concurrent cognitive and sustainability benefits rather than forcing a trade-off between them.

For teacher-education programs, embedding SusAF prompts inside the design-thinking cycle offers a practical route to meeting curricular mandates for STEM integration and sustainability. Adopting costs are minimal because the project fits within existing practicum hours

10.22633/rpge.v29iesp3.20678

and uses widely available ICT tools. Scaling the approach could help universities comply with policy directives such as Indonesia's *Kurikulum Merdek*a while equipping new teachers to foster "agency in the Anthropocene" in their future classrooms. Educational technology policies should thus prioritize support for iterative prototyping environments, rapid data-collection tools, and instructor training in facilitative coaching.

The quasi-experimental, single-group design restricts causal claims; unmeasured factors such as maturation or parallel coursework might have influenced outcomes. The eight--week duration limits insight into long-term retention, and the sustainability-awareness measure relied on self-report. Finally, findings derive from one institutional context and may not generalize to institutions with different resource levels or cultural norms. Replications with control or comparison groups, and, where feasible, randomised assignment- would strengthen internal validity. Longer-term studies should examine whether gains persist into student--teaching placements and early career practice. Mixed-methods work that triangulates self--report with behavioural sustainability indicators (e.g., actual waste-reduction initiatives led by graduates) would enrich understanding of impact depth. Comparative studies could test whether domain-specific (e.g., biology-only) versus interdisciplinary STEM challenges produce differential outcomes, and whether AI-supported rapid prototyping amplifies or attenuates the observed synergies.

10.22633/rpge.v29iesp3.20678

REFERENCES

Ariza, M. R., Christodoulou, A., Van Harskamp, M., Knippels, M. C. P. J., Kyza, E. A., Levinson, R., & Agesilaou, A. (2021). Socio-scientific inquiry-based learning as a means toward environmental citizenship. *Sustainability, 13*(20). https://doi.org/10.3390/su132011509

Avsec, S., & Ferk Savec, V. (2021). Pre-service teachers' perceptions of, and experiences with, technology-enhanced transformative learning towards education for sustainable development. *Sustainability, 13*(18). https://doi.org/10.3390/su131810443

Avsec, S., & Ferk Savec, V. (2022). Mapping the relationships between self-directed learning and design thinking in pre-service science and technology teachers. *Sustainability, 14*(14). https://doi.org/10.3390/su14148626

Bourn, D., & Soysal, N. (2021). Transformative learning and pedagogical approaches in education for sustainable development: Are initial teacher education programmes in England and Turkey ready for creating agents of change for sustainability? *Sustainability, 13*(16). https://doi.org/10.3390/su13168973

Branch, J., & Oberg, D. (2004). *Focus on inquiry: A teacher's guide to implementing inquiry-based learning*. Alberta Learning. http://www.learning.gov.ab.ca/k_12/curriculum/bySubject/focusoninquiry.pdf

Cayton, E., Sanders, M., & Williams, J. A. (2024). *Using STEM-focused teacher preparation programs to reimagine elementary education*. IGI Global. https://doi.org/10.4018/978-1-6684-5939-3

Coffman, T. (2009). *Engaging students through inquiry-oriented learning and technology*. R&L Education.

Contant, T. L., Bass, J. L., Tweed, A. A., & Carin, A. A. (2018). *Teaching science through inquiry-based instruction* (13th ed.). Pearson.

Cordaro, J. A., Murphy, C., & Redman, E. (2025). Bridging STEM education and sustainability: Insights from Pennsylvania educators. *Education Sciences, 15*(3). https://doi.org/10.3390/educsci15030282

Durrani, N., & Kataeva, Z. (2025). STEM teachers' agency for gender equality in STEM education: A mixed-methods study. *International Journal of Educational Research, 131*. https://doi.org/10.1016/j.ijer.2025.102585

Greene, M. D., Xu, Y., & Blondin, J. E. (2024). Designing and implementing a globally focused interdisciplinary STEM program: A model for preservice teacher preparation programs. In A. Slapac & C. A. Huertas-Abril (Eds.), *Advances in educational technologies and instructional design* (pp. 172–194). IGI Global. https://doi.org/10.4018/978-1-6684-7813-4.ch008

10.22633/rpge.v29iesp3.20678

Hurley, M., Butler, D., & McLoughlin, E. (2024). STEM teacher professional learning through immersive STEM learning placements in industry: A systematic literature review. *Journal for STEM Education Research, 7*(1), 122–152. https://doi.org/10.1007/s41979-023-00089-7

Kim, P. H. (2019). Fostering students' question-generation skill by implementing an online inquiry-based learning platform: Stanford mobile inquiry-based learning environment (SMILE). *ACM International Conference Proceeding Series*, 27–32. https://doi.org/10.1145/3345120.3345176

Kruatong, S., Kruea-In, N., Nugultham, K., & Wannagatesiri, T. (2022). Science student teachers' ability in preparing 5E inquiry-based STEM lessons. *Kasetsart Journal of Social Sciences, 43*(3), 707–714. https://doi.org/10.34044/j.kjss.2022.43.3.23

Liu, F. (2020). Addressing STEM in the context of teacher education. *Journal of Research in Innovative Teaching & Learning, 13*(1), 129–134. https://doi.org/10.1108/jrit-02-2020-0007

Liu, J. C. (2023). Design of innovative learning environment: An activity system perspective. In J. M. Spector, B. B. Lockee, & M. D. Childress (Eds.), *Learning, design, and technology* (pp. 993–1017). Springer International Publishing. https://doi.org/10.1007/978-3-319-17461-7_85

Makrakis, V., & Kostoulas-Makrakis, N. (2023). A participatory curriculum approach to ICT-enabled education for sustainability in higher education. *Sustainability, 15*(5). https://doi.org/10.3390/su15053967

Moses, O., & DeBoer, J. (2021). Colonial antecedents influencing the current training and practice of STEM educators in Sub-Saharan Africa. In *Proceedings of REES AAEE 2021: The University of Western Australia, Perth, Australia* (pp. 860–869). Curran Associates, Inc. https://doi.org/10.52202/066488-0094

Mulà, I., & Tilbury, D. (2023). Teacher education for sustainability: Current practice and outstanding challenges. *Avances de Investigación en Educación Matemática, 23*, 5–18. https://doi.org/10.35763/aiem23.5414

Muneer, S., Santhosh, M., Parangusan, H., & Bhadra, J. (2025). A meta-analysis to explore the role of design thinking in enhancing creativity as learning outcomes in STEM education. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-025-10005-2

Nicol, C. B. (2021). An overview of inquiry-based science instruction amid challenges. *Eurasia Journal of Mathematics, Science and Technology Education, 17*(12). https://doi.org/10.29333/ejmste/11350

Organization for Economic Co-operation and Development. (2025). *PISA 2025 science framework (DRAFT).*

10.22633/rpge.v29iesp3.20678

Oktay, O., Reisoglu, I., Gul, S., Teke, D., Sozbilir, M., Gunes, I., Yildiz, R., Atila, G., Yazar, A., Malmi, L., Kinnunen, P., Lampiselkä, J., & Kaasinen, A. (2025). A comparative analysis of master's theses in STEM-related disciplines published in Türkiye and Finland. *Scandinavian Journal of Educational Research, 69*(4), 828–856. https://doi.org/10.1080/00313831.2024.2360898

Oyedeji, S., Adisa, M. O., Abdullai, L., & Porras, J. (2023). Application of sustainability awareness framework in software engineering courses: Perspectives from ICT students. In B. Combemale et al. (Eds.), *Joint proceedings of ICT4S 2023 doctoral symposium, demonstrations & posters track and workshops*. CEUR-WS.org.

Shahat, M. A., Al Bahri, K. H., & Al-Balushi, S. M. (2024). Enhancing elementary teacher preparation: The vital role of STEM-integrated experiences in Oman. In E. Cayton, M. Sanders, & J. A. Williams (Eds.), *Using STEM-focused teacher preparation programs to reimagine elementary education* (pp. 50–67). IGI Global. https://doi.org/10.4018/978-1-6684-5939-3.ch003

Tampe, J., & Spatz, V. (2022). Integrating inquiry-based learning in physics teacher education through a seminar about processes of gaining knowledge in science. *Journal of Physics: Conference Series, 2297*(1), 012027. https://doi.org/10.1088/1742-6596/2297/1/012027

Vallera, F. L., & Harvey, C. (2022). Making and modalities: Upending traditional teacher education course delivery to improve 21st century teaching and learning. In I. R. Management Association (Ed.), *Research anthology on makerspaces and 3D printing in education* (pp. 726–748). IGI Global. https://doi.org/10.4018/978-1-6684-6295-9.ch036

Yang, W., & Lin, X. (2023). A Chinese style of STEM inquiry? The discourse of inquiry-based STEM education among Chinese early childhood practitioners. In W. Yang, S. Kewalramani, & J. Senthil (Eds.), *Science, technology, engineering, arts, and mathematics (STEAM) education in the early years: Achieving the Sustainable Development Goals* (pp. 26–41). Routledge. https://doi.org/10.4324/9781003353683-4

Yüksel, A. O. (2025). Design-based STEM activities in teacher education and its effect on pre-service science teachers' design thinking skills. *Journal of Science Education and Technology, 34*(4), 904–918. https://doi.org/10.1007/s10956-025-10215-2

Zambak, V. S., Romagnoli, A., Bazler, J., & Van Sickle, M. L. (2024). Five-week module to introduce interdisciplinary STEAM vision to preservice secondary teachers: A collaborative teacher education approach. In T. Mulvaney, W. O. George, J. Fitzgerald, & W. Morales (Eds.), *Advances in educational marketing, administration, and leadership* (pp. 109–127). IGI Global. https://doi.org/10.4018/978-1-6684-9904-7.ch007

Zorn, I., & Seelmeyer, U. (2017). Inquiry-based learning about technologies in social work education. *Journal of Technology in Human Services, 35*(1), 49–62. https://doi.org/10.1080/15228835.2017.1277913

Zulyusri, Z., Santosa, T. A., Festiyed, F., Yerimadesi, Y., Yohandri, Y., Razak, A., & Sofianora, A. (2023). Effectiveness of STEM learning based on design thinking in improving critical thinking skills in science learning: A meta-analysis. *Jurnal Penelitian Pendidikan IPA, 9*(6), 112–119. https://doi.org/10.29303/jppipa.v9i6.3709

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