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STEAM education for sustainable futures: A pedagogical framework for education for sustainable development

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ABSTRACT

This study examines the design and implementation of a six-week science, technology, engineering, arts, and mathematics (STEAM) education program aligned with education for sustainable development (ESD) through interdisciplinary and arts-integrated learning. Conducted in early 2025 with 28 upper elementary and middle school students (ages 10-14), the exploratory pilot program integrated STEAM domains to support systems-oriented thinking, ethical reflection, and interdisciplinary engagement with sustainability-related challenges. Grounded in an exploratory qualitative design, the program employed project-based learning, reflective dialogue, and arts-based inquiry to operationalize ESD principles in classroom practice. Qualitative data from student journals, facilitator observation logs, and reflective debriefs were analyzed thematically to examine patterns in learner engagement, cross-domain conceptual connections, and emerging value-oriented reasoning. Thematic analysis revealed recurring and increasingly articulated patterns of systems awareness, ethical reflection, creative risk-taking, and interdisciplinary transfer as students engaged in iterative design processes and expressive problem framing. Rather than claiming measurable learning gains or confirmed transformation, the study offers a descriptive account of how STEAM-ESD integration can be enacted pedagogically and how such integration may support conditions associated with transformative learning rather than demonstrable transformation. The findings contribute a practice-informed framework and empirical illustration relevant to educators and curriculum designers exploring interdisciplinary approaches to ESD in pilot and non-formal educational settings.

Keywords: STEAM education, education for sustainable development, systems thinking, interdisciplinary curriculum, sustainability education

INTRODUCTION

Global crises, including climate change, biodiversity loss, widening inequality, and geopolitical instability, underscore the urgency of rethinking how education is conceptualized and delivered. These challenges are not discrete but deeply interconnected through complex economic, social, and ecological systems. Such conditions demand educational approaches capable of addressing complexity, uncertainty, and value conflict, capacities that are central to education for sustainable development (ESD), which frames sustainability not as content to be mastered but as a way of thinking, reasoning, and acting within interconnected systems. In response, ESD has emerged as a prominent international framework for preparing learners to engage with this complexity by fostering competencies such as critical thinking, ethical reasoning, cultural awareness, and collaborative problem-solving. However, despite strong normative and policy-level endorsement, these competencies remain unevenly cultivated within conventional, discipline-siloed educational structures.

In parallel, the growing adoption of science, technology, engineering, arts, and mathematics (STEAM) education, which integrates science, technology, engineering, arts, and mathematics, reflects a growing recognition that disciplinary fragmentation constrains creative, systems-oriented thinking. The inclusion of the arts in STEAM is often justified on the grounds that it supports creativity, emotional engagement, and multiple modes of meaning-making. Conceptually, this positions STEAM as a promising pedagogical vehicle for advancing the transformative aims of ESD, particularly those related to systems thinking and ethical reflection (Auh & Kim, 2024).

Despite this apparent alignment, the empirical literature at the intersection of STEAM and ESD remains underdeveloped in several critical respects. First, while a growing body of scholarship advocates for STEAM-ESD integration at the conceptual or policy level, relatively few empirical studies examine how this integration is designed, enacted, and experienced in formal school settings, particularly at the middle school level. Second, many existing arts-integrated or STEAM-based ESD frameworks remain largely theoretical, offering limited insight into classroom-level pedagogical practices, learner responses, or observable learning outcomes. Third, although ESD foregrounds ethical reasoning and value-oriented learning, much of the empirical STEAM literature prioritizes creativity, innovation, or technical problem-solving, often underplaying the ethical and sustainability dimensions central to ESD.

As a result, current scholarship offers limited guidance on how STEAM can be operationalized not merely as an interdisciplinary approach but as a pedagogical structure that substantively supports sustainability-oriented competencies, including ethical awareness, conceptual transfer across domains, and systems-level understanding. This gap leaves educators and curriculum designers with insufficient empirical evidence to inform the design of STEAM-based ESD programs that move beyond aspirational integration.

Addressing this gap, the present study critically examines the design and implementation of a STEAM-based ESD program in a formal educational setting. Rather than treating ESD as an additive theme or supplementary content, the study embeds sustainability principles in the core structure, pedagogy, and assessment of interdisciplinary learning. By foregrounding classroom enactment and learner experience, this research provides empirical insight into how STEAM-ESD integration can be realized in practice and the pedagogical consequences that follow.

Objectives and Purpose of the Study

The purpose of this study is twofold:

1. To design and implement an interdisciplinary STEAM-based curriculum explicitly aligned with ESD principles; and
2. To examine how this integrated model supports the development of sustainability-oriented competencies, including sustainability literacy, critical inquiry, systems thinking, and ethical awareness, among adolescent learners.

The study is guided by the following research questions:

1. How can STEAM education be structured to meaningfully support the learning objectives of ESD in formal school settings?
2. What pedagogical approaches facilitate interdisciplinary learning while foregrounding sustainability-oriented and ethical competencies?
3. What observable impacts does a STEAM-based ESD program have on student engagement, conceptual transfer, and ethical awareness?

Consistent with an exploratory qualitative design, the research questions are intended to document pedagogical processes and observable learning patterns rather than to measure outcomes or test causal relationships.

The specific objectives of the study are to

(1) design and implement a curriculum that integrates STEAM and ESD through interdisciplinary and experiential learning,

(2) employ project-based, inquiry-driven, and reflective pedagogical strategies that support diverse modes of learning and meaning-making,

(3) evaluate the program’s effectiveness using qualitative classroom observation and student self-reflection, and

(4) contribute empirically grounded insights to the theoretical and practical literature on STEAM-ESD integration within 21st century learning environments.

This study contributes to the existing literature by providing an empirically grounded examination of how a STEAM-based ESD curriculum can be designed and implemented at the middle school level, demonstrating how arts-integrated, project-based pedagogies can operationalize sustainability and ethical reasoning, dimensions that remain largely conceptual or underexamined in prior STEAM-ESD research.

LITERATURE REVIEW

ESD

ESD is not merely a content area but a paradigm that reorients education toward ecological, social, and ethical responsibility. As outlined in UNESCO’s *education 2030 agenda* and *ESD roadmap* (UNESCO, 2020), ESD aims to empower learners with the knowledge, values, and capacities to contribute to sustainable societies. It promotes a shift from transmissive education (focused on knowledge reproduction) to transformative learning that cultivates agency, participation, and critical consciousness (Auh et al., 2021).

Central to ESD are competencies such as systems thinking, future thinking, collaboration, and the ability to reflect critically on one’s assumptions and values. However, these competencies remain underdeveloped in many national education systems, which continue to emphasize high-stakes testing, content-heavy curricula, and narrow disciplinary silos.

STEAM Education and Interdisciplinary Learning

STEAM education emerged in the early 2000s as a response to both the growing emphasis on science, technology, engineering, and mathematics (STEM) in global education policy and its limitations. Originally promoted in the USA as a strategy to enhance workforce competitiveness and technological innovation, STEM curricula often prioritized technical mastery, content knowledge, and standardized assessment, often to the detriment of creativity, ethical reasoning, and emotional engagement (Auh & Kim, 2024). In response, educators and scholars introduced the “A” for arts, evolving STEM into STEAM to foreground the importance of creativity, cultural understanding, and design thinking in solving complex real-world problems (Sousa & Pilecki, 2013; Yakman & Lee, 2012).

The inclusion of the arts was not merely aesthetic but epistemological: it sought to humanize technical education by promoting imagination, empathy, and narrative understanding, capacities often overlooked in purely scientific training. By bridging analytical and expressive modalities, STEAM education fosters a more holistic understanding of knowledge as situated, relational, and socially embedded (Auh et al., 2021).

Interdisciplinary education within the STEAM framework supports deeper, more flexible learning by enabling students to transfer knowledge across domains and synthesize novel insights. Kangas et al. (2022) highlight that such integration equips students with the adaptive reasoning skills necessary for engaging with "wicked problems" such as climate change, urban inequality, and global health, problems that resist linear solutions and demand cross-sectoral collaboration.

STEAM and ESD Integration

Recent scholarship has begun to explore how STEAM education and ESD can be meaningfully integrated to cultivate systems thinking, ethical inquiry, and civic engagement (Chistyakov et al., 2023; Hsiao & Su, 2021). Both approaches emphasize real-world relevance, participatory learning, and interdisciplinary problem-solving. Yet, despite these synergies, many current STEAM implementations remain superficial or tokenistic. In such cases, the "A" for arts is often reduced to decorative add-ons or one-off creative projects, rather than being structurally embedded as a way of knowing and a mode of inquiry. This risks reinforcing the very disciplinary silos STEAM was intended to dismantle.

Moreover, in standardized curriculum systems, STEAM is frequently co-opted into performance-driven metrics, where the arts are valued only insofar as they improve test scores or support marketable innovation. This instrumentalization dilutes STEAM's transformative potential to foster the ethical, emotional, and cultural competencies essential to sustainability education.

The current study addresses this gap by offering a deeply integrative model that fuses STEAM and ESD both conceptually and pedagogically. Rather than using STEAM as a delivery mechanism for isolated sustainability topics, the program embeds ESD principles, such as critical reflection, systems awareness, and value formation into the very design and facilitation of interdisciplinary learning experiences. In doing so, it offers an empirically grounded illustration of an ethically grounded STEAM-ESD education model.

Educational Rationale: Why STEAM for ESD?

The rationale for combining STEAM and ESD is their shared emphasis on interconnectedness, creativity, and relevance. In an age of uncertainty, learners must be equipped not only with disciplinary knowledge but also with the ability to synthesize, evaluate, and act ethically.

Key benefits include:

- **Cognitive depth and flexibility:** STEAM-based ESD encourages learners to navigate both abstract systems and concrete problems, enabling transfer across domains.
- **Cultural and ethical sensitivity:** The inclusion of the arts foregrounds emotional engagement and social justice, essential for addressing equity within sustainability education.
- **Multiple intelligences activation:** Visual, spatial, interpersonal, logical, and kinesthetic intelligences are engaged through diverse modes of inquiry and expression.
- **Relevance to the Fourth Industrial Revolution:** As automation and complexity increase, creativity and systems thinking become indispensable life skills.

By embedding sustainability concerns into the very structure of interdisciplinary learning, the model shifts from teaching "about" sustainability to creating *sustainable ways of learning and knowing*.

Program Design and Implementation

The design of the STEAM-based ESD program was guided by the principle that learning for sustainability must move beyond content acquisition to engage students as critical thinkers, creative problem-solvers, and ethically conscious global citizens. As such, the program adopted an integrative, participatory, and iterative approach to curriculum development and implementation. It was grounded in constructivist and experiential learning theories, with a particular emphasis on project-based learning (PBL), systems thinking, and value formation.

Program Structure and Timeline

The program was implemented as a six-week after-school initiative between March and April 2025. Each week, students participated in a 75-minute session (50 face-to-face, 25 online), structured into three core segments:

1. **Concept introduction (15 minutes):** Short lectures, multimedia materials, and interactive demonstrations introduced the week's theme. These segments were designed to anchor abstract concepts in real-world relevance and spark student inquiry.
2. **Hands-on collaborative project work (35 minutes):** Students worked in small groups (4-5 members) to co-design solutions or complete challenges related to the weekly theme. Each project was scaffolded to involve multiple STEAM domains and explicitly linked to one or more of the United Nations Sustainable Development Goals (SDGs).

3. **Reflective virtual dialogue and sharing (25 minutes–Online):** Sessions concluded with group discussions, guided reflection prompts, and online peer-to-peer presentations. Students were encouraged to articulate their learning process, question assumptions, and explore how their ideas connected to larger sustainability concerns.

The format was flexible enough to accommodate differentiated instruction and allowed facilitators to make real-time adjustments based on student engagement and emerging interests.

Thematic Units and Learning Goals

Each week of the program centered around a carefully curated theme that aligned STEAM content with ESD learning objectives. The themes were selected based on three criteria:

(1) conceptual richness,

(2) global-local relevance, and

(3) potential for interdisciplinary exploration.

Week 1. Energy and sustainability–"Designing the future of power"

- Focus: Renewable vs. non-renewable energy, solar and wind energy principles
- STEAM domains: Science (energy transfer), technology (solar panels), engineering (wind turbines), arts (designing informative posters), math (calculating energy efficiency)
- SDGs: #7 (affordable and clean energy), #13 (climate action)
- Task: Teams built small solar-powered devices and evaluated energy output under different conditions.

Week 2. Waste and material science–"Rethinking trash"

- Focus: Life cycle of materials, recycling systems, biodegradable alternatives
- STEAM domains: Chemistry (material decomposition), engineering (product redesign), math (waste audit), arts (visual storytelling)
- SDGs: #11 (sustainable cities), #12 (responsible consumption)
- Task: Students designed everyday products using biodegradable or recycled materials.

Week 3. Eco-urban design–"Building resilient cities"

- Focus: Urban ecosystems, infrastructure resilience, access, and equity
- STEAM domains: Environmental science (green spaces), engineering (urban planning models), math (resource distribution), arts (mapping and narrative design)
- SDGs: #11 (sustainable cities and communities)
- Task: Students constructed scale models of inclusive, resilient urban neighborhoods.

Week 4. Climate monitoring and data–"Seeing change"

- Focus: Data visualization, climate indicators, sensor technology
- STEAM domains: Technology (climate sensors), science (weather systems), math (data graphing), arts (infographics)
- SDGs: #13 (climate action), #9 (innovation and infrastructure)
- Task: Teams collected and interpreted microclimate data around the school and visualized their findings.

Week 5. Future innovation–"Designing for the planet"

- Focus: Ethical innovation, speculative design, ecological imagination
- STEAM domains: Design thinking, engineering, arts (prototyping), ethics
- SDGs: #9 (industry, innovation, and infrastructure), #17 (partnerships)
- Task: Students created prototypes of sustainable technologies (e.g., water filtration kits and wearable climate tech).

Week 6. Community and values–"Sustainability starts with us"

- Focus: Collective action, civic responsibility, personal reflection
- STEAM domains: Communication, design, social science, emotional intelligence
- SDGs: All (integrative)
- Task: Students co-designed a community awareness campaign (posters, videos, installations) to advocate for local environmental or social change.

Each week's design was cumulative, building conceptual complexity and reinforcing prior knowledge through recursive application.

Learning Environment and Facilitation

The program was implemented in a non-formal learning environment, a flexible classroom setting transformed into a collaborative studio. Materials included modular tables, mobile whiteboards, digital devices (tablets/laptops), recycled building supplies, and craft tools. This environment was intentionally configured to decenter the traditional teacher role, positioning facilitators as mentors and co-learners. Facilitators received a two-week training program emphasizing:

- Interdisciplinary curriculum planning
- Dialogic pedagogy and Socratic questioning
- Culturally responsive teaching
- Formative assessment and real-time feedback

Throughout the program, facilitators maintained learning journals to record student progress and adapt strategies as needed. They also held weekly debriefs to reflect on instructional challenges, share observations, and co-design the next session's learning arc.

Inclusion, Equity, and Differentiation

A key feature of the program was its emphasis on inclusive pedagogy. Activities were designed to be multimodal, giving students multiple ways to engage, through building, drawing, storytelling, coding, or debating. This approach supported neurodiverse learners and allowed students with different strengths (e.g., verbal, spatial, logical, and kinesthetic) to contribute meaningfully.

Cultural responsiveness was also embedded through:

- Use of local sustainability examples (e.g., nearby river pollution and traditional ecological knowledge)
- Multilingual materials and visual scaffolding for English learners
- Peer-to-peer mentoring to ensure all voices were heard during collaborative tasks

Documentation and Portfolio Development

Each student maintained a personal sustainability portfolio throughout the program. These portfolios included:

- Sketches and design drafts
- Data analysis charts
- Reflective journal entries
- Photos and documentation of prototypes
- Weekly self-assessments linked to learning objectives

The portfolio served as both an assessment tool and a narrative of growth, reinforcing metacognitive awareness and giving learners ownership of their progress.

The program's design prioritized interdisciplinarity, relevance, creativity, and ethical inquiry. By situating sustainability challenges within hands-on, collaborative STEAM activities, the program offered students a multidimensional platform for thinking systemically, acting responsibly, and imagining alternative futures. This holistic implementation model demonstrates how even short-term interventions can embody the transformative potential of STEAM-aligned ESD.

METHODOLOGY

Research Design and Participants

This study employed an exploratory qualitative design, enabling iterative refinement of pedagogical practices and close observation of student learning behaviors. The research focused on documenting the effects of an integrated STEAM-ESD curriculum on learners' competencies, ethical reasoning, and interdisciplinary transfer.

Participant Selection and Consent

Participants were recruited from two partner public middle schools in Korea, selected through an existing institutional collaboration with the research team. Both schools are government-funded, comprehensive schools serving students in grade 3-grade 7. They operate under the national curriculum while allowing limited site-level flexibility for interdisciplinary enrichment programming. The schools are located in Seoul and in areas of Gyeonggi Province and serve communities with mixed socioeconomic backgrounds, including families from working- and middle-income sectors and a proportion of students receiving fee support and free lunch. The primary language of instruction is Korean, with English as a second language available at the school level.

Regarding prior learning experiences, students' exposure to STEAM and ESD varied. Although both schools had previously implemented occasional project-based learning, science fairs, arts-integration activities, or environmental clubs, neither had a formal, sustained STEAM-ESD integrated curriculum prior to this study. Some students reported prior participation in after-school STEM/arts activities, sustainability campaigns, eco-clubs, robotics, or maker programs, but systematic instruction in ESD competencies (e.g., systems thinking and ethical reasoning about sustainability dilemmas) had been limited to sporadic units or

Table 1. Participant demographics

Category	Detail
Total participants	28 students
Age range	11-14 years (grade 6-grade 8)
Gender distribution	16 female and 12 male
School type	Public schools (urban and suburban)
Language profiles	18 native Korean speakers and 10 bilingual (Korean-English or Korean-Vietnamese)
Learning profiles	5 students identified with mild learning disabilities (ADHD and dyslexia) and 4 English language learners
Prior exposure to STEAM	Minimal to none (25 students) and moderate (3 students) through robotics or science clubs

extracurricular activities, consistent with the broader tendency for ESD to be treated as an add-on rather than embedded in the curriculum.

Recruitment was conducted through schoolwide announcements and teacher recommendations to ensure broad awareness and inclusive participation. Participation was voluntary, and selection was based on student interest, parental consent, and scheduling availability. No academic prerequisites were required. The recruitment strategy aimed to include a diverse cohort reflecting a range of academic performance levels, learning profiles, and social backgrounds, rather than a high-achieving or preselected enrichment group. Informed consent was obtained from all parents or guardians, and assent was obtained from all participating students. The study protocol was reviewed and approved by the host institution's Ethics Committee for Educational Research in January 2025.

Participant Demographics

The cohort included students with a broad range of abilities, cultural backgrounds, and prior exposure to interdisciplinary learning. This diversity enriched collaborative dynamics and allowed for robust examination of differentiated learning pathways (**Table 1**).

Methodological Limitations

This study has several methodological limitations that should be acknowledged. First, the analysis relied on a single primary coder who was also involved in curriculum design and facilitation, which may have shaped interpretive judgments despite reflexive safeguards. While strategies such as iterative coding, peer debriefing, and audit trails were employed to mitigate bias, alternative interpretations remain possible. Second, the short-term duration of the intervention limits claims about the sustainability or longitudinal development of observed competencies. Third, formal member checking with students was not conducted, which constrains the extent to which interpretations can be said to reflect participant validation. Finally, as a qualitative case-based study situated in specific institutional and cultural contexts, the findings are not intended to be statistically generalizable but rather analytically transferable to comparable STEAM-ESD learning environments.

Data Collection and Instruments

Data were collected over a six-week instructional period during the implementation of the STEAM-based ESD program. The study employed multiple qualitative instruments to capture learner experiences, instructional processes, and pedagogical decision-making as they unfolded in situ. The use of multiple data sources was intended to support interpretive depth and contextual richness rather than measurement precision. Three primary instruments were utilized:

1. **Field observation logs:** Facilitators maintained structured observation logs during each instructional session. These logs documented student interactions, collaborative dynamics, problem-solving behaviors, and moments of conceptual, systems-oriented, or ethical engagement. Observations focused particularly on how students navigated interdisciplinary tasks, responded to open-ended challenges, and negotiated collective decision-making.
2. **Student journals and sustainability portfolios:** Students completed written reflective journals after each session, responding to prompts on project decisions, learning challenges, value-based considerations, and evolving understandings of sustainability. These journals were complemented by sustainability portfolios that included design sketches, prototypes, visual representations, and explanatory narratives generated during project-based activities. Together, these artifacts provided insight into both cognitive processes and trajectories of meaning-making over time.
3. **Facilitator debriefs:** Weekly facilitator debriefing sessions were conducted to reflect on instructional experiences, emergent challenges, and observed learning patterns. These sessions were audio-recorded and transcribed verbatim. Debriefs served as a reflective space for documenting pedagogical adjustments and facilitators' evolving interpretations of student engagement and interdisciplinary learning processes.

Examples of Data Collection Prompts and Observation Foci

To enhance methodological transparency, representative examples of prompts and observation foci used during data collection are provided below.

Sample student journal prompts included

- What sustainability challenge did your group work on today, and what ideas from different subjects helped you address it?
- What trade-offs or tensions did your group encounter, and how did you decide which factors mattered most?

- Did today's activity change how you think about the relationship between people, technology, and the environment? Why or why not?

Key observation foci in facilitator logs included

- Evidence of interdisciplinary transfer (e.g., mathematical reasoning applied to design decisions or artistic representation used to explain scientific ideas)
- Moments of systems-oriented reasoning (e.g., recognition of interdependencies or unintended consequences)
- Instances of ethical reflection or value-based discussion during group decision-making
- Expressions of uncertainty, experimentation, or creative risk-taking in problem-solving

Guiding questions for facilitator debriefs included

- Where did students demonstrate conceptual integration across STEAM domains today?
- What moments of ethical tension, ambiguity, or disagreement emerged during the session?
- What instructional adjustments were made, and what prompted those decisions?

Development of the Codebook

The initial codebook was developed deductively based on established ESD and STEAM competency frameworks, with particular reference to UNESCO's ESD key competencies (UNESCO, 2020) and sustainability-oriented competencies articulated by Rieckmann (2018). These a priori categories included constructs such as *systems thinking*, *interdisciplinary knowledge integration*, *ethical reasoning*, and *collaborative problem-solving*.

Following this initial phase, inductive coding was conducted to identify patterns, practices, and forms of expression that emerged directly from the data and were not fully captured by the predefined framework. Inductive codes were grounded in students' language, design behaviors, and reflective statements, allowing themes such as *creative risk-taking* and *comfort with ambiguity* to surface organically.

Comfort with ambiguity was coded when students demonstrated tolerance for uncertainty, including willingness to revise designs without clear answers, verbal acceptance of multiple possible solutions, or reflective statements acknowledging unresolved tensions.

Ethical reasoning was coded when students articulated value-based judgments, considered social or environmental consequences of design choices, or engaged in deliberation about fairness, responsibility, or trade-offs affecting people or ecological systems.

The codebook was iteratively refined across analytic cycles, with code definitions adjusted to reduce overlap and improve conceptual clarity.

Coding Process and Analytic Reflexivity

All coding was conducted by the lead researcher. As the study did not involve multiple independent coders, no inter-coder reliability statistics were calculated. To address potential single-coder bias, several analytic safeguards were employed, including iterative coding cycles, constant comparative analysis across data sources, and reflexive memo-writing within NVivo to document analytic decisions, assumptions, and interpretive shifts. These practices were intended to enhance analytic rigor and transparency rather than to assert neutrality or objectivity.

Trustworthiness and Rigor

Multiple strategies were employed to strengthen the trustworthiness of the qualitative analysis:

- Triangulation was used by cross-referencing themes across student journals, facilitator observation logs, and debrief transcripts. Convergence was interpreted as thematic salience rather than evidentiary confirmation.
- Peer debriefing occurred through structured discussions with an experienced qualitative researcher not directly involved in data collection, focusing on code coherence, thematic plausibility, and alternative interpretations.
- Audit trails were maintained through NVivo project logs, analytic memos, and successive versions of the codebook, documenting how themes evolved over time.
- Reflexivity was explicitly addressed by acknowledging the researcher's dual role as curriculum designer and analyst and examining how this positionality informed interpretation.

Triangulation was conducted at the theme level rather than at the variable or outcome level. For example, systems awareness was identified through student journal reflections describing interdependencies within sustainability challenges, facilitator observation notes documenting causal or relational reasoning during interdisciplinary design tasks and debrief discussions noting cross-domain conceptual connections. Ethical reasoning was triangulated through students' written value statements and reflections, observed dialogue during group deliberation and decision-making, and facilitator reflections on moments of moral tension or uncertainty. This thematic convergence across distinct data sources was used to support interpretive depth rather than to assert causal validity.

Table 2. Emergent themes from thematic analysis

Theme	Description	Representative data excerpt
1. Systems awareness	Students recognized interconnections across ecological, technological, and social systems.	"If you change one part of a city—like the bus route—it affects pollution, people's jobs, and even school time." (student journal, week 3)
2. Transfer of learning	Evidence of students applying knowledge or methods from one domain to another.	"We used math when we made our city map to plan out where water would flow best. It was like science and design working together." (facilitator note, week 3)
3. Creative risk-taking	Students demonstrated willingness to experiment, revise, and pursue novel ideas.	"At first, we didn't think a windmill made from cardboard could spin, but we tried three times, and it finally worked." (group reflection, week 1)
4. Ethical reasoning	Students are engaged in moral or civic reflection about fairness, equity, or justice.	"I noticed we all had computers, but some people in real life don't. What if we made tech that works without Wi-Fi for those places?" (Student journal, week 4)

Table 3. UNESCO's ESD key competencies

ESD key competency	Linked emergent theme
Systems thinking	Systems awareness
Integrated problem-solving	Transfer of learning
Creativity and innovation	Creative risk-taking
Normative and critical	Ethical reasoning

Formal member checking with students was not conducted due to ethical and developmental considerations; however, facilitators reviewed and synthesized thematic summaries during later debrief sessions to assess interpretive resonance with classroom observations. Coding saturation was reached by Week 5, as no substantively new themes emerged and existing categories appeared consistently across data sources.

Emergent Themes and Interpretive Outcomes

Thematic analysis yielded four dominant themes, each reflecting a core dimension of integrated STEAM-ESD learning (Author, 2024c) (**Table 2**).

1. **Systems awareness:** Emerging most strongly during week 2-week 4, this theme reflected students' growing ability to articulate inter-dependencies among environmental, social, and infrastructural systems. Activities such as eco-urban planning prompted learners to consider cascading effects across domains. This aligns with Rieckmann's (2018) conceptualization of systems thinking as central to ESD.
2. **Transfer of learning:** Students demonstrated the ability to apply concepts across disciplinary contexts, such as integrating geometric reasoning into spatial design or applying environmental science data to engineering decisions. This interdisciplinary transfer supports adaptive problem-solving, which is essential to sustainability education (Beers, 2011).
4. **Creative risk-taking:** Across open-ended design tasks, students increasingly engaged in iterative experimentation, revised ideas in response to failure, and expressed comfort with uncertainty. This pattern aligns with existing research linking STEAM pedagogy to innovation and resilience (Chistyakov et al., 2023; Land, 2013).
5. **Ethical reasoning:** Students moved beyond technical optimization to engage in value-based reflection on equity, access, and environmental justice, particularly through activities aligned with SDG 11 and SDG 13. These reflections illustrate ESD's transformative emphasis on moral imagination and civic responsibility (Freire, 1970; UNESCO, 2020).

Synthesis of Outcomes

Taken together, these themes suggest that STEAM-based ESD learning can serve as an integrative pedagogical framework, linking the cognitive, creative, ethical, and civic dimensions of learning. Rather than functioning as isolated disciplinary exercises, STEAM activities became sites for sustained inquiry into socially meaningful sustainability challenges.

Mapping the emergent themes onto UNESCO's ESD Key Competencies framework (**Table 3**) indicates that the program supported multiple sustainability-oriented competencies within a short implementation period. While the findings are context-specific, they offer empirically grounded insight into how STEAM-ESD integration can be enacted pedagogically and what kinds of learning processes it may enable.

Pedagogical Strategies

The pedagogical architecture of the STEAM-based ESD program was built on a synthesis of constructivist, experiential, and critical pedagogies. The instructional approach emphasized learner agency, multimodal engagement, real-world relevance, and ethical inquiry, grounded in both contemporary educational theory and practical design principles. This section outlines the seven core strategies for effectively implementing the program, supported by relevant research.

Integrated Curriculum Design

At the heart of the program was a thematic, integrated curriculum in which each unit deliberately fused content and practices from at least two STEAM domains while simultaneously addressing a core sustainability concept. This approach aligns with Yakman and Lee's (2012) STEAM framework, which emphasizes contextualized learning through the interconnectedness of disciplines.

Curriculum integration in this model went beyond superficial links; rather, it built epistemic bridges across disciplines, enabling students to view knowledge as relational and applied. For example, in the urban resilience module, students explored climate change (science), urban planning (engineering), demographic equity (social studies), and design mapping (art), embodying the concept of *cognitive weaving* (Beers, 2011).

Project-Based and Inquiry Learning

The program adopted project-based learning (PBL) as the central pedagogical method, underpinned by inquiry-based learning (IBL) strategies. According to Rahman et al. (2024), PBL fosters student autonomy, promotes deeper understanding, and supports the transfer of knowledge to novel situations. Similarly, IBL encourages curiosity, hypothesis testing, and iterative exploration, key behaviors in both scientific and sustainable inquiry.

Each project was driven by open-ended, real-world questions (e.g., How can we reduce food waste in our school?), requiring students to frame problems, collect data, develop prototypes, and reflect on the social implications of their solutions. The sustainability anchor in every project ensured that inquiry was not only epistemic but also ethical and civic (Wals & Lenglet, 2016).

Multimodal Learning

Drawing on the theory of multiple intelligences (Gardner, 1983), the program deliberately designed activities that activated different cognitive and expressive modalities. Students are engaged in tactile construction, spatial design, mathematical modeling, visual mapping, and storytelling.

Multimodal design was particularly important for inclusion and engagement, as recent research confirms that multisensory instruction enhances student retention, problem-solving, and creativity (Sousa & Pilecki, 2013; Lin, 2021). Experiential tasks such as building water filters from household materials or mapping carbon footprints made abstract sustainability concepts visible and tangible.

Formative Assessment

Traditional assessment methods were replaced by flexible, process-oriented tools, including learning journals, formative check-ins, peer reviews, and portfolio documentation. These alternative assessment strategies emphasize progress, reflection, and metacognition over product completion or test scores.

Recent literature on ESD pedagogy supports the use of formative and authentic assessment to measure values-based and systems-oriented learning (Mochizuki & Yarime, 2015). Students were encouraged to assess not only their outputs but also their learning processes, collaboration efforts, and ethical reasoning. Facilitators also provided ongoing descriptive feedback, fostering a growth mindset and a culture of revision.

Peer Collaboration

Collaboration was not treated as a soft skill but as a core method of knowledge construction. Students worked in diverse, rotating groups throughout the program, allowing them to practice distributed problem-solving, dialogic learning, and collective creativity (Hargreaves & Fullan, 2012).

Research indicates that peer interaction is essential for developing both cognitive and social-emotional skills in sustainability contexts (Burnard et al., 2021). Moreover, collaboration across disciplines encouraged students to develop empathy, respect for alternative perspectives, and the ability to communicate complex ideas to different audiences.

Situated Sustainability

Sustainability education in this program was not limited to thematic content; it was embedded in the classroom’s structure and ethos. This aligns with Wals and Corcoran’s (2012) notion of *learning as sustainability*, where pedagogy itself becomes an enactment of sustainable values such as interdependence, responsibility, and care.

For example, prototyping materials were sourced from recycled or biodegradable materials, and student teams conducted waste audits and energy-use analyses of their learning environment. This approach made sustainability an embodied experience, cultivating not just knowledge but disposition.

Ethical Reflection

Each session concluded with structured reflective practices, including written prompts, small-group dialogues, and circle sharing. Students were guided to examine not only what they learned but also how it related to their values, identities, and responsibilities as members of a global society.

This practice draws from critical pedagogy (Freire, 1970) and more recent work in transformative sustainability learning, which emphasizes reflexivity, moral reasoning, and worldview awareness (Mezirow, 2000; Rieckmann, 2018). Through reflection, students began to ask meta-level questions: Whose voices are missing in this solution?, What trade-offs are involved?, and How does this connect to justice?

Together, these seven pedagogical strategies created a dynamic, responsive, and socially conscious learning environment. They promoted not only academic depth and interdisciplinarity but also agency, empathy, and ethical awareness, hallmarks of high-quality ESD. When embedded within STEAM contexts, these strategies support the kind of learning that is not only about sustainability but sustainable in its own right.

OBSERVATIONS AND PRELIMINARY FINDINGS

The observational and qualitative data from the six-week STEAM-ESD program revealed several significant patterns that support the program's theoretical framework and instructional design. These findings reflect development across cognitive, affective, and ethical domains and underscore the potential for integrated STEAM education to fulfill the aims of transformative ESD. The following themes emerged as consistent and noteworthy:

High Engagement Across Abilities and Learning Profiles

One of the most prominent outcomes of the program was broad-based student engagement across diverse learning styles and academic profiles. Students who typically exhibited lower engagement in traditional classroom settings were observed participating more confidently in group tasks, especially during the design and construction phases.

This finding supports existing research on the differentiated affordances of STEAM learning, which has been shown to support inclusion by offering multimodal entry points for learners with visual, spatial, kinesthetic, or interpersonal strengths (Gardner, 1983; Sousa & Pilecki, 2013). In particular, visual mapping, physical prototyping, and collaborative storytelling appeared to reduce performance anxiety and foster self-efficacy. As noted by one facilitator, "Students who are usually shy or struggle with reading were leading their teams in building tasks and presenting their designs. The creative aspect gave them a different kind of voice" (facilitator debrief, week 2).

The availability of non-verbal and visual communication pathways enabled students with limited language proficiency or neurodivergent learning profiles to contribute meaningfully, thereby increasing participation and enhancing a sense of classroom belonging.

Emergence of Systems Thinking

Students demonstrated an increasing ability to identify, articulate, and reason through interdependencies among environmental, social, and technological systems, an outcome directly aligned with UNESCO's (2020) systems-thinking competency in ESD.

This shift was most visible in group discussions during the urban resilience and renewable energy units, where students began to describe problems and solutions in terms of cause-and-effect feedback loops, trade-offs, and unintended consequences. They also began to ask "what if" questions that showed anticipatory thinking, an important sub-skill within systems literacy. As one student reflected during the eco-urban design module, "When we moved the playground closer to the street, we realized we needed more trees to block the noise. But then we had less space for the garden. So we had to change both" (student, week 3).

Such examples indicate that, even in a relatively short timeframe, exposure to recursive, real-world challenges can support the development of integrative reasoning skills, reinforcing Rieckmann's (2018) claims that systems thinking can be cultivated through experiential, problem-centered pedagogy.

Improved Interdisciplinary Transfer

The program encouraged learners to draw upon and synthesize knowledge across disciplines in meaningful and novel ways, a key indicator of successful interdisciplinary transfer (Beers, 2011). Students were seen applying mathematical concepts to design problems, scientific data to engineering models, and ethical reasoning to technology proposals. One student group explained, "We decided to use math to calculate the water pressure in the filter design but also used our science notes about how fast water absorbs through layers" (student group log, week 5).

In multiple sessions, students demonstrated fluid movement between domains, indicating that STEAM-based design thinking allowed them to internalize disciplinary tools not as isolated content but as integrated practices. This supports Land's (2013) assertion that STEAM environments enhance learners' ability to transfer and adapt knowledge to new contexts, especially those with social and environmental relevance.

Increased Ethical and Civic Awareness

Perhaps the most transformative shift observed was students' growing attention to the ethical, civic, and equity dimensions of sustainability. While early sessions focused more on technical problem-solving, later reflections and final projects revealed a heightened awareness of who benefits, who is left out, and what justice means in sustainable futures.

This was especially evident during Week 6, when students developed community outreach proposals and public advocacy campaigns tied to the SDGs. Several groups proposed inclusive solutions, such as:

- An energy-saving initiative for families without stable housing
- Eco-literacy workshops for younger students in the school
- A mobile community garden cart for neighborhoods with limited green space

One group explained, "We made our park design wheelchair-accessible and added benches so that older people can use it too. Cities should be for everyone" (student presentation, week 6). Such reflections and project outcomes demonstrate the emergence of normative competence, the ability to understand, evaluate, and act upon ethical dimensions of sustainability (Wals & Lenglet, 2016). They also reflect civic engagement and ownership, as students began to see themselves not just as learners but as potential contributors to local change.

Summary of Findings

The preliminary findings of this study affirm the efficacy of integrating STEAM with ESD in fostering holistic learner development. The four observed domains, engagement, systems thinking, interdisciplinary synthesis, and ethical awareness, align with key competencies outlined in global sustainability education frameworks (Mochizuki & Yarime, 2015; UNESCO, 2020).

Furthermore, the findings highlight that STEAM-ESD programs have the potential to level participation barriers, foster cognitive depth, and support value formation. In the context of a short, six-week pilot, the depth of student insight and observable shifts in behavior suggest that even modest interventions can support learning trajectories associated with transformative learning.

Terminological Calibration in Results and Discussion

Throughout the Results and Discussion, claims regarding learning change are framed using calibrated language consistent with the exploratory qualitative design of the study. Rather than asserting that transformative learning occurred or that students experienced full transformation, findings are interpreted in terms of transformative potential, conditions associated with transformative learning, and early indicators consistent with transformative learning theory. Observed shifts in student engagement, reasoning, and reflection are therefore described as learning patterns aligned with early phases of transformative learning, rather than as confirmed transformational outcomes. In keeping with qualitative reporting conventions, the theoretical framing of transformative learning is developed primarily in the Discussion section, while the Results section remains focused on descriptive patterns emerging from the data.

DISCUSSION

This study affirms the pedagogical and philosophical compatibility between STEAM education and ESD and demonstrates that their integration can foster deeper learning, critical reflection, and transformative potential. The study does not claim that students underwent full perspective transformation as defined by Mezirow (2000) but rather identifies pedagogical conditions and learning patterns consistent with early phases of transformative learning. Observed shifts are therefore interpreted as indicative of transformative potential rather than confirmed transformational outcomes. The findings suggest that interdisciplinary, arts-integrated, and inquiry-based education can activate not only cognitive development but also ethical awareness, systems thinking, and civic consciousness—outcomes that remain difficult to achieve through traditional STEM or content-centered curricula.

At its core, the program operationalized the key sustainability competencies identified by Rieckmann (2018), particularly systems thinking, normative competence, collaboration, and anticipatory thinking. These were not taught in isolation but embedded organically into learning experiences that fused real-world challenges with hands-on design, group deliberation, and ethical reflection.

Beyond Disciplinary Boundaries: Epistemic Shifts in Learning

One of the most critical insights of this study is the imperative to move beyond the segmentation of knowledge, a persistent feature of modern schooling that fragments learning and masks the complexity of real-world problems. Conventional education systems often compartmentalize science, mathematics, engineering, and social studies into isolated silos, thereby obscuring the cross-disciplinary nature of sustainability challenges such as climate change, inequality, and urban resilience (Beers, 2011; Land, 2013).

In contrast, the STEAM-based ESD model implemented here constructed “problem ecologies” in which knowledge domains were treated not as discrete disciplines but as interdependent lenses for inquiry. Students engaged in iterative cycles of design, stakeholder analysis, and systems modeling, enacting knowledge as a relational and action-oriented tool rather than a static body of facts.

Crucially, this pedagogical shift also addressed deeper concerns of epistemic justice. As defined by Fricker (2007), epistemic injustice occurs when individuals or groups are systematically excluded from knowledge production or their ways of knowing are devalued. By integrating artistic expression, emotional reasoning, and collaborative storytelling alongside scientific and mathematical problem-solving, the program elevated diverse epistemologies, including non-verbal, intuitive, and culturally situated forms of learning. This approach resonates with decolonial critiques of Western-centric knowledge hierarchies and supports a pluralistic educational ethos where multiple ways of knowing are validated and woven into collective problem-solving (Santos, 2014).

In this way, the program not only restructured the architecture of learning but challenged dominant epistemological norms, affirming that knowledge is always partial, situated, and enriched by difference.

Creativity and Ethics as Core Learning Outcomes

Another key contribution of this study is its demonstration that creativity and ethical reasoning are not ancillary “soft skills,” but core educational outcomes essential for sustainability and democratic participation. These findings challenge technocratic paradigms that valorize standardized content mastery while marginalizing ethical deliberation and creative risk-taking.

Students in this program were not only building prototypes or visualizing climate data, but they were also grappling with questions of fairness, access, and systemic inequity. Their designs emerged through iterative negotiation between technical feasibility and moral responsibility, a learning process we refer to as interethical: a fusion of interdisciplinary inquiry with ethical dialogue.

This concept aligns with what Mezirow (2000) terms "transformative learning", a process triggered by disorienting dilemmas that prompt learners to re-examine assumptions and engage in reflective reframing. Furthermore, it resonates with Costanza-Chock's (2020) design justice framework, which calls for participatory design processes that center marginalized voices, challenge structural inequalities, and redistribute agency.

In several cases, students revised their proposals after discussions revealed exclusionary impacts (e.g., inaccessible public spaces and inequitable access to technology). These moments signaled a shift from utilitarian problem-solving to moral imagination. The capacity to envision ethically inclusive futures. By embedding ethical reasoning within design tasks, the program helped cultivate civic agency and value-based decision-making in a way rarely achieved in conventional STEM or civics curricula.

Limitations and Challenges

While the program showed strong outcomes, several limitations emerged. Resource demands for materials, facilitator training, and flexible scheduling pose challenges in under-resourced settings; modular, low-cost adaptations and digital toolkits may support scalability. Balancing interdisciplinary breadth with conceptual depth also proved difficult, underscoring the value of follow-up modules that enable deeper, interest-based learning. Assessment relied primarily on reflective tools that require skilled facilitation; future implementations may benefit from rubric-based formative approaches aligned with ESD competencies to enhance consistency. Finally, the short six-week duration of the intervention, combined with the exploratory qualitative design, limited the study's capacity to assess long-term learning trajectories or durable perspective transformation. Accordingly, the study does not claim that participants experienced full perspective transformation as defined by Mezirow (2000) but instead documents pedagogical conditions and learner responses that are theoretically consistent with early stages of transformative learning.

Global Relevance and the Future of Curriculum Design

Despite these limitations, the study contributes to the growing global discourse on reorienting education toward planetary well-being, democratic engagement, and human dignity. It echoes the vision of UNESCO's (2021) futures of education report (2021), which calls for "pedagogies of cooperation, curiosity, and care."

The STEAM-ESD framework presented here can serve as a scalable prototype for local adaptation. In different cultural or national contexts, the thematic units, materials, and technologies can be adjusted, but the core pedagogical principles, interdisciplinarity, critical reflection, and co-creation remain robust and transferable.

Ultimately, this model suggests that we must stop asking "What should students know?" and start asking "What kinds of humans, citizens, and collaborators do we need to co-create a just and sustainable future?" The answer cannot lie in technical knowledge alone but must be forged in classrooms where science meets storytelling, where ethics meets design, and where knowledge is wielded not as power, but as shared responsibility.

CONCLUSION AND FUTURE DIRECTIONS

Empirical Synthesis of Findings

This study provides both conceptual and empirical support for integrating STEAM education with ESD. Through a six-week exploratory program, students demonstrated qualitatively observable learning patterns in systems awareness, ethical reflection, interdisciplinary problem-solving, and creative risk-taking. These findings suggest that even short-term interventions can create pedagogical conditions conducive to sustainability-oriented learning when interdisciplinarity, reflection, and ethical inquiry are structurally embedded in instructional design. Rather than positioning STEAM-ESD integration as a supplemental pedagogical strategy, the study underscores its significance as an epistemological and ethical orientation toward learning in contexts of complexity and uncertainty.

As documented in the four emergent themes identified in the Results section, students engaged in learning processes that became increasingly articulated over time through sustained interdisciplinary inquiry, collaborative design, and reflective engagement with sustainability challenges. These observations do not indicate measurable learning gains; rather, they document learning patterns consistent with early phases of sustainability-oriented and transformative learning.

Pedagogically, student engagement was strongest when sustainability challenges were addressed through open-ended, collaborative, and multimodal STEAM activities. Design-based tasks positioned uncertainty, iteration, and dialogue as productive features of learning rather than obstacles to be resolved. Reflective journals and sustainability portfolios supported students in externalizing their thinking and connecting technical problem-solving with ethical reflection, suggesting that short-term, non-formal STEAM-ESD interventions can foster the emergence of sustainability-oriented learning processes when relational and reflective structures are intentionally designed.

Theoretical and Pedagogical Contributions

Building on these empirical observations, this study advances a process-oriented pedagogical framework that clarifies how STEAM education can function as a mechanism for enacting ESD competencies in practice. Rather than treating sustainability competencies as abstract outcomes to be aligned with disciplinary content, the framework conceptualizes learning as emerging through relational pedagogical processes, including interdisciplinary inquiry, collaborative design, ethical deliberation, and

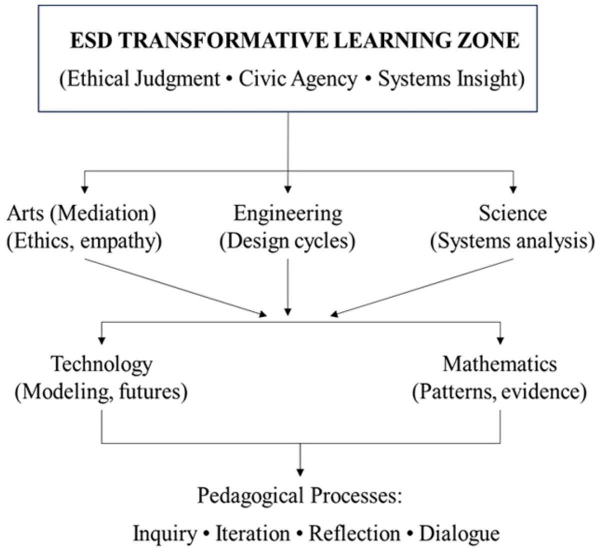

Figure 1. STEAM-ESD pedagogical framework for transformative sustainability learning (Source: Authors' own elaboration)

reflective iteration. In this sense, the study contributes not a rearticulation of existing competency taxonomies but to an empirically grounded account of how sustainability-oriented competencies can be cultivated through everyday classroom practice.

The findings also highlight the pedagogical significance of arts integration as a mediating domain within STEAM-ESD learning. Arts-based practices supported meaning-making, ethical reflection, and emotional engagement, enabling students to grapple with value conflicts and social implications that were less accessible through technical reasoning alone. This reinforces the argument that the ethical and civic dimensions of sustainability learning are not ancillary to STEAM education but central to its transformative potential when sustainability is approached as a mode of learning rather than a topic of instruction.

While existing STEAM-ESD models and UNESCO's competency frameworks provide valuable descriptive accounts of sustainability-related capacities, they offer limited guidance on how to enact these competencies pedagogically. The framework proposed in this study addresses this gap by conceptualizing STEAM not as a set of aligned disciplines but as a pedagogical mechanism through which ESD competencies are generated, negotiated, and internalized. Rather than mapping competencies onto subject areas, the model foregrounds the relational and generative processes, interdisciplinary inquiry, ethical deliberation, creative risk-taking, and reflective iteration, through which sustainability-oriented learning emerges in practice.

Figure Integration and Conceptual Framing

Figure 1 presents the STEAM-ESD Pedagogical Framework developed in this study. Distinct from competency-mapping or content-alignment approaches, the framework conceptualizes STEAM as a process-oriented mechanism through which ESD competencies are enacted in practice. Each STEAM domain contributes distinct epistemic affordances: science supports systems analysis and environmental literacy; technology enables data visualization and future-oriented modeling; engineering facilitates iterative problem-solving and sustainable design; mathematics provides tools for pattern recognition and evidence-based reasoning; and the arts function as a mediating domain that enables ethical reflection, cultural expression, empathy, and normative judgment.

These domains interact dynamically within a central learning zone in which interdisciplinary inquiry, ethical deliberation, and reflective practice converge. Within this zone, ESD competencies, such as systems thinking, anticipatory thinking, normative competence, critical thinking, collaboration, creativity, and integrated problem-solving, are not taught as discrete skills but emerge through sustained engagement with complex, value-laden sustainability challenges. By embedding sustainability within the structure of interdisciplinary learning itself, **Figure 1** reframes ESD from an object of instruction ("learning about sustainability") to a mode of knowing and acting ("learning sustainably").

Figure 2 articulates the key ESD competencies that inform and anchor the pedagogical framework presented in **Figure 1**. Adapted from UNESCO (2020) and Rieckmann (2018), these competencies represent the multidimensional capacities learners need to engage meaningfully with complex sustainability challenges. Rather than functioning as discrete or sequential outcomes, the competencies in **Figure 2** are conceptualized as relational and co-emergent, developing through interdisciplinary inquiry, ethical deliberation, and collaborative problem-solving.

In this study, **Figure 2** serves as a conceptual framework for curriculum design and analytic interpretation. While UNESCO's model specifies the core capacities central to ESD, it remains largely non-prescriptive regarding pedagogy. **Figure 1** builds on this foundation by illustrating how these competencies are pedagogically enacted through a STEAM-based learning structure, positioning STEAM as a generative process through which sustainability-oriented competencies emerge in practice rather than as abstract or standalone outcomes.

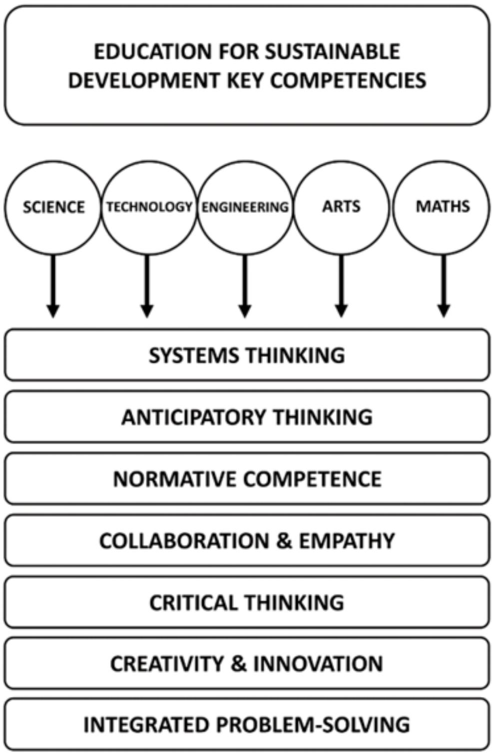

Figure 2. ESD key competencies (Source: Authors' own elaboration)

Implications for Practice

The findings of this study suggest several practice-oriented implications for educators, curriculum designers, and school leaders, each grounded in observed instructional and learning dynamics within the STEAM-ESD program.

1. **Institutional support for interdisciplinary learning:** Classroom observations and facilitator debriefs indicated that effective STEAM-ESD implementation required substantial collaborative planning and iterative redesign of learning activities. Facilitators frequently noted that aligning scientific inquiry, design tasks, ethical discussion, and reflective practice across domains demanded significantly more preparation time than conventional subject-based instruction. Accordingly, schools should provide structural support for interdisciplinary collaboration, including shared planning time, flexible scheduling, and curricular latitude that allows teachers to work across subject boundaries without being constrained by rigid pacing guides or assessment calendars.
2. **Capacity building for teachers:** The study's findings underscore the need for targeted professional development that extends beyond technical STEAM skills. Facilitators reported that the most challenging aspects of instruction involved mediating ethical dialogue, supporting students' comfort with ambiguity, and scaffolding systems-level reasoning, particularly during open-ended design tasks. Professional learning opportunities should therefore emphasize ESD-related pedagogical content knowledge, interdisciplinary facilitation strategies, and reflective teaching practices that enable educators to guide inquiry, manage uncertainty, and support value-based reasoning alongside technical problem-solving.
3. **Localized and culturally responsive design:** Student reflections revealed that engagement deepened when sustainability challenges were framed in relation to local contexts, lived experiences, and community concerns. This suggests that STEAM-ESD curricula are most effective when they are not treated as generic templates but are adapted to reflect place-based sustainability issues and culturally relevant knowledge systems. Educators should be encouraged to co-design learning experiences that connect global sustainability goals to locally meaningful problems, thereby strengthening relevance and fostering civic agency.
4. **Portfolio-based and process-oriented assessment:** Across data sources, both students and facilitators identified assessment as one of the most challenging dimensions of the program. In particular, students struggled to articulate and evaluate learning related to ethical reasoning, anticipatory thinking, and iterative decision-making, competencies central to ESD but poorly captured by conventional testing. These findings point to the need for assessment literacy in STEAM-ESD contexts, including the use of portfolios, reflective journals, and design artifacts that document learning processes over time. Such approaches allow educators to evaluate growth in complex, integrative competencies rather than isolated content mastery.

Implications for Policy

At the policy level, the findings of this study suggest several directions for aligning educational structures with the pedagogical demands of STEAM-ESD integration. While derived from a small-scale, short-term pilot, the implications outlined below are intended as directional insights rather than prescriptive recommendations. These implications should be interpreted as hypotheses for further design-based research rather than as evidence-ready policy prescriptions.

- **Integration of ESD across curriculum mandates:** The observed interdependence of disciplinary knowledge, ethical reasoning, and systems thinking reinforces the need for national and regional curriculum frameworks to embed ESD competencies across subject areas rather than confining them to discrete units or standalone subjects.
- **STEAM as a strategy for advancing SDG 4.7:** The study provides empirical support for positioning STEAM-ESD integration as a viable strategy for advancing SDG Target 4.7, which emphasizes ESD, global citizenship, and cultural diversity (UNESCO, 2020). Policies that explicitly recognize STEAM as a pedagogical pathway, rather than merely a curricular category, can better support transformative sustainability learning.
- **Funding for design-based innovation and assessment development:** Given the intensive planning, facilitation, and assessment demands observed in this study, policymakers should consider targeted funding for design-based innovation labs, maker spaces, and interdisciplinary pilot programs, as well as resources to develop assessment frameworks suited to sustainability-oriented competencies. Such investments can enable schools to prototype, refine, and scale STEAM-ESD models grounded in authentic practice.

Closing Reflection

The world our students are inheriting is shaped by irreversible environmental disruption, algorithmic governance, fragile democracies, and widening inequality. In such a context, education can no longer remain neutral, fragmented, or technocratic. It must become a site of ethical imagination and collective agency. The findings of this study advocate for a pedagogy grounded in integration, creativity, and moral coherence, a pedagogy where science converges with ethics, where artistic expression informs civic responsibility, and where learning becomes a deliberate practice of co-creating more just and sustainable futures.

The integration of STEAM and ESD presented here is not merely a curricular strategy; at its most transformative, it is a quiet reorientation in pedagogical practice. One that expands the very definition of education, not as transmission of knowledge, but as the activation of the full spectrum of human capacities in service of planetary well-being. It invites educators, learners, and communities to imagine differently, to design with care, and to act with purpose.

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