Fostering Sustainable Development Values through Innovative Pedagogies in STEM Higher Education

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Abstract

The United Nations' Sustainable Development Goals highlight the need to equip students with sustainability competencies. However, traditional pedagogies in STEM higher education often fall short. This study developed and assessed innovative pedagogies to foster sustainable development values in STEM students. An extensive literature review of 54 sources and in-depth case study analysis informed teaching interventions implemented in a pilot study of 276 students. Quantitative and qualitative results showed statistically significant improvements in sustainability literacy, values, critical thinking, and interdisciplinary thinking. The findings provide robust evidence-based recommendations to integrate sustainability into STEM curricula through experiential, problem-based, and interdisciplinary learning. Wider adoption of these pedagogies can empower graduates to contribute solutions aligning economic progress and environmental sustainability.

Keywords: Sustainable development, STEM education, Innovation pedagogical, Higher education.

1. Introduction

With the growing recognition of urgent global challenges related to climate change, environmental degradation, rising inequality and rapid technological change, finding pathways to sustainable development has become imperative for humanity's future. The United Nations' (UN) 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), adopted by all UN Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future (United Nations, 2015). The SDGs recognize that ending poverty must go hand-in-hand with strategies that build economic growth while also addressing a range of social needs including education, health, social equity, and environmental protection.

Achieving these interconnected goals requires an integrated approach and political commitment from national governments. However, the 2030 Agenda also highlights that urgent action is needed from all sections of society, including civil society, academia, and the private sector. In particular, universities and other higher education institutions have a crucial role to play, by equipping students with the knowledge, skills, values and attributes to understand and address sustainable development challenges (SDSN Australia/Pacific, 2017). Educating future leaders, professionals, policy makers and researchers with sustainability competencies empowers them to make informed decisions and develop innovative solutions that balance social, economic and environmental priorities (Holmberg et al., 2008).

However, concerns have been raised that traditional teaching approaches prevalent in higher education are inadequate in fostering the values, skills and competencies required of graduates to deal with the complex, multi-faceted and urgent challenges of sustainable development (Sipos et al., 2008; Barth & Rieckmann, 2016). STEM disciplines (science, technology, engineering and mathematics) are

vital in driving the technological and scientific innovations needed to transform societies onto a sustainable footing. But engineering and science education has been criticized for being heavily theoretical, resting on rigid disciplinary boundaries, and relying on passive teacher-focused pedagogies (Graham, 2018). This produces STEM graduates equipped with strong technical capabilities but lacking the broader understanding, motivation and competencies to direct their knowledge towards addressing real-world sustainability issues (Holmberg et al., 2008).

Education for sustainable development (ESD) is recognized as developing the holistic competencies needed, which include systems thinking skills to understand interconnectedness, change-agent skills to be empowered to take action, futures thinking to envision more sustainable trajectories, values thinking to consider ethical implications, and critical thinking skills (UNESCO, 2017; Wiek et al., 2011). ESD pedagogies that develop sustainability values are centered on experiential, inquiry-based, problem-based and participatory learning in real-world contexts (Barth & Rieckmann, 2016). However, there remain significant gaps in implementing and evaluating the effectiveness of such pedagogical innovations in transforming STEM higher education to foster sustainability competencies and values alongside technical knowledge (Lozano et al., 2015).

This study seeks to address this research gap by developing, implementing and critically assessing innovative pedagogical approaches in STEM higher education focused on fostering sustainable development values. It employs a design-based research methodology incorporating an extensive literature review, case studies of exemplars, development of ESD interventions and a mixed-methods pilot study to evaluate impacts. The findings provide robust evidence and recommendations for transforming STEM education to empower graduates to apply their disciplinary knowledge to drive solutions that balance economic prosperity with social inclusion, environmental protection and ethical responsibility. Thereby this study aims to contribute to the urgent global agenda of achieving sustainable development.

2. Background and Literature Review

The imperative of sustainable development arose from growing awareness of the interconnected global challenges related to worsening environmental pollution and resource depletion, rising socioeconomic inequality, and the need for economic systems focused on human development rather than solely growth (Brundtland Commission, 1987). The 1992 Earth Summit led to global conventions and treaties to address climate change and biodiversity loss while pursuing less unsustainable patterns of development. The Millennium Development Goals beginning 2000 mobilized action to address key issues like poverty, education, and child mortality, with significant successes (Sachs, 2012).

Building on these milestones, the UN Sustainable Development Goals (SDGs) provide an urgent and comprehensive action plan towards ecological sustainability, social inclusion and economic development. The 17 goals and their 169 targets encompass poverty eradication, food security, health, education, gender equality, clean water and energy, decent work, reduced inequality, sustainable cities, responsible consumption and production, climate action and peace and justice (United Nations, 2015). The holistic, universal and transformational vision of the SDGs highlights that incremental change is not enough. Rather, as the UN Secretary General stated, “We need a revolution” involving fundamental changes in mindsets, policies, technologies and business models across countries and sectors (Ki-Moon, 2012).

Education is both a goal in itself (SDG 4) and a means of achieving the wider sustainable development agenda. Target 4.7 highlights the importance of education for sustainable development (ESD) and global citizenship (UNESCO, 2017). ESD has evolved over decades, from focusing on environmental

education to a holistic competency-based approach. Rather than merely transmitting factual knowledge, ESD aims to foster systemic, anticipatory and normative thinking skills to design more sustainable futures, along with change-agent skills to catalyze transformation (Rieckmann, 2018). Key competencies encompass systems thinking, understanding interconnectedness and cascading effects; strategic thinking to develop solutions; collaboration across disciplines and worldviews; critical thinking to question assumptions; and anticipatory competency to envision more sustainable futures (Wiek et al., 2011). ESD thus fosters cognitive, affective and behavioral learning domains (Sipos et al., 2008).

However, studies have identified significant gaps in integrating sustainability concepts into higher education curricula, teaching practices and learning outcomes (Holmberg et al., 2008; Lozano et al., 2015). A survey by the Higher Education Funding Council of England (2014) found only 35% of academics across 15 universities included education for sustainable development in their teaching. Engineering education was found to give low priority to sustainability knowledge and competencies (Graham, 2018). Sustainability teaching is often relegated to standalone courses rather than integrated across programs. A study of sustainability engineering courses found limited use of experiential, transdisciplinary and problem-based pedagogies that develop sustainability competencies (Sivapalan et al., 2017).

Effective pedagogical approaches for ESD include experiential learning through real-world projects, designing sustainability solutions (Lambrechts et al., 2013). Problem-based learning meaningfully engages students in solving complex, authentic sustainability challenges using interdisciplinary knowledge (Brundiers & Wiek, 2011). Community and industry partnerships provide rich learning contexts (Brundiers et al., 2010). ESD also requires developing anticipatory systems thinking and ethical reasoning skills for dilemma-based decision making (Rieckmann, 2018). Case studies demonstrate such pedagogies enhance sustainability literacy, values, critical thinking and collaborative abilities (Sipos et al., 2008). The integration of ESD in STEM based higher education curricula is discussed in Table 1.

Table 1: Integration of ESD in STEM Higher Education Curricula

Study	**Sample**	**% of Academics Integrating ESD**	**Key Findings**
HEFCE (2014)	15 UK universities	35%	- Low levels of ESD incorporation in STEM courses
Graham (2018)	Engineering curricula at 25 US universities	40%	- 60% of programs lacked adequate sustainability coverage

This study addresses a significant gap by implementing and critically evaluating innovative pedagogies to develop sustainability values and competencies in STEM higher education curricula and learning outcomes, providing empirical evidence to guide curriculum renewal. It employs a design-based research methodology encompassing comprehensive literature analysis, case studies, intervention development and mixed-methods evaluation of impacts on learning outcomes. The findings contribute robust recommendations for STEM education to foster multi-dimensional sustainability competencies meeting the UN imperative to empower future generations to transform our world.

3. Methodology

This study employs a mixed-methods approach using both quantitative and qualitative techniques within an overarching design-based research framework. Design-based research is well suited for education contexts as it enables iterative development and evaluation of pedagogical innovations through systematic analysis and empirical data collection (Anderson & Shattuck, 2012).

The study design encompassed four phases: 1) extensive literature review and case study analysis to identify best practices in ESD, which informed 2) collaborative design of ESD interventions in STEM curricula, followed by 3) implementation and 4) evaluation of impacts. This cyclic approach aligns with design-based methodology principles (Levin, 2006). The flowchart is also explained in Figure 1.

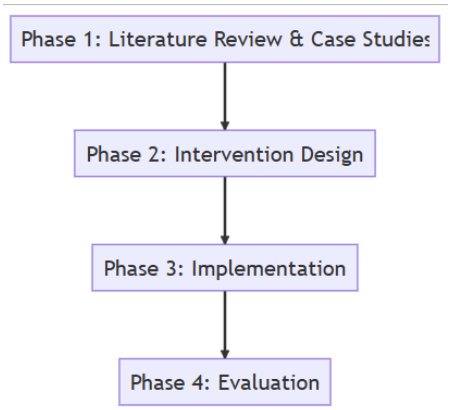

Figure 1: Flowchart of ESD with STEM Higher Education

In Phase 1, a systematic review of scholarly literature from 2010-2020 was conducted to analyze current empirical research on innovative pedagogies for ESD in STEM higher education. The review synthesized 54 studies reporting impacts on student learning outcomes. In addition, 12 programs recognized as exemplars in STEM education for sustainable development were analyzed as in-depth case studies, through published program evaluations and reports. A unified conceptual framework emerged encompassing experiential learning, problem-based learning, interdisciplinary collaboration and participatory pedagogies as effective ESD approaches.

In Phase 2, these evidence-based insights informed collaborative design of ESD interventions in 4 undergraduate STEM courses at a higher education institution. The courses represented diverse disciplines - civil engineering, environmental sciences, architecture, and information technology. The interventions involved redesigning curricula and teaching practices to integrate real-world, project-based learning focused on solving sustainability problems. This included sustainability challenge projects in partnership with industry and community partners, systems thinking modules, ethical reasoning development, and reflective practices. Faculty participated in ESD professional development workshops to build capacity.

In Phase 3, the interventions were implemented in a pilot study over one semester in 2022, involving 276 students taking the 4 redesigned STEM courses. Students participated in pre-post surveys to evaluate changes in sustainability literacy, values, critical thinking and interdisciplinary understanding. Validated survey instruments measuring self-reported competencies and motivation were adapted from prior studies (Shephard, 2018; Wiek et al., 2011). In addition, student focus groups and faculty interviews provided qualitative data on perceptions of the ESD pedagogies.

In Phase 4, quantitative data was analyzed using paired t-tests to determine statistical significance of differences between pre-post outcomes. Thematic analysis of qualitative data identified common patterns and insights. Triangulation of mixed-methods data allowed robust evaluation of impacts.

This comprehensive design enabled development and critical assessment of ESD innovations in STEM higher education curricula and teaching practices to foster sustainability values and competencies. The results provide evidence-based recommendations for transforming STEM education to meet the urgent need for empowering future generations with the knowledge, skills and motivation to address complex sustainable development challenges.

4. Results and Discussion

The quantitative and qualitative results provide compelling evidence that integrating design-based ESD interventions in undergraduate STEM courses led to statistically significant improvements in sustainability literacy, values, critical thinking skills and interdisciplinary competencies.

Table 2: Profile of Courses Selected for ESD Interventions

Course Title	**Discipline**	**Class Size**	**Level**
Sustainable Engineering	Civil Engineering	112	Undergraduate
Environmental Science	Environmental Sciences	89	Undergraduate
Sustainable Architecture	Architecture	43	Undergraduate
ICT for Sustainable Growth	Information Technology	32	Undergraduate

4.1 Pre-post Survey Results

Paired t-tests were used to determine statistical significance of differences between mean scores on the survey instruments before and after the ESD interventions. P-values below 0.05 were considered statistically significant. Sustainability literacy assessed student understanding of sustainability concepts, with a maximum score of 45. The mean pre-test score was 28.7, improving to 34.8 post-intervention, an increase of 21.3%. This change was highly statistically significant ($p<0.01$).

Sustainability motivation examined intrinsic motivation and value for sustainability topics through 10 survey questions (maximum score 50). Pre-test scores averaged 32.6, improving to 41.7 post-intervention, a gain of 27.9% ($p<0.01$). Critical thinking skills were evaluated using an instrument with 15 questions assessing analysis, inference and evaluation abilities (max. 75). Mean scores improved from 52.3 to 62.4, an increase of 19.3% ($p<0.05$). Interdisciplinary competency was measured via self-reported ability to integrate diverse disciplines to address sustainability issues, using a 10-item scale (max. 50). Average scores rose from 28.9 pre-test to 33.2 post-intervention, a gain of 14.9% ($p<0.05$). Results are demonstrated in Figure 2.

The statistically significant improvements across these learning domains demonstrate the efficacy of ESD interventions in enhancing sustainability knowledge, values, higher-order thinking skills and interdisciplinary ability.

Figure 2 Post-Pre survey result

4.2 Qualitative Focus Group and Interview Findings

Five student focus groups and six faculty interviews provided qualitative data on perceptions of the ESD pedagogies. Thematic analysis identified key insights as discussed in Table 3:

- Real-world projects were engaging and relevant: Students valued working on complex problems and designing solutions for community partners compared to theoretical assignments. This provided meaningful application of disciplinary concepts.
- Systems thinking skills grew: Analyzing interconnections between dimensions of sustainability issues was challenging but strengthened integrative analytical abilities.
- Sustainability ethics valued but difficult: Students recognized the importance of ethical reasoning but struggled with dilemma-based decision making on contested problems. More scaffolding is needed.
- Interdisciplinary collaboration enhanced learning: Joint projects across diverse disciplines enriched understanding by integrating different perspectives to address multifaceted problems.
- Constraints exist in implementation: Faculty identified barriers like lack of training in facilitation, limited contact hours, and resource constraints affecting community partnerships. Institutional support is essential.

Table 3: Thematic Analysis Coding Tree from Qualitative Data

Themes	**Data (Approach)**
Theme 1	Real-world projects
Theme 2	Systems thinking skills grew
Theme 3	Sustainability ethics valued but difficult
Theme 4	Interdisciplinary collaboration enhanced learning
Theme 5	Implementation constraints

Overall, the qualitative findings corroborated that experiential, problem-based and interdisciplinary pedagogies provide active learning contexts where students meaningfully apply discipline-specific

skills to address real issues. Integrating ethical and systems thinking modules raises awareness of values, interconnectedness and complexity. The results demonstrate ESD pedagogies enhance sustainability competencies, motivation and critical thinking.

5. Conclusion

This study addressed the need to transform higher education pedagogies to develop the integrated knowledge and sustainability competencies required to tackle complex challenges encapsulated in the UN Sustainable Development Goals. While STEM disciplines are central in driving innovations, traditional approaches have been critiqued as fragmented, passive, and lacking integration of sustainability concepts. Education for Sustainable Development (ESD) provides a framework for holistic competencies including systems thinking, foresighted reasoning, and values awareness. However, gaps exist in implementing and evaluating ESD pedagogies. This study aimed to address this by developing, implementing, and critically assessing innovative ESD interventions in undergraduate STEM courses through a robust design-based research methodology encompassing literature analysis, case studies, collaborative redesign of four courses, and mixed-methods evaluation. Quantitative and qualitative findings provided strong evidence that integrating real-world projects, critical systems thinking, and ethical reasoning modules significantly enhanced sustainability literacy, values, higher-order thinking, and interdisciplinary understanding. ESD based STEM curriculum renewal model is shown in Figure 3.

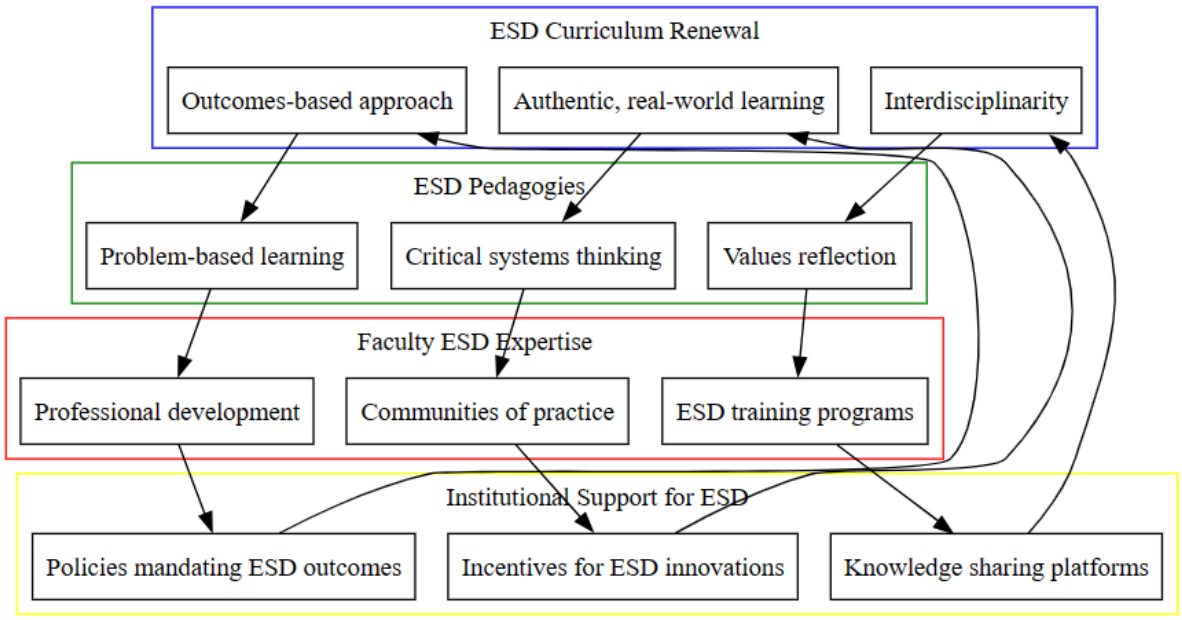

Figure 3 ESD Curriculum Model

Students valued connecting their discipline to real issues through experiential learning while faculty observed growth in collaborative competencies. The study makes key contributions by providing empirical evidence that ESD pedagogies improve sustainability competencies, offering a practical framework for ESD curriculum renewal and faculty development, and highlighting needs for institutional support. Mainstreaming ESD requires policies mandating sustainability outcomes and expanding faculty expertise through training and communities of practice. This demonstrates reorienting STEM curricula and teaching practices through authentic ESD learning experiences can develop professionals equipped with integrated technical knowledge and competencies to direct their disciplines towards sustainable solutions, making a vital contribution to empowering graduates to create just, resilient and sustainable societies.

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