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What's Wrong with 'Engineering Education for Sustainable Development?': It Must Be Required

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Abstract

We are living in a period marked by climate disruption, resource depletion and scarcity, and environmental pollution with persistent pollutants, hence sustainability is not an aspirational goal but an urgent pursuit. Unfortunately, engineering education has been slow to respond to this reality. While engineers have been critical in driving technological advancements, they have also contributed to the challenges that threaten the presence and survival of all living species on earth. Engineers are not only a contributor to the climate crisis but also a key player in its solution. To enable engineers to be the stewards of the future of life on earth, sustainability must be embedded as a core component in all engineering curricula, rather than being offered as an elective course, a single module, or, in some cases, being omitted entirely.

This paper highlights that sustainability should be a mandatory part of every engineering student's education, regardless of discipline. We emphasize that integrating sustainability into the engineering curriculum is critical for equipping future engineers with the knowledge and skills necessary to design solutions that are not only technically sound but also socially, economically, and environmentally sustainable. By adopting a holistic approach to sustainability education, engineering programs can better prepare graduates to tackle the complex and interconnected challenges of our time.

We evaluate different strategies for embedding sustainability across the engineering curriculum, drawing on examples from programs that have already made significant advancement in this area. These approaches range from developing new courses specifically focused on sustainable engineering practices to weaving sustainability principles throughout existing courses in engineering. We examine the relative benefits and limitations of each approach, considering factors such as faculty expertise, industry expectations, accreditation requirements, and the need for interdisciplinary collaboration.

1. Introduction

There is a critical need for a shift in engineering education as we stand at a crossroads, faced with climate disruption, loss of biodiversity, resource depletion, and environmental degradation (IPCC, 2022). Engineers, while having significantly contributed to progress of the society, also need to assume the responsibility for some of the consequences we deal with today. The practice that the needs of humans are unlimited and the belief that the economic growth is critical to overall wellbeing, and that the environment and economy are separate cause our unsustainable approaches (Mair *et al.*, 2020). Engineers affect societal and environmental outcomes, making it critical for engineering curricula to move sustainability from optional electives to integrated, mandatory content. The current engineering curricula often lack integration

of sustainability as a core competency, resulting in engineering graduates to lack the ability to address the interconnected environmental and societal challenges they will need to address (Lozano *et al.*, 2017).

Higher education institutes are able to play an important role to promote sustainability, and to achieve this the faculty need to embed sustainability in the curricula (Cortese, 2003). Competency-based sustainability education promotes the redefinition of the learning outcomes, emphasizing interdisciplinary thinking, systems understanding, ethical reasoning, and long-term vision (Wiek *et al.*, 2011). As we instill awareness around our unsustainable practices in our students, and through providing them with the tools through our curricula, we will inspire them to work within existing structures to cause a positive change. In doing so, however, value tensions are inevitable, so the students must be prepared to navigate conflicts between economic growth and environmental protection, technological advancement and social equity, short-term efficiencies and long-term resilience. Navigating these tensions requires educators and students to develop awareness of value systems, competing interests, and ethical frameworks that inform engineering practice (Frisk & Larson, 2011). Mandating sustainability across curriculum ensures that students engage with these tensions proactively, developing critical thinking and ethical judgment skills essential for responsible practice. The traditional approach of focusing only on technical aspects can be expanded to discuss more complex systems, the needs of and impacts to society, and ethical considerations (Miñano *et al.*, 2019). Embedding sustainability ensures future engineers are prepared to create solutions that are resilient, equitable, and environmentally sound (Wiek *et al.*, 2011). Without mandatory sustainability education, engineers risk continuing to engage in solutions that neglect broader societal and ecological impacts. Embedding sustainability ensures that graduates are prepared to design resilient systems, assess environmental risks, incorporate life cycle analysis, and prioritize social and environmental justice (Scordato and Gulbrandsen, 2024). Enhancing sustainability education in engineering curricula aligns engineering practice with the public interest, upholds professional ethical canons, and prepares graduates to lead in industries driven by sustainability performance metrics, regulatory frameworks, and stakeholder expectations. By institutionalizing sustainability, engineering programs commit to graduate not only technically competent engineers but also thoughtful guards of the planet's wellbeing (Lozano *et al*., 2017).

This paper aims to spark a much needed dialogue on the future of engineering education for sustainable development and inspire engineering faculty to advocate for and implement curricular changes that reflect the urgent realities of our time. By making sustainability a required element of all engineering programs, we can equip future engineers to lead the way in achieving a sustainable and resilient future for all.

2. Strategies for Sustainability Incorporation into Curriculum

To integrate sustainability into engineering education, a variety of pedagogical strategies can be employed. These strategies must go beyond just creating awareness and aim to develop specific competencies including systems thinking, critical reflection, collaboration, and ethical reasoning. Successful incorporation of sustainability requires a mix of approaches, tailored to local contexts, faculty strengths, and institutional goals. The strategies discussed below can be enhanced further by interdisciplinary collaboration, stakeholder partnerships, and assessment of learning outcomes.

Standalone Courses on sustainable development, life cycle assessment, or environmental ethics provide foundational knowledge. However, when isolated from core engineering content, they risk being perceived as peripheral. The authors have taken this approach at Colorado State University but this elective course suffers from some of the shortcoming described below. To ensure relevance and continuity, these courses should be integrated with hands-on projects and case studies from engineering practice.

Curriculum Integration embeds sustainability principles across traditional engineering topics such as thermodynamics, fluid mechanics, and design courses rather than standalone modules. This approach helps students understand sustainability not as a separate issue but as an integral design criterion through adapting existing course content to include sustainability perspectives and analyses (Thürer *et al.*, 2018). Bolstad *et al.* (2025) described the successful integration of sustainability into an engineering program by embedding sustainability objectives directly into technical course outcomes and emphasizing active student engagement with real-world sustainability challenges. The Engineering for One Planet (EOP) Framework supports this model by offering detailed, course-specific integration examples. Their guide provides activity templates aligned with ABET criteria and core sustainability competencies, demonstrating how engineering educators can adapt or modify existing activities to foster systems thinking, environmental literacy, and social responsibility (The Lemelson Foundation, 2023). Activities such as sustainability-focused bridge design problems in statics courses or life-cycle analysis exercises in introductory engineering courses mean that embedding sustainability does not require major curricular changes but thoughtful adaptation of existing content. Through curriculum integration strategies, engineering programs can normalize sustainability as a foundational design criterion and an essential part of professional practice.

Problem-Based Learning (PBL) is one of the most effective strategies for developing sustainability competencies through students working in collaborative teams to solve complex, real-world challenges performing critical thinking (Guerra, 2017) while applying knowledge to develop sustainable solutions (Jollands & Parthasarathy, 2013). Sustainability-focused PBL enhances systems thinking and encourages interdisciplinary collaboration. In a PBL environment, students collaboratively engage with authentic problems, shifting the instructor's role from information provider to learning facilitator. This pedagogical approach aligns with the goals of Education for Sustainable Development (ESD), which emphasizes systemic, future-oriented, and transformative learning processes. Capstone design courses or cross-departmental projects, where environmental, economic, and social dimensions can be simultaneously explored is an ideal opportunity to incorporate sustainability. One approach that integrates the UN SDGs into engineering programs is the for People design challenge sponsored by EWB-UK. (EWB, 2025) This challenge engages students in sustainability problem solving in communities across the world and includes many of traditional PBL learning. Despite growing interest, integration of PBL and sustainability in higher education has yet to fully meet the systemic needs required for a sustainable future (d'Escoffier *et al*., 2024).

Gamification is an effective pedagogical strategy for teaching sustainability concepts in engineering education. Unlike traditional lecture-based methods, game-based learning (GBL) promotes active engagement, critical thinking, and systems-level understanding of sustainability issues. Waite *et al.* (2024) examined the use of multiple GBL approaches to teach circular economy principles to international and interdisciplinary student cohorts. Their findings highlighted that combining multiple GBL methods was more effective than using a single approach, and elements such as sensory experiences, rewards, and collaborative tasks significantly enhanced student engagement and motivation. Similarly, Jain *et al*. (2022) introduced two gamified activities, SDGs Newspaper Mapping and an Entropy and Sustainability Game, to undergraduate engineering students in India and the U.S. These activities were designed to contextualize sustainability challenges, develop an understanding of the interconnectedness of SDGs, and highlight the influence of human actions on entropy and sustainability. Their analysis, revealed that gamification enhanced students' autonomy, competence, and relatedness, leading to deeper learning outcomes and a greater appreciation for sustainability issues.

Flipped and Challenge-Based Learning (CBL) processes ask students to explore global sustainability problems using research, discussion, and self-directed inquiry. These active learning strategies develop higher-order thinking skills and promote deeper engagement with sustainability content. Flipped classroom (FC) and CBL have proven to be highly effective pedagogical strategies for enhancing sustainability education among engineering students. FC enables students to take ownership of their learning by engaging with foundational materials outside the classroom, allowing in-class time to be devoted to deeper discussion, analysis, and application of complex concepts such as sustainability and circular economy principles. However, while FC promotes critical thinking, creativity, and collaborative skills, it does not require real-world problem-solving. Therefore, combining FC with CBL provides a more holistic learning opportunity (Rodríguez-Chueca et al., 2020).

Storytelling and Narrative-Based Approaches build emotional engagement and connection, value-based learning, and contextual understanding of sustainability issues that is typically missing from the traditional lecture based teaching. Shafique *et al*. (2024) found that when students hear or co-create stories around sustainability challenges, especially those rooted in social justice, they gain empathy, critical perspective, and ethical awareness, while internalizing and retaining sustainability concepts. By presenting sustainability through human stories, about water injustice, energy poverty, or climate migration, students connect with characters and contexts that humanize sustainability issues (Waite *et al.*, 2024). Stories that include authentic conflicts, human-centered narratives, and holistic problem contexts are particularly effective in promoting deeper learning and triggering behavioral change for addressing global sustainability challenges (Shafique *et al*., 2024). This approach would complement more technical instruction of sustainability and allow educators to achieve desired learning outcomes.

Living Labs (LL) present a physical and social environment where students, educators, and stakeholders co-create and test and co-create sustainable solutions in collaboration to bridge the gap between theoretical learning and real-world sustainability challenges (Evans *et al.*, 2015). These labs are not just physical spaces but are socio-technical arrangements that promote experiential, collaborative, and participatory learning processes critical to sustainability competency development. Students working in LL engage with authentic, messy problems, navigate uncertainty, and are challenged to think systemically and ethically about real-world impacts. LL support learning that promotes critical reflection, and re-imaginative learning that encourages envisioning alternative futures (van der Wee et al., 2024).

Service-Learning and Community-Engaged Projects allow students to explore real-world, community-centered projects, and the act of service-learning develops critical thinking, systems thinking, leadership, civic engagement, and professional skills essential for sustainable practice. These type of projects have shown that students achieve higher levels of learning, leadership development, and metacognitive growth when their coursework is intentionally aligned with sustainability efforts and community needs (Davis *et al.*, 2024). These projects also link engineering analysis with social justice, encouraging civic responsibility and cultural competence (Clevenger & Ozbek, 2013). Projects that may be aligned with the SDGs and local community needs would offer students meaningful engagement with issues such as water equity, energy access, and waste management. Embedding sustainability through service-learning would allow students to bridge academic content with societal challenges while developing practical solutions for real-world issues.

Generative Artificial Intelligence (AI) can be utilized as a strategy for embedding sustainability into curriculum. AI tools such as ChatGPT can enhance educational methods by enabling students to quickly analyze large datasets, simulate complex environmental scenarios, and visualize social, environmental and economic impacts of emerging engineering technologies. Through these activities, students may engage in

more critical thinking and make meaningful connections between engineering and sustainable development. This approach may address the concern of losing time on technical content coverage by efficient incorporation of sustainability and ethics in engineering curricula (Cañavate *et al*., 2025).

3. Factors Affecting Sustainability Incorporation into Curriculum

While the efforts for integrating sustainability into engineering education is growing, several obstacles still slow the progress. These obstacles are systemic, institutional, pedagogical, and cultural, and overcoming them will require intentional strategies. It is important to note that leadership commitment, interdisciplinary initiatives, and the acknowledgment of the role sustainability plays in engineering education. One of the biggest barriers is curricular rigidity. Engineering programs traditionally have a heavy emphasis on technical content which leaves little room to add interdisciplinary topics. Faculty usually view sustainability as something extra to add on, rather than essential content on how engineers should think and work. Students also perceive sustainability as secondary to core technical skills, reflecting a broader educational culture where environmental and societal impacts are viewed as peripheral concerns rather than integral to engineering practice sustainability (Rampasso *et al.*, 2018). Faculty preparedness have a big influence on sustainability coverage as well. Many instructors report feeling underprepared to teach sustainability topics because they do not have formal training themselves. Leifler and Dahlin (2020) found that although many program directors believe in the importance of sustainability, systematic support such as faculty development opportunities, accessible teaching materials, and incentives is often lacking. Without institutional commitment to support faculty members to teach sustainability effectively, integration efforts remain inefficient (Wilson, 2019). Assessment practices also present a significant barrier. Traditional engineering education emphasizes quantifiable problem-solving skills, making it difficult to assess complex competencies like systems thinking, ethical reasoning, and interdisciplinary collaboration, which are essential for sustainability (Sánchez-Carracedo *et al*., 2021). Existing assessment methods and tools do not easily accommodate the qualitative and value-based dimensions of sustainability, creating misalignment between learning objectives and evaluation methods. Finally, institutional inertia intensify these issues. Although accreditation bodies such as ABET have introduced sustainability language into their standards, there is insufficient follow-up to ensure that programs incorporate these competencies into curricula (Leifler & Dahlin, 2020). In the absence of accountability measures or incentives, sustainability education stays treated as an optional or superficial addition rather than an educational priority. These challenges highlight that embedding sustainability in engineering education is not a technical curriculum development task but an institutional transformation that demands strategic action across multiple levels of higher education.

4. Examples of Successful Sustainability Incorporation into Curriculum

Several universities around the world have implemented successful models for integrating sustainability into their curricula, each using strategies aligned with their institutional contexts and goals. At Colorado State University, critical thinking development was paired with sustainable development themes for first-year civil engineering students, helping students tackle the complex sustainability problems and develop reflective judgment as a core professional skill (Siller, 2001). At Ohio State University, an interdisciplinary faculty group created a framework that organizes diverse sustainability efforts without favoring any discipline, providing a scaffold for guiding future curriculum development while encouraging disciplinary depth and transdisciplinary connections (Conroy et al., 2024). In France, a competency-based model was introduced to support engineering programs in embedding sustainability into technical training, emphasizing ethical reasoning and systemic thinking alongside technical skills (Perpignan, 2021). In

Sweden, Dahlin (2020) found that integration efforts were most successful when institutional leadership, faculty incentives, and accreditation standards aligned. A study of Australian universities showed that although sustainability incorporation was uneven, more institutions were engaging internal and external stakeholders and developing targeted courses, minors, or modules (Arefin et al., 2020). These examples prove that successful incorporation of sustainability into curricula requires more than adding isolated courses, it requires approaches that include competency frameworks, interdisciplinary structures, continuous assessment, faculty support, and student-centered learning strategies.

5. Recommendations for Sustainability Incorporation into Curriculum

Building on the available pedagogical strategies discussed and successful case studies discussed above as well as the challenges identified prior, below are recommendations for promoting and supporting the integration of sustainability into engineering education:

1- Engineering programs should develop a clear institutional vision for sustainability education.
2- Curriculum mapping and gap analysis should be employed to identify opportunities for embedding sustainability and to create plans that align sustainability learning outcomes with course objectives, professional competencies, and accreditation standards.
3- Sustainability education should emphasize outcome-based learning by defining clear and measurable outcomes related to sustainability competencies.
4- Engineering programs should support and encourage interdisciplinary collaboration as addressing sustainability challenges requires engineers to work across disciplinary boundaries and engage with social, environmental, and policy dimensions.
5- Institutions should support faculty development through professional development initiatives, workshops, and interdisciplinary research opportunities.

6. Conclusions

The urgent environmental and societal challenges facing humanity today demand that engineering education undergoes a fundamental shift. Sustainability must no longer be treated as an elective or peripheral topic, but rather incorporated as a core element of every engineering curriculum. Through a holistic approach that integrates sustainability principles into coursework, projects, and assessments, and by preparing faculty and institutions for this transformation, engineering programs can guarantee that their graduates possess the competencies needed to design resilient, ethical, and equitable solutions.

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