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Advancing Sustainability Competencies through Pedagogical Alignment in Engineering Education

Cherish C. Vance, The Ohio State University

Cherish C. Vance (she/her) teaches in the Department of Food, Agricultural, and Biological Engineering at The Ohio State University, where her work centers on engineering for sustainable development, inclusive pedagogy, and the cultivation of sustainability competencies in engineering education. A proud first-generation college graduate, she holds both a B.S. and M.S. in Biological and Agricultural Engineering from Texas A&M University and is currently completing a Ph.D. in Interdisciplinary Engineering. She remains committed to bridging technical rigor with human and environmental well-being—and to doing it with as little unnecessary suffering as possible.

Dr. Kristi J. Shryock, Texas A&M University

Dr. Kristi J. Shryock is the Frank and Jean Raymond Foundation Inc. Endowed Associate Professor in Multidisciplinary Engineering and Affiliated Faculty in Aerospace Engineering in the College of Engineering at Texas A&M University. She also serves as Director of the Craig and Galen Brown Engineering Honors Program. She received her BS, MS, and PhD from the College of Engineering at Texas A&M. Kristi works to improve the undergraduate engineering experience through evaluating preparation in areas, such as mathematics and physics, evaluating engineering identity and its impact on retention, incorporating non-traditional teaching methods into the classroom, and engaging her students with interactive methods.

Dr. Kelly Brumbelow P.E., Texas A&M University

Dr. Kelly Brumbelow is the Associate Head of the Department of Multidisciplinary Engineering and Associate Professor in that department and the Zachry Department of Civil & Environmental Engineering at Texas A&M University. He has been a faculty member at Texas A&M since 2002.

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Abstract

Engineering graduates are increasingly expected to address sustainability challenges that require capabilities beyond technical problem solving. In response, sustainability competency frameworks emphasize capacities such as systems thinking, collaboration, anticipatory reasoning, and ethical judgment [1], [2]. While these competencies are widely articulated across policy, disciplinary, and accreditation contexts, less clarity exists regarding how they are structurally supported through common pedagogical practices in undergraduate engineering education.

This paper examines sustainability competencies through a pedagogy-centered analytic lens. Sustainability competencies were normalized across three influential frameworks: UNESCO Education for Sustainable Development competencies, the Engineering for One Planet framework, and ABET student outcomes. This normalized competency structure was used to examine alignment with pedagogical practices identified through a document-based institutional landscape survey of undergraduate engineering programs.

Publicly available program and course materials were analyzed using descriptive coding to identify recurring pedagogical features, including design experiences, project-based learning, teamwork, communication, community engagement, and reflection. Alignment was treated as evidence of pedagogical visibility rather than of enacted instruction or student learning [3].

Findings indicate that sustainability competencies aligned with dominant engineering pedagogies, such as systems thinking, collaboration, and communication, are consistently supported across programs. In contrast, competencies related to anticipatory thinking, normative reasoning, and self-awareness appear weakly or inconsistently embedded, despite their prominence in sustainability frameworks [4]. These patterns suggest that uneven sustainability competency development reflects pedagogical compatibility rather than lack of institutional intent. The paper contributes an analytic approach for examining how sustainability competencies are structurally supported within engineering curricula.

1. Introduction

Engineering graduates are increasingly expected to address sustainability challenges that extend beyond technical problem solving. Contemporary sustainability discourse emphasizes the need for engineers to reason across systems, anticipate long-term consequences, navigate ethical tradeoffs, and collaborate across disciplinary and social boundaries [1], [2]. In response, sustainability competency frameworks have emerged to articulate the capabilities engineers should develop to engage effectively with complex socio-environmental problems.

Despite broad agreement on the importance of sustainability competencies, their integration into undergraduate engineering education remains uneven. Many programs reference sustainability in mission statements or learning outcomes, yet it is often unclear how sustainability competencies are structurally supported through pedagogy. Prior research has documented a persistent gap between aspirational competency frameworks and the instructional practices that dominate engineering curricula [3], [4]. Sustainability preparation in engineering has often focused on adding sustainability-related content, while leaving underexamined the competencies students must develop to practice sustainability-oriented engineering.

This paper addresses this challenge by developing a normalized set of sustainability competencies across three influential frameworks and using this structure as an analytic lens to examine pedagogical alignment in undergraduate engineering education. The study asks:

1. How can sustainability competencies be normalized across policy, disciplinary, and accreditation frameworks for analytic use?
2. Which sustainability competencies appear to be structurally supported through common pedagogical practices in undergraduate engineering programs?
3. Which competencies appear weakly or inconsistently supported, despite prominence in sustainability frameworks?

By focusing on how pedagogical structures support or constrain sustainability competencies—rather than on sustainability content coverage or student outcomes—this work offers an analytic approach for examining how sustainability-oriented engineering preparation is currently embedded within undergraduate curricula.

2. Background and Framing

2.1 Sustainability Competencies and Pedagogical Mediation

Sustainability competencies emerged in higher education in response to recognition that sustainability challenges require integrated capacities rather than isolated technical knowledge. Competency frameworks emphasize what learners should be able to do, including analyzing complexity, engaging uncertainty, reasoning about values, and acting collaboratively [1], [5].

Across higher education, sustainability competency frameworks have been used to guide curriculum design, articulate educational goals, and connect learning to societal sustainability objectives [6]. These frameworks are intentionally high-level and cross-disciplinary, prioritizing transferability over prescriptive instructional guidance.

Research consistently shows that competencies develop through active, experiential, and participatory learning rather than content exposure alone [3], [5]. Pedagogies such as project-based learning, problem-based learning, community engagement, and reflection are frequently associated with sustainability learning [4].

This pedagogical turn reframes sustainability competencies as emergent and context-dependent, positioning instructional design as a mediating structure between frameworks and student learning.

2.2 Frameworks Shaping Engineering Sustainability Education

Sustainability competencies in engineering education are shaped by multiple frameworks that originate in different institutional and intellectual contexts. These frameworks do not operate as a unified system, nor were they designed to be read together. Instead, they influence engineering education through distinct mechanisms, including global policy guidance, discipline-specific translation, and accreditation requirements. Understanding how sustainability competencies are operationalized in engineering curricula therefore requires attention to the roles these frameworks play individually and to the tensions that emerge when they coexist.

UNESCO Education for Sustainable Development Competencies

The Education for Sustainable Development (ESD) competencies articulated by UNESCO provide a broad, normative framing of the capabilities learners need to contribute to sustainable futures. These competencies emphasize systems thinking, anticipatory thinking, normative reasoning, collaboration, and self-reflection, and are intentionally designed to apply across educational levels and disciplinary contexts [2].

The strength of the UNESCO framework lies in its articulation of aspirational goals. It foregrounds values, futures-oriented judgment, and collective responsibility, making explicit dimensions of sustainability that are often underemphasized in technical education. At the same time, the framework does not specify how these competencies should be embedded within professional curricula, nor how they might be assessed in discipline-specific contexts such as engineering. As a result, UNESCO ESD competencies function primarily as a conceptual reference point within engineering education, shaping discourse and framing rather than instructional structure.

Engineering for One Planet Framework

The Engineering for One Planet (EOP) framework represents a discipline-specific effort to translate sustainability principles into engineering-relevant language and practice [7]. Developed within the context of engineering education reform, EOP emphasizes systems thinking, design under constraint, professional responsibility, and contextual awareness, and explicitly acknowledges pedagogy as a mechanism for sustainability competency development.

Unlike policy-oriented frameworks, EOP attends to instructional forms familiar to engineering educators, including design projects, team-based work, and experiential learning. In doing so, it provides a bridge between abstract sustainability competencies and engineering practice. However, EOP is not an accreditation framework, and its adoption remains voluntary.

EOP foregrounds competencies that align well with design-oriented engineering pedagogies while providing less explicit guidance on competencies that challenge conventional instructional norms, such as anticipatory thinking or reflexive self-awareness. This selective visibility reflects the framework's pragmatic orientation toward curricular feasibility within engineering education.

ABET Student Outcomes

ABET Student Outcomes shape engineering education through accreditation requirements that define the conditions under which programs are evaluated and recognized. These outcomes emphasize abilities such as problem solving, teamwork, communication, ethical responsibility, and lifelong learning [8]. While sustainability is not named explicitly, several ABET outcomes align closely with sustainability-related competencies identified in the literature.

From an analytic perspective, ABET makes visible the competencies that are institutionally stabilized within engineering education. At the same time, it renders less visible those sustainability competencies that require alternative pedagogical approaches or forms of evidence. This dynamic helps explain why certain competencies emphasized in sustainability frameworks remain weakly embedded in engineering curricula despite widespread rhetorical support. Because ABET outcomes are tied to assessment and program review, they exert a structural influence on curricular priorities, leading competencies that can be readily demonstrated and evaluated to be embedded more consistently than those that resist conventional assessment.

Tensions Across Frameworks

Together, the UNESCO ESD competencies, EOP, and ABET Student Outcomes articulate complementary but incomplete views of sustainability competencies in engineering education. UNESCO foregrounds normative and futures-oriented aspirations. EOP translates sustainability into engineering-relevant pedagogical terms. ABET constrains how competencies can be embedded, assessed, and sustained within curricula.

These frameworks overlap conceptually, yet differ in terminology, scope, and emphasis. Competencies that appear central in one framework may be implicit or peripheral in another. As a result, direct comparison across frameworks risks either overstating differences or overlooking shared functional intent. Moreover, reliance on any single framework obscures important dimensions of sustainability competency development that are emphasized elsewhere.

An integrative analytic approach is therefore required to examine how sustainability competencies are structured across frameworks and how they interact with pedagogical practice. The following section introduces a competency normalization approach designed to support cross-framework comparison and to enable examination of how sustainability competencies are structurally supported through pedagogy in undergraduate engineering education.

3. Methods

3.1 Analytical Approach

This study employed a qualitative, document-based analytic approach using publicly available program- and course-level materials. Sustainability competencies were examined as they are signaled through documented pedagogical structures rather than as enacted instructional practice or student learning outcomes. Accordingly, the analysis treats the presence or absence of competency support as evidence of structural visibility, not of instructional quality or effectiveness.

This approach carries several important limitations. Publicly available materials reflect how programs present their curricula rather than how instruction is enacted in practice. As such, the analysis may overrepresent formalized or program-level commitments while underrepresenting informal, instructor-driven, or classroom-level pedagogical variation. In addition, the absence of explicit reference to a competency in program materials does not indicate that it is not addressed in practice. These limitations are consistent with the study's focus on structural visibility rather than enacted instruction.

3.2 Institutional Landscape Survey

Institutions were selected from recognized engineering program rankings. A total of n = 15 institutions were included in the analysis, encompassing multiple programs, tracks, and co-curricular initiatives where applicable. The majority of institutions reviewed included some explicit reference to sustainability or sustainability-oriented learning, although the level of specificity and integration varied. Publicly available program- and course-level materials were reviewed, including degree requirements, course descriptions, curricular pathways, and sustainability-related program materials. Initial review was limited to materials accessible within four navigational steps from institutional landing pages, with additional exemplars included where sustainability engagement was clearly signaled. These materials are treated as evidence of pedagogical visibility rather than enacted instruction.

3.3 Descriptive Coding of Pedagogical Practices

Materials were coded descriptively for pedagogical features, including project-based learning, design experiences, teamwork, communication, community engagement, and reflection. Coding captured presence rather than quality or intensity.

3.4 Competency Normalization and Alignment

Sustainability competency frameworks relevant to engineering education differ not only in terminology, but also in how competencies are scoped, operationalized, and positioned relative to pedagogy and assessment. Some frameworks articulate broad capacities intended to guide educational systems, while others translate sustainability into discipline-specific practices or evaluative criteria. As a result, direct comparison across frameworks risks focusing on labels rather than on the functional roles competencies play in educational contexts.

To support cross-framework analysis, this study employed a competency normalization approach. Normalization was used as an analytic strategy to make sustainability competencies comparable across frameworks, rather than as an attempt to reconcile them into a single authoritative model. The goal was to enable examination of how competencies articulated in different contexts align with pedagogical practices commonly found in undergraduate engineering education.

Normalization proceeded by identifying competencies that serve similar functional purposes, even when described using different language or levels of specificity. Decisions were guided by conceptual intent and by the kinds of learning experiences competencies appear to require, rather than by strict definitional boundaries. This approach reflects the reality that sustainability competencies are often developed in integrated ways and are difficult to isolate cleanly within instructional settings [1], [3].

Worked Example: Anticipatory Thinking Across Frameworks

The competency commonly described as *anticipatory thinking* illustrates the need for normalization. In the UNESCO Education for Sustainable Development competencies, anticipatory thinking is framed as the ability to evaluate possible futures, assess long-term consequences, and engage uncertainty in decision-making [2]. This framing foregrounds futures-oriented judgment and explicitly connects sustainability to temporal responsibility.

Within the Engineering for One Planet framework, anticipatory dimensions are present but less explicitly named. Futures-oriented reasoning appears implicitly through emphasis on design under constraint, life-cycle considerations, and long-term system performance [7]. Rather than being articulated as a standalone competency, anticipatory thinking is embedded within design practice and professional responsibility.

In contrast, ABET Student Outcomes do not explicitly reference futures-oriented reasoning. However, anticipatory elements can be inferred indirectly through outcomes related to problem solving, ethical responsibility, and consideration of constraints [8]. These outcomes create space for anticipatory reasoning, but do not require it, nor do they specify pedagogical structures that would foreground long-term consequences or scenario-based thinking.

Considered separately, these framings appear distinct. Considered functionally, however, they point toward a shared underlying competency: the capacity to reason about future consequences and uncertainty in decision-making. Normalization collapses these variations into a single analytic category, *anticipatory thinking*, enabling examination of whether and how pedagogical practices support this capacity across curricula.

This example illustrates why normalization is necessary for pedagogical analysis. Without normalization, anticipatory thinking would appear prominent in policy-oriented frameworks, peripheral in discipline-specific frameworks, and absent in accreditation criteria. Normalization reveals instead that the competency may be unevenly articulated, rather than entirely missing, and allows analysis to focus on whether pedagogical structures exist that could plausibly support it.

Outcome of the Normalization Process

Applying this process across frameworks yielded a consolidated set of ten sustainability competencies that capture the primary constructs emphasized in UNESCO ESD competencies, the Engineering for One Planet framework, and ABET Student Outcomes. These competencies are not intended to function as learning outcomes or curricular standards. Rather, they serve as analytic categories that support comparison across frameworks and alignment with pedagogical practices.

The normalized competencies prioritize conceptual coherence and analytic usability over exhaustiveness. In some cases, distinctions maintained within individual frameworks were collapsed to avoid artificial separation of closely related capacities. In other cases, broader competencies were retained to reflect how sustainability learning tends to occur through integrated instructional experiences rather than isolated activities.

Throughout the analysis, normalization decisions were revisited iteratively as alignment work progressed. This iterative approach reflects both the complexity of sustainability education and the exploratory nature of examining competency–pedagogy relationships at the curricular level. The resulting competency structure provides the analytic foundation for examining patterns of pedagogical alignment in the sections that follow.

4. Normalized Sustainability Competencies

The normalization process described in the previous section resulted in a consolidated set of ten sustainability competencies (Table 1). These competencies are used in this study as analytic categories for examining how sustainability is structurally supported through pedagogy in undergraduate engineering education. They are not intended to function as learning outcomes, curricular standards, or measures of student achievement.

Each competency represents a broad area of capability that appears, in varying forms, across the source frameworks. Normalization involved grouping competencies based on shared intent and functional role, rather than preserving distinctions tied to specific terminology or framework structure. As a result, the competencies should be read as interpretive categories that support comparison across frameworks and alignment with pedagogical practices.

Table 1 presents the normalized competencies and their correspondence across frameworks. For reference, ABET outcomes are cited by number: (1) problem solving, (2) engineering design under constraints, (3) communication, (4) ethics and professional responsibility, (5) teamwork, (6) experimentation and data analysis, and (7) lifelong learning.

Table 1. Competency Framework Alignment Table (Integrated Across UNESCO, EOP, and ABET)

Competency	Definition	UNESCO	EOP	ABET Outcomes
Systems Thinking	Understanding and analyzing complex systems, interactions, and feedback.	Systems thinking; Integrated problem solving.	Systems Thinking; Environmental Impact Assessment; Design.	2, 4, 6; sometimes 1.
Anticipatory / Futures	Developing and evaluating future scenarios, risks, and long-term consequences.	Anticipatory competency.	Systems Thinking; Design; Responsible Business/Economy.	2, 6.
Normative / Ethics	Analyzing values, justice, equity, and ethical dimensions of sustainability problems.	Normative competency.	Social Responsibility; Responsible Business/Economy.	4, 2.
Strategic / Action-Oriented	Designing and planning effective interventions toward sustainability goals.	Strategic competency.	Design; Environmental Impact Assessment.	2, 5, 7.

Competency	Definition	UNESCO	EOP	ABET Outcomes
Collaboration and Teamwork	Working productively and equitably with others across roles and expertise.	Collaboration competency.	Communication and Teamwork; Social Responsibility.	5, 4.
Communication	Communicating complex ideas clearly for diverse audiences.	Embedded across competencies.	Communication and Teamwork.	3.
Critical Thinking and Problem Framing	Examining assumptions, biases, frames, and multi-perspective interpretations.	Critical thinking competency.	Critical Thinking; overlaps with Systems Thinking and Design.	1, 6.
Self-Awareness and Reflection	Reflecting on positionality, motivations, and learning processes.	Self-awareness competency.	Skills and Behaviors; leadership/professional skills.	4, 7.
Intercultural and Socio-Cultural Competence	Engaging across cultural differences with humility and awareness of power.	Distributed across competencies.	Social Responsibility; Communication and Teamwork.	2, 4, 6.
Integrated Problem Solving	Synthesizing all competencies to design context-appropriate solutions.	Integrated problem-solving meta-competency.	Intersection of design, systems, and skills.	1, 2, 5, 6, 7.

Correspondence indicates conceptual alignment rather than equivalence in emphasis or implementation. Likewise, the absence of a correspondence does not imply that a competency is incompatible with a given framework, only that it is not articulated explicitly or consistently within that source.

The normalized competencies are intentionally broad. This reflects how sustainability-related learning tends to occur in practice, where multiple competencies are often engaged simultaneously through a single instructional experience. Attempting to define competencies more narrowly would risk creating analytic distinctions that are difficult to observe meaningfully at the curricular level.

The analysis focuses on which competencies appear to be structurally supported through common instructional practices and which appear weakly or inconsistently supported, based on the documented pedagogical features identified in program and course materials.

5. Findings: Pedagogical Alignment Patterns

Analysis of publicly available program- and course-level materials revealed clear and recurring patterns in how sustainability competencies are structurally supported through pedagogy in undergraduate engineering education. These patterns reflect the degree to which sustainability competencies align with dominant instructional forms rather than the presence or absence of sustainability intent. Across institutions, some competencies appeared consistently embedded through common pedagogical structures, while others were weakly or inconsistently supported despite prominence in sustainability frameworks.

5.1 Competencies with Strong Structural Support

Several sustainability competencies showed strong and consistent structural support across the surveyed programs. These competencies aligned closely with pedagogical practices that are already well established within engineering curricula.

Systems thinking was the most consistently supported competency. Program and course materials frequently emphasized system-level reasoning, interconnected components, and contextual constraints. It was most visible in design-oriented coursework, where students were expected to account for interacting technical, environmental, and operational factors. References to system performance, boundary conditions, and tradeoffs appeared frequently, suggesting that systems thinking is readily embedded when framed through design and analysis practices familiar to engineering education.

Collaboration and teamwork were also strongly supported. Team-based projects, group design assignments, and collaborative problem-solving activities appeared widely across programs and course sequences. They were often framed in terms of professional preparation or project efficiency rather than sustainability explicitly. Nonetheless, they created consistent opportunities for developing interpersonal and collaborative competencies emphasized across sustainability frameworks.

Communication likewise showed strong structural support. Written reports, oral presentations, and project documentation were common requirements, particularly in capstone courses and multi-course design sequences. Communication was typically framed as a professional or technical skill, yet these practices align closely with sustainability competencies related to translating complex ideas for diverse audiences and stakeholders.

5.2 Competencies with Moderate or Indirect Support

A second group of sustainability competencies exhibited moderate or indirect structural support. These competencies were often present implicitly through pedagogical design, but were less consistently articulated or foregrounded.

Critical problem framing appeared in coursework that emphasized open-ended or ill-structured problems. Design challenges that required students to define objectives, interpret constraints, or navigate incomplete information provided opportunities for questioning assumptions and reframing problems. However, such activities were rarely described explicitly in terms of critical reflection or problem framing. As a result, support for this competency appeared to depend heavily on instructor emphasis rather than on shared curricular intent.

Integrated problem solving showed similar patterns. Multi-stage design projects and capstone experiences created opportunities for synthesizing technical, contextual, and procedural considerations. While these structures align well with integrated sustainability competencies, explicit connections among systems thinking, ethics, and long-term consequences were uncommon. Integration often occurred in practice, but without being named or assessed as such.

Contextual and intercultural awareness appeared sporadically. Some programs referenced global contexts, community engagement, or societal impacts, particularly within environmental or humanitarian engineering tracks. These experiences often supported multiple sustainability competencies simultaneously. However, they were typically elective or peripheral rather than embedded across core curricula, limiting their structural reach.

5.3 Competencies with Weak or Inconsistent Support

Several sustainability competencies were weakly or inconsistently supported across the surveyed materials. These competencies tended to require pedagogical approaches that extend beyond conventional engineering instructional forms.

Anticipatory thinking, defined as reasoning about future consequences and uncertainty, was rarely articulated explicitly. References to long-term impacts, scenario analysis, or futures-oriented decision-making appeared infrequently and were most often associated with policy-adjacent or environmental electives. Within core engineering design sequences, anticipatory considerations were more often implicit than explicit, limiting opportunities for sustained engagement with futures-oriented reasoning.

Normative and ethical reasoning related to sustainability also showed inconsistent support. While ethics instruction was commonly referenced, it was often framed narrowly in terms of professional responsibility or compliance. Explicit engagement with values-based tradeoffs, justice considerations, or normative sustainability questions was uncommon within technical coursework. When present, such engagement was more likely to occur in standalone ethics courses rather than being integrated into engineering design contexts.

Self-awareness and reflection were the least visible competencies across programs. Structured reflection activities, positionality statements, or explicit prompts encouraging students to examine their own assumptions and roles as engineers were rare in publicly described pedagogical practices. Where reflection appeared, it was typically informal or optional rather than positioned as a core instructional strategy.

5.4 Cross-Cutting Patterns

Several cross-cutting patterns emerged across competency categories. First, sustainability competencies that align closely with dominant engineering pedagogies were more consistently supported than those requiring alternative instructional forms. Design projects, teamwork, and communication tasks readily supported systems thinking and collaboration, while competencies related to futures, values, and self-awareness lagged structurally.

Second, many pedagogical practices supported multiple sustainability competencies simultaneously, yet these overlaps were rarely articulated. As a result, opportunities for intentional competency development may be underrecognized, even where relevant instructional structures already exist.

Finally, programs often articulated sustainability goals broadly, but the pedagogical mechanisms available within conventional curricula shaped which competencies were embedded consistently and which remained peripheral.

6. Discussion and Implications

Together, the findings suggest that competencies that map cleanly onto established instructional forms are more readily supported, while those that require alternative pedagogical approaches remain weakly embedded.

6.1 Pedagogical Compatibility as a Structuring Force

The strong structural support observed for systems thinking, collaboration, and communication reflects their compatibility with long-standing engineering pedagogies. Design projects, team-based work, and capstone experiences have long been central to engineering education, and these pedagogical forms readily accommodate competencies related to system-level reasoning and interpersonal coordination. Importantly, this alignment does not require sustainability to be explicitly named. Competencies can be supported implicitly through pedagogical structure alone.

In contrast, competencies such as anticipatory thinking, normative reasoning, and self-awareness appear to challenge prevailing instructional norms. These competencies often require sustained engagement with uncertainty, values, and reflexive judgment, which are less easily accommodated within problem-solving paradigms that emphasize optimization, closure, and technical correctness. As a result, even when sustainability frameworks foreground these competencies, they struggle to gain structural footholds within conventional engineering curricula.

In addition to pedagogical fit, accreditation and assessment structures reinforce these patterns. ABET Student Outcomes emphasize competencies that can be clearly demonstrated and evaluated within conventional engineering coursework, such as problem solving, design, teamwork, and communication. Competencies related to anticipatory reasoning, values-based judgment, and self-awareness are less easily translated into observable, assessable outcomes using standard instruments. As a result, these competencies are less likely to be embedded consistently at the curricular level, even when they are recognized as important within sustainability frameworks. This dynamic reflects not only pedagogical preference, but also the influence of assessment feasibility on curricular design.

This pattern suggests that pedagogy, rather than framework articulation, functions as a primary mediating structure in sustainability competency development. Frameworks can articulate aspirations, but pedagogy determines which competencies are likely to be cultivated consistently.

6.2 Framework Fragmentation and Partial Visibility

The use of multiple frameworks to guide sustainability education introduces both opportunity and fragmentation. UNESCO Education for Sustainable Development competencies articulate normative and futures-oriented goals that expand the scope of sustainability learning. Discipline-specific initiatives such as Engineering for One Planet translate sustainability into engineering-relevant language and pedagogy. Accreditation outcomes, meanwhile, stabilize certain competencies through institutional requirements.

Each framework makes particular competencies visible while rendering others less salient. When these frameworks are considered in isolation, they offer partial accounts of sustainability competency development. The normalization approach employed in this study makes these partialities visible by revealing how competencies emphasized strongly in one framework may be weakly articulated or structurally constrained in another.

This fragmentation helps explain why sustainability competencies often appear rhetorically present but unevenly operationalized. It is not that competencies are absent from frameworks, but that they are differentially reinforced through pedagogical and institutional structures.

6.3 Implications for Engineering Curricula

For engineering curricula, these findings suggest that expanding sustainability competency development is less a matter of adding new content than of examining how existing pedagogical structures support or constrain different competencies. Many programs already possess instructional forms capable of supporting a broader range of sustainability competencies than is currently recognized. However, without intentional framing, these opportunities may remain underleveraged.

At the same time, the findings highlight the limits of relying solely on dominant pedagogies. Competencies related to futures-oriented reasoning, values-based judgment, and reflexivity may require instructional approaches that are less familiar within engineering education, such as structured reflection, scenario-based analysis, or engagement with contested problem definitions. Without attending to these pedagogical demands, sustainability competency frameworks risk remaining aspirational rather than operational.

6.4 Implications for Sustainability Education Research

From a research perspective, this study underscores the value of treating sustainability competencies as analytic categories rather than as fixed outcomes. The normalization approach enables examination of structural patterns without presuming how competencies should be taught or assessed. This analytic stance complements empirical studies of student learning by clarifying the curricular and pedagogical conditions under which competency development is more or less likely to occur.

The findings also point to the importance of examining pedagogy as a site of constraint and possibility in sustainability education. Framework proliferation alone is unlikely to resolve gaps in competency development unless accompanied by careful attention to instructional structure.

By foregrounding pedagogy, this work contributes a structural lens for understanding persistent patterns in sustainability education within engineering.

7. Conclusions

This paper examined how sustainability competencies are structurally supported within undergraduate engineering education through an integrative analysis of competency frameworks and pedagogical practices. By normalizing sustainability competencies across UNESCO Education for Sustainable Development competencies, the Engineering for One Planet framework, and ABET Student Outcomes, the study developed a common analytic structure for examining how sustainability competencies intersect with dominant instructional forms.

The findings indicate that sustainability competencies are unevenly embedded within engineering curricula. Competencies that align closely with established pedagogical practices, including systems thinking, collaboration, and communication, are consistently supported across programs. In contrast, competencies related to anticipatory thinking, normative reasoning, and self-awareness appear weakly or inconsistently embedded, despite their prominence in sustainability frameworks. These patterns suggest that pedagogical compatibility, rather than lack of institutional intent, plays a central role in shaping sustainability competency development.

The normalization approach used in this study contributes an analytic tool for examining sustainability education across fragmented frameworks. Rather than proposing new competencies or curricular standards, this work demonstrates how existing frameworks can be brought into dialogue to reveal structural patterns that are otherwise difficult to see. Treating competencies as analytic categories allows attention to shift from debates about terminology to questions of pedagogical affordance and constraint.

Several limitations should be acknowledged. The analysis relied on publicly available program and course materials and therefore reflects stated curricular structures rather than enacted instruction or student learning. Alignment was treated as indicative of pedagogical affordance rather than evidence of competency development. As such, the findings do not speak to the effectiveness of specific pedagogical approaches, nor to how students interpret or experience sustainability-oriented instruction.

Despite these limitations, the study offers a framework-sensitive, pedagogy-centered lens for examining sustainability competency integration in engineering education. By clarifying which competencies are structurally supported and which remain constrained, this work provides a foundation for future research examining how sustainability competencies are cultivated in practice and how pedagogical design can more intentionally support the full range of competencies articulated in sustainability frameworks.

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