Depósito Legal: PPI 200802ZU2980 / ISSN: 1856-9331. Vol. 34. Núm. 29. (2026): Octubre 2026 - Marzo 2027

Educating Engineers for Climate Action – Competencies, Pedagogies, and Epistemologies for Sustainability

Educando a los ingenieros para la acción climática: competencias, pedagogías y epistemologías para la sostenibilidad

Educare gli ingegneri all'azione per il clima: competenze, pedagogie ed epistemologie per la sostenibilità

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Recibido: 14/03/2026. **Aceptado:** 02/06/2026. **Publicado**: 16/10/202.6

Abstract

Universities play a fundamental role in training professionals with the ethical principles and technical skills needed to combat climate change. The transition to a carbon-neutral society requires a skilled workforce capable of contributing to sustainable development in fields as diverse as engineering, law, communication, and administration. This article focuses on engineering, given that this discipline has the potential both to exacerbate climate change through the solutions it generates and to contribute to mitigation and adaptation to this phenomenon. This article investigates current trends in the teaching of climate change and sustainability in engineering through a review of the literature from the past 15 years (2011–2025). Forty-two studies are analyzed, identifying their main themes and synthesizing their contributions in areas such as competency-based education, curriculum evaluation, and the ethical foundations required in teaching. Key frameworks are discussed, including Wiek's competency model for sustainability, Jensen and Schnack's competence for action, and transdisciplinary education. Although these represent significant theoretical advances, engineering education is rooted in reductionism, disciplinary silos, and depoliticization, all of which hinder the transition toward a holistic, action-oriented education capable of addressing the challenges of sustainability.

Keywords: climate change, sustainability, higher education, engineering, sustainable development

Resumen

Las universidades tienen un papel fundamental en la formación de profesionales con los principios éticos y las competencias técnicas necesarias para combatir el cambio climático. La transición hacia una sociedad neutra de carbono requiere de una fuerza de trabajo capacitada para contribuir al

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desarrollo sostenible, en áreas tan diversas como la ingeniería, el derecho, la comunicación y la administración. Este artículo se centra en la ingeniería, dado que esta disciplina tiene la capacidad tanto de agravar el cambio climático con las soluciones que genera, como a contribuir con la mitigación y adaptación a este fenómeno. Este artículo investiga las tendencias actuales en la enseñanza del cambio climático y la sostenibilidad en ingeniería a través de una revisión de la literatura de los últimos 15 años (2011-2025). Se analizan 42 trabajos, identificando sus temáticas principales y sintetizando sus contribuciones en áreas como la formación por competencias, la evaluación curricular y los fundamentos éticos requeridos en la enseñanza. Se discuten marcos de trabajo fundamentales como el modelo de competencias para la sostenibilidad de Wiek, la competencia de acción de Jensen y Schnack y la formación transdisciplinaria. Aunque estos representan importantes avances teóricos, la formación en ingeniería tiene sus raíces en el reduccionismo, los hilos disciplinarios y la despolitización, los cuales dificultan la transición hacia una educación holística y orientada a la acción que permita asumir los retos de la sostenibilidad.

Palabras clave: cambio climático, sostenibilidad, educación superior, ingeniería, desarrollo sostenible

Riassunto

Le università svolgono un ruolo fondamentale nella formazione di professionisti dotati dei principi etici e delle competenze tecniche necessarie per combattere il cambiamento climatico. La transizione verso una società a emissioni zero richiede una forza lavoro qualificata in grado di contribuire allo sviluppo sostenibile in settori così diversi come l'ingegneria, il diritto, la comunicazione e l'amministrazione. Il presente articolo si concentra sull'ingegneria, poiché questa disciplina ha la capacità sia di aggravare il cambiamento climatico con le soluzioni che propone, sia di contribuire alla mitigazione e all'adattamento a questo fenomeno. Questo articolo indaga le tendenze attuali nell'insegnamento del cambiamento climatico e della sostenibilità in ingegneria attraverso una rassegna della letteratura degli ultimi 15 anni (2011-2025). Vengono analizzati 42 lavori, identificandone i temi principali e sintetizzandone i contributi in aree quali la formazione per competenze, la valutazione curricolare e i fondamenti etici richiesti nell'insegnamento. Vengono discussi quadri di riferimento fondamentali quali il modello delle competenze per la sostenibilità di Wiek, la competenza d'azione di Jensen e Schnack e la formazione transdisciplinare. Sebbene questi rappresentino importanti progressi teorici, la formazione in ingegneria affonda le sue radici nel riduzionismo, nei filoni disciplinari e nella depoliticizzazione, che ostacolano la transizione verso un'istruzione olistica e orientata all'azione, in grado di affrontare le sfide della sostenibilità.

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Parole chiave: cambiamento climatico, sostenibilità, istruzione superiore, ingegneria, sviluppo sostenibile.

Introduction

In 2017, UNESCO's 195 member states adopted the Declaration of Ethical Principles in Relation to Climate Change, outlining the ethical guidelines that should inform climate policies and decisions by states, individuals, institutions, and corporations. The declaration also calls for equipping all people with the skills needed for climate change mitigation and adaptation, while fostering social transformation toward sustainable lifestyles and economic development that respects planetary boundaries.

There are several influential alliances of higher education institutions that have been created to support these goals. The Higher Education Sustainability Initiative (HESI) comprises more than 1,200 institutions and aims to advance sustainable development at universities through collective action and the exchange of best practices in education. Meanwhile, the Race to Zero for Universities and Colleges campaign, which also has more than 1,200 members, enables institutions to commit to achieving net-zero greenhouse gas emissions within a specific timeline.

Higher education institutions have a responsibility to promote education for sustainable development for both ethical and practical reasons. From an ethical standpoint, universities have historically been the setting where the knowledge and human values that society needs to progress are developed (Boulton and Lucas, 2011). From a practical perspective, over the past 15 years, industry demand for sustainability-related skills has increased significantly (Finnveden & Schneider, 2023), requiring universities to update their educational programs to meet this demand.

In the context of climate change, numerous university degree programs need to adapt and expand their curricula to address the environmental and social challenges triggered by this phenomenon. Engineering, in particular, is

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a key discipline in society's transition toward a net-zero economy. This is reflected in the number of advancements such as renewable energy systems, energy storage technologies, and zero-emission vehicles developed by engineering as part of this transition, which must continue to evolve to provide cost-effective and viable alternatives to fossil fuels.

However, there are several obstacles preventing the engineering discipline from adapting to the new needs of society. On the one hand, both science and engineering tend to adopt a reductionist approach. While this principle allows for effective problem-solving, it also fosters a narrow perspective that overlooks the potential positive or negative impacts that developed products may have on society and the environment. One study found that as engineering students progress through their university studies, their motivation to contribute to public welfare decreases (Bielefeldt and Canney, 2016). Among the various engineering disciplines, students in computer engineering, software engineering, and bioengineering or biomedical engineering express the least commitment to mitigating climate change through their careers (Shealy et al., 2021a).

The teaching of sustainability and climate change in higher education has experienced significant growth over the past two decades (Monroe et al., 2019; Shahidul, 2020). However, some important limitations still prevail in this field. There is no consensus on whether sustainability should be taught as a subtopic within other disciplines or as a separate discipline (Eilam, 2022). Sustainability competencies are often associated with STEM competencies, leaving out some essential personal skills such as the ability to cope with uncertainty, critical thinking, and empathy (Kwauk and Casey, 2022). Interdisciplinary sustainability programs often compete for resources with traditional degree programs organized along disciplinary silos (Vincent et al., 2016).

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This study offers an overview of the main developments in the teaching of climate change and sustainability in engineering programs, produced through an analysis of literature from the past 15 years in this field. This systematization can be used by educators and program directors to guide sustainability education within their institutions.

Materials and methods

A documentary analysis was performed to explore current practices, theories, and methods in teaching climate change and sustainability in engineering at the higher education level. To this end, publications in English on this topic, published over the past 15 years (2011–2025), were collected. The following search terms were used:

- teaching climate change in engineering
- teaching sustainability in engineering

These searches were conducted in both Google Scholar and EBSCOhost. Only open-access texts, as well as those available in full through the EBSCOhost platform, were considered. The first 50 records found in each search were included. This yielded an initial set of 57 studies, of which 13 were excluded because they were not directly related to higher education, and another two were excluded because they were literature reviews and were not considered as part of the category analysis.

This initial set of 42 documents was analyzed, and additional bibliographic sources were added during the writing process to support the definition of certain concepts and theories. The main themes within the publications were identified: competencies; teaching methods (including project-based learning, problem-based learning, action-oriented teaching, games, and STEAM); assessment (of attitudes toward climate change, beliefs, and the curriculum); international cooperation within the framework of the

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Sustainable Development Agenda; systems thinking; interdisciplinary approach; ethics; epistemology; circular economy; and case studies.

Results

This section presents the main emerging themes identified in the literature review, along with a description of the objectives and results of each study analyzed.

Competencies

Various authors have addressed the question of which key competencies should be developed for sustainability education. Among the proposed models, the one by Wiek et al. (2011) is one of the most widely recognized and frequently cited. This model defines a set of essential competencies, as well as a general framework from which these competencies can be derived, considering sustainability both as an autonomous discipline and as a cross-cutting component in other areas of knowledge.

According to Wiek, the analysis begins with the recognition of the current state or status quo, represented, for example, by the widespread use of vehicles with internal combustion engines, which generate significant carbon emissions. In light of this reality, a desirable future goal is proposed: a transition toward vehicle fleets composed predominantly of zero-emission technologies, such as electric or fuel-cell vehicles.

To move toward this goal, it is necessary to develop multiple sustainability competencies. Systems-thinking competence enables the identification of the various economic, social, and technological factors contributing to the prevalence of combustion vehicles. Anticipatory competence is key to foreseeing the possible effects of new policies and the adoption of emerging technologies. Normative competence guides decision-making toward ethically desirable objectives aligned with sustainability principles, while strategic competence facilitates the planning and execution of

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progressive actions that lead to systemic change. Finally, Wiek includes interpersonal competence, which enables the effective articulation and application of the other competencies, as it fosters collaboration, leadership, and communication among the various actors involved in sustainable transformation processes.

The competencies needed for a sustainability-oriented career should be considered complementary to basic competencies, such as research skills and problem analysis (Wiek, 2011). Brundiers et al. (2021) validated Wiek's set of competencies using the Delphi method in collaboration with fourteen experts in sustainability education. As a result, they proposed the incorporation of two additional competencies: intrapersonal competence and implementation competence. They defined specific learning objectives for each competence, and emphasized the need to establish the hierarchy and interrelationships among them.

Semerikov et al. (2020) proposed a set of general competencies aimed at training software engineers capable of performing their professional duties sustainably, including skills such as abstract thinking, commitment to environmental preservation, and willingness to act with social responsibility.

Teaching Methods

This section describes the main pedagogical strategies identified in the literature.

Project-Based Learning

One of the most widely promoted instructional methods for teaching sustainability is project-based learning (PBL), which is grounded in principles of pragmatism and constructivist theory. This approach typically begins with the formulation of a project to be developed individually or in groups, ideally aimed at addressing an authentic need in the surrounding environment (Alacapinar, 2008). The process culminates with the presentation of a final

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product that, in the best-case scenario, has tangible value for the community and can continue to be developed by students in future courses (Lake et al., 2016; Massat, 2012).

The effectiveness of PBL has been the subject of debate. Based on a meta-analysis, Balemen and Keskin (2018) conclude that this approach produces significant improvements in academic performance. However, Guo et al. (2020) warn that most existing studies focus on affective and behavioral outcomes, without rigorously evaluating the final product or thoroughly analyzing the learning process. There are two types of projects: classical and creative, the latter being more open and flexible (Alacapinar, 2008). In the field of STEM education, it is important to promote interdisciplinary experiences aimed at solving complex real-world problems (McCright et al., 2013). In this regard, climate science which involves the analysis of data, satellite images, and time series presents a particularly suitable opportunity for the development of integrative projects centered on science education.

Aktas (2015) questions the compartmentalized ("silo-based") approach that predominates in university-level teaching and research, and documents three interdisciplinary sustainability projects with direct impact on his institution: one on chemistry laboratories, another on green buildings, and a third on photovoltaic systems. Similarly, Lake et al. (2016), present a qualitative study of a transdisciplinary course focused on developing projects in collaboration with local communities to mitigate specific environmental issues.

Problem- and Project-Based Learning

Problem- and project-based learning (PPBL) is an instructional approach focused on solving questions through a systematic investigative process conducted by students. This approach has been widely adopted in sustainability education, with courses implemented in higher education institutions in the United States, Europe, Australia (Brundiers and Wiek, 2013; Wiek et al., 2014), and Canada (Kricsfalusy et al., 2018).

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Brundiers and Wiek (2013) conceptualize PBL and PBLP as a continuum, where the former is characterized by addressing more structured and well-defined situations, while the latter involves tackling real-world problems with a higher degree of complexity.

Among the main advantages of PBLP over traditional instructional methods is its ability to foster the development of authentic competencies directly linked to professional practice. However, Wiek et al. (2014) highlight some disadvantages. Some fatigue has been reported in the communities involved, whose members have expressed frustration at the lack of continuity in the projects. Furthermore, it has been noted that PBL-based courses entail higher costs compared to other teaching modalities and require greater institutional support (Kricsfalusy et al., 2018; Wiek et al., 2014).

Action-Oriented Knowledge

The theory of action competence (Jensen and Schnack, 1997) is based on the principle that knowledge alone does not directly lead to the initiatives and actions that are so necessary for our society. Likewise, traditional teaching focuses on modifying behavior and imparting knowledge to students, rather than on fostering experiences and values that enable them to take action of their own accord. These authors developed an instructional theory aimed at preparing people to undertake concrete initiatives that transform society. This methodology revolves around four questions that students must answer: *what* is the current situation, *why* is society facing it, *where* do we want to go, and *how* can we move in this direction strategically (Van Poeck et al., 2024). This framework is closely related to Wiek's competency model, which proposes the transformation of society based on the competencies of systems thinking, anticipatory thinking, normative thinking, and strategic thinking.

Jensen and Schnack (1997) originally formulated the concept of action competence in the context of environmental education, and various recent studies have expanded and deepened this line of research. For example, Van

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Poeck et al. (2024) developed a theory of learning based on transactional learning theory to explain how students acquire knowledge that leads them to take concrete actions. In a complementary vein, Jiusto et al. (2013) introduced the concept of learning through shared action, a process in which students, teachers, and community representatives interact directly to address local environmental problems. Through this collaborative experience, joint learning takes place that promotes sustainable impacts in communities and fosters an understanding of their actual expectations, thereby increasing the relevance and effectiveness of interventions.

Games

Games are a highly effective educational tool, as they allow for interaction with complex systems and the development of skills needed to navigate such environments through simulated experiences. A representative example is the video game Clim'Way, which allows players to build a metropolis with buildings, power plants, transportation systems, forest areas, and other elements, and simulating its development over 50 years with the goal of reducing greenhouse gas emissions (UC Santa Barbara, n.d.; Wu and Lee, 2015). Games also incorporate an emotional dimension that fosters players' identification with the simulated environment, thereby enhancing learning effectiveness (Ouariachi et al., 2019).

The first games that simulated the increase in atmospheric carbon dioxide concentration were described in 1983 and consisted of physical games (Robinson and Ausubel, 1983). Today, there is a wide variety of video games dedicated to the topic of climate change, many of which incorporate advanced features such as social networks, virtual reality, and interaction with the real world (Wu and Lee, 2015). In this regard, Ouariachi et al. (2019) argue that video games can serve as an effective pedagogical tool, providing an

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integrated—cognitive, emotional, and behavioral—experience that is particularly appealing to so-called digital natives.

STEAM

Although the STEM movement (an acronym for Science, Technology, Engineering, and Mathematics) originated in the early 1990s, it gained momentum around 2007, when various U.S. institutions began warning about the country's lag in STEM education compared to other nations (Martín-Páez et al., 2018). Beyond developing specific competencies in each of these disciplines, STEM education promotes their integration and fosters the resolution of complex problems through interdisciplinary thinking (Martín-Páez et al., 2018).

In this context, the STEAM approach emerged, incorporating the Arts (represented by the letter "A") as a fundamental component of the curriculum. This perspective was proposed by Yakman (2008), who argues that the arts are essential to the formation of well-rounded citizens (p. 15). According to the author,

> We now live in a world where you cannot understand science without technology, which focuses most of its research and development on engineering, and where you cannot create without understanding the arts and mathematics. (Yakman, 2008, p. 17)

Connor et al. (2015) present a case study of sustainability projects developed under the STEAM approach as part of a course at the Auckland University of Technology. Students collaborated with a community organization in a rural area of Nepal to design solutions aiming to improve the inhabitants' quality of life. Among the products developed were a rainwater harvesting tank and housing construction models adapted to local conditions.

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Competencies and Teaching Methods

Several recent studies indicate that although there is a vast academic output on both sustainability competencies and teaching methods, there is a need to systematically connect these two areas. In this regard, Lozano et al. (2017) proposed a hermeneutic approach aimed at linking sustainability competencies with a set of pedagogical strategies, with the purpose of identifying the most appropriate methods for the development of each competency.

Subsequently, Lozano et al. (2023) conducted a survey in which they related competencies and teaching methods through principal component analysis and regression analysis. In their study, the authors categorized pedagogical approaches into three groups (universal, social, and environmental) and competencies into another three (extrospective, introspective, and cognitive-processual). The results indicated that universal and social pedagogical methods are the most effective for fostering the development of all identified competency categories.

For their part, Kioupi and Voulvoulis (2019) argue that the Sustainable Development Goals (SDGs) encompass extremely broad and interconnected goals, which makes it difficult to define specific learning outcomes related to them. Consequently, it is also unfeasible to clearly articulate the objectives of education geared toward sustainable development. As an alternative, the authors propose an integrated framework in which the SDGs represent the desired state toward which today's society must move. Within this approach, and through a participatory process, educators are the ones who define the key competencies, pedagogical strategies, and assessment mechanisms—the latter understood as an evaluation of the educational system as a whole, rather than of individual students—that enable progress toward achieving these goals.

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Evaluation

The ADDIE methodology is an instructional design process consisting of the stages of Analysis, Design, Development, Implementation, and Evaluation (Molenda, 2003). This final step is an essential component for providing feedback and ensuring continuous improvement of the process (Bhuttah et al., 2019). Similarly, in the curriculum design model proposed by Wheeler (1967), evaluation occupies the final phase of the cycle, allowing for adjustments and updates in future curriculum iterations. For his part, Tyler (2013) argues that the purpose of evaluation is to determine whether learning experiences, as planned and implemented, effectively lead to the expected outcomes.

The following section presents various research instruments related to climate change and sustainability, organized according to their primary purpose: assessment of attitudes, assessment of beliefs, and assessment of curriculum alignment.

Evaluation of Attitudes

Attitudes refer to the degree of importance and value that students place on sustainable development. These can be expressed through questions such as: `Which is more important, economic development or environmental protection?' or `Do I want to contribute to climate change mitigation through my future profession?' Given that one of UNESCO's goals within Education for Sustainable Development (ESD) is the transformation of learning environments (UNESCO, 2024), an attitude scale can be used to measure the impact of this transformation within an institution.

Along these lines, Biasutti and Frate (2017) developed a quantitative scale based on a twenty-item questionnaire designed to assess attitudes toward sustainable development. The instrument was validated through a study conducted with 484 undergraduate students at an Italian university. Through

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factor analysis, the authors identified four main dimensions that structure the scale: environment, economy, society, and education. This approach represents an advancement over previous instruments by explicitly incorporating the educational dimension.

For their part, Shealy et al. (2021) conducted a national survey of 4,605 engineering students in the United States to identify the factors that predict students' willingness to address climate change in their future professions. The results revealed that the main predictive variables are a sense of personal responsibility toward climate change and the perception of global warming as a technical rather than a social problem. Furthermore, a higher level of commitment was observed among students in environmental or ecological engineering, general engineering, and structural engineering or architecture. In contrast, the fields with the lowest levels of commitment were computer engineering, software engineering, and bioengineering or biomedical engineering.

Furthermore, Kuusisto and Schutte (2023) explored sustainability as a life purpose among higher education students in the Netherlands. The study, conducted at Hanze University of Applied Sciences with a sample of 549 students, adopted a mixed-methods approach. In the quantitative phase, the authors identified four purpose profiles: determined (32%), dreamer (32%), self-centered (18%), and detached (17%). Based on these findings, they conclude that a considerable proportion of students classified as "dreamers" require more in-depth training in sustainability in order to turn their aspirations into concrete initiatives with a positive impact on the environment. Furthermore, it was found that students in technology-related fields generally exhibit a more self-centered profile and a lower level of commitment to sustainability compared to their peers in other disciplines. In a second phase of the study, interviews were conducted with a selected group of students to gain a deeper understanding of their level of commitment (or lack thereof) to the environment.

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Evaluation of Beliefs

Beliefs refer to students' knowledge and conceptions about the environment. Shealy et al. (2021b) studied both the accurate knowledge and misconceptions of civil engineering students regarding global warming. They surveyed a national sample of engineering students (n = 4,364) and found that the majority of civil engineering students (83%) and students in other engineering disciplines (81%) accept global warming as a reality. They also reported that 74% of civil engineering students and 71% of other engineering students believe this phenomenon is caused by human activity. However, most students in both groups did not demonstrate a clear understanding of the causes of climate change or mitigation strategies. For instance, a significant number of students believed that nuclear energy generation contributes to climate change, while others mistakenly identified the hole in the ozone layer as a cause.

Furthermore, it was found that civil and construction engineering students show greater interest in learning about climate change and sustainability throughout their university studies compared to other engineering disciplines (Coleman et al., 2018).

Evaluation of the Curriculum

Numerous studies have focused on defining strategies to evaluate the presence of sustainability and climate change in higher education curricula. Rampasso et al. (2019) identified the main challenges associated with teaching sustainability at the university level, based on a sample of Brazilian students. The most notable obstacles include: the tendency to address sustainability issues only in specific courses and in a limited way; difficulty integrating knowledge from different disciplines to provide a comprehensive sustainability education; and a lack of practical, contextualized examples illustrating how to incorporate sustainability into each field of study.

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Sánchez-Carracedo et al. (2021) developed three tools aimed at integrating sustainability into curricula through a top-down approach. The first consists of a set of sustainable development competencies adapted to engineering programs; the second evaluates the presence of these competencies in curricula; and the third measures students' perception of the extent to which they have acquired these competencies. These tools have been implemented in various engineering programs at three universities in Spain.

Axelithioti et al. (2023) conducted a study at a higher education institution in England to determine the extent to which climate change mitigation and adaptation (CCMA) is included in the curriculum. They found that, in most cases, CCMA is absent from course descriptions and learning objectives. The authors also proposed a methodology for integrating CCMA into course programs through small wording changes, without requiring a complex curriculum transformation process

Cooperation and International Organizations

Having explored various approaches to incorporating sustainability and climate change into engineering curricula, the question arises as to whether there is a standard program for these disciplines that is being systematically implemented across higher education institutions. Based on available information, no such large-scale initiative exists unlike in disciplines such as Computer Science and Business Administration, which have professional organizations, such as the Association for Computing Machinery (ACM) and the Association to Advance Collegiate Schools of Business (AACSB), that issue reference curriculum guidelines and contribute to the global standardization of programs.

A significant step in this direction is the study by Lozano et al. (2013), who compiled 24 institutional statements related to sustainability issued by

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universities and international organizations between 1972 and 2009. Recurring themes in these documents include:

- Focus on environmental degradation, threats to society, and unsustainable consumption;
- Ethical or moral obligation of university leaders and faculties to work toward sustainable societies, including an intergenerational perspective;
- Inclusion of sustainable development in all curricula across all disciplines;
- Promotion of research on sustainable development. (Lozano et al., 2013, p. 3)

Other elements that should be included, according to the authors, are collaboration with other universities, incorporation of sustainable development as a core part of institutional structure, experiential activities on campus, and teacher training programs. Sustainable development should be a “golden thread” running throughout the university system, as the authors state (p. 9).

An important mechanism for international cooperation is the reporting on Climate Change Education and Communication (CCEC) by member countries of the United Nations Framework Convention on Climate Change (UNFCCC). These reports, submitted every four years, must detail progress in these areas. McKenzie (2021) analyzed all National Communications and Nationally Determined Contributions received by the UNFCCC office in 2018 and found that all countries report some CCEC outcomes, although the focus is mainly on formal education and not enough on other learning pathways. Another gap identified is that few countries provided quantitative data that could be systematically used to assess progress at the global level.

There is an opportunity to establish greater international cooperation agreements among universities to support educational research on climate

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change, monitor progress in this area, and develop studies that inform decision-making within these institutions (McKenzie, 2021).

Systems Thinking

Systems thinking is the most important competency for teaching sustainability and climate change (Lozano et al., 2017; Kioupi and Voulvoulis, 2019; Wiek et al., 2011; Nhamo and Njimba, 2020b, p. 16). According to Hofman-Bergholm (2018), “the basic idea of systems thinking is that the world is a complex system where everything is interconnected” (Hofman-Bergholm, 2018, p. 4). The different components that interact with each other can themselves be described as systems. The purpose of this theory is not to learn how to control and predict systems, since they are inherently unpredictable. On the contrary, this approach opens the possibility of designing and redesigning systems.

For Lozano et al. (2017), the systems thinking competency consists of the following principles:

> Analysis of complex systems across different scales and domains of inquiry; comprehension, empirical verification, and articulation of a system’s key components, structure, and dynamics; attention to systemic features such as feedback, inertia, stocks and flows, and cascading effects; understanding of complex systems phenomena, including unintended consequences, path dependency, systemic inertia, and intentionality; understanding of connectivity and cause–effect relationships; application of modelling (qualitative or quantitative). (Lozano et al., 2017, p. 4)

Systems thinking not only refers to considering the climate system as a process made up of interconnected components (Roychoudhury, 2017), but also includes the socioeconomic system (Kioupi and Voulvoulis, 2019, p. 9).

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The SDGs which are as diverse as eradicating poverty, ensuring healthy lives, providing affordable and clean energy, combating climate change, and protecting biodiversity can only be addressed as a whole through systems theory (Sanneh, 2018).

Based on systems thinking, Kioupi and Voulvoulis (2019) designed an integrated framework for teaching sustainable development. Starting from the envisioned society to be achieved, this tool allows for inferring the necessary conditions, such as competencies, pedagogical strategies, and educational assessment processes. Green et al. (2022) developed an online tool for ESD based on system dynamics and demonstrated that this interactive environment significantly improves learning outcomes.

Interdisciplinary and Transdisciplinary Approaches

Climate change is an interdisciplinary problem (McCright et al., 2013) because it involves interactions between the climate system, the economy, and the social sciences. Mitigation and adaptation to climate change require an interdisciplinary approach to engineering (Martin et al., 2022).

Within STEM education, an interdisciplinary approach enables the development of competencies such as mathematical modeling of real-world problems, decision-making based on quantitative data, and solving ill-structured problems to create social impact in communities (McCright et al., 2013; Lake et al., 2016).

Although there has been a significant increase in interdisciplinary programs in recent decades (Vincent et al., 2013), they also face institutional obstacles. Vincent et al. (2016) report that most interdisciplinary programs do not receive resource allocations comparable to those of discipline-based programs, which tend to hold higher institutional status.

Interdisciplinary research integrates areas of study that were traditionally considered separate to solve problems that cannot be addressed

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within these boundaries. In contrast, transdisciplinary research goes a step further by building new epistemological foundations through the joint work of professionals from different disciplines (Aktas et al., 2015).

Tejedor et al. (2018) identify five distinct types of transdisciplinarity in the literature: the transcendence approach, which seeks to unite the different branches of knowledge by transcending the boundaries between them; the real-world problem-solving approach, in which science serves society and becomes transdisciplinary when addressing socially relevant problems; the innovation approach, which aims to integrate basic sciences, health sciences, and engineering to provide solutions that are close to being implemented; the transcendent interdisciplinary research approach, which seeks to produce new methodological and conceptual approaches to improve human well-being; and the transgression approach, which emerges from cultural critique, urban studies, feminist and environmental studies, as well as post-normal science (Thomson Klein, 2014). The authors conduct a documentary analysis and classify various works on sustainability in higher education within different transdisciplinarity discourses, noting that there are few publications within the transgression approach.

Ethics

According to Martins et al. (2022), climate change presents two new challenges for engineering: the first is achieving the transition to energy systems without carbon emissions or with negative emissions. The second is building resilient systems capable of withstanding the impacts of climate change to minimize risks to populations, particularly the most vulnerable. The authors point out that addressing these challenges “requires adapting both the technological and philosophical frameworks used in engineering education” (Martins et al., 2022, p. 740). Furthermore, engineers will need to (1) understand how climate change and sustainability redefine the role of design

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in engineering; (2) adopt an interdisciplinary approach; (3) reconsider the ethical aspects of engineering and understand its impact on social justice; and (4) work collaboratively with diverse communities in different parts of the world.

Brooks et al. (2022) conducted a documentary analysis of various codes, frameworks, and ethical guidelines related to engineering practice in the context of climate change. The authors emphasize the importance of training engineers who develop climate solutions to adhere to these ethical principles. For example, many professionals involved in geoengineering projects, such as solar radiation management, may lack sufficient knowledge of climate ethics codes, potentially resulting in actions that fall outside these guidelines.

Epistemology

Several works explore epistemological questions such as: What is sustainability? What is its relationship to education? How can education guide individuals toward behaviors that foster sustainability?

DuPuis and Ball (2013) state that sustainability is an overly broad approach that seems to be about “everything and nothing at the same time” (p. 65). This has led universities toward a reductionist view in which the concept of sustainability degenerates into a list of technologies and behaviors deemed “good”. The authors argue that it is necessary to teach the “how” rather than the “what” of sustainability. To achieve this, traditional pedagogies based on the mere transfer of information must be replaced by new interactive and collaborative approaches that exercise three types of knowledge: subjective, discursive, and practice-based.

Sterling (2013) proposes two approaches to sustainability education. The first, called the instrumentalist approach, begins with a pre-established concept of sustainable development goals and teaches them to raise awareness and promote social change. The second, called the intrinsic approach, focuses on developing students’ abilities to act under conditions of

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uncertainty and to confront unpredictable scenarios that will arise in the future as a consequence of environmental degradation. The author argues that these perspectives are complementary and develops a vision called sustainable education, which integrates both approaches along with the concept of a resilient individual within socioecological systems.

Michelsen and Fischer (2017) recognize the tension between the two forms of education for sustainable development instrumentalist and intrinsic and claim that this discipline has made significant progress compared to traditional environmental education approaches (p. 8). The authors contrast the traditional perspective with the new concept of ESD and note that advances have been made: (1) from teaching threat scenarios to modernization scenarios; (2) from a normative approach to confronting values; (3) from modifying behavior to promoting decision-making; (4) from transmitting information to pluralistic education; and (5) from knowledge-centered education to action-oriented education.

Tryggvason et al. (2023) argue that although pluralism has been applied in ESD over the past 30 years, this approach faces three threats today: the polarization of public debate on climate change; the growing instrumentalization of education and the trend toward measuring its performance through standardized tests; and the prevailing sense of urgency over climate change in the public sphere. The authors emphasize the need to promote pluralistic education in this context, noting that the concept is closely tied to the strengthening of democracy.

Circular Economy

The circular economy offers an alternative to the linear economy inherited from the Industrial Revolution, characterized by growth driven by planned obsolescence and a culture of waste (Andrews, 2015; Kopnina, 2018). The design profession has been shaped by this tendency to create short-lived

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products that deplete natural resources. Andrews (2015) highlights that sustainable design is not included in designer training in the United Kingdom and that sustainable development appears in learning objectives only as a minor criterion. He emphasizes that education for sustainability and circular design should be fully integrated into the design curriculum.

De los Rios and Charnley (2017), through a case study of companies such as Audi, Nokia, and Philips, identify the competencies required to develop products within a closed cycle and specify the relevant competencies for different business roles.

Case Studies

Several works present case studies of pedagogical experiences. Kopnina (2018), in an article with a critical view of EDS, questions three principles prevalent in the SDGs: economic growth, inclusion, and resilience. According to the author, economic growth is contradictory to social justice, as indefinite growth will lead to further environmental degradation, competition for natural resources, and poverty. Inclusion, understood as fostering the development of non-industrialized countries, increases economic growth and with it environmental degradation, while also making these countries dependent on aid. Resilience is not always desirable; rather, it is preferable to encourage incremental change, as resilience can perpetuate current unsustainable societies. Kopnina applies the principles of pluralistic, participatory, and transformative teaching in her classes to critically discuss sustainable development with students in light of these points.

Leal Filho et al. (2018) examine the role of transformation within higher education institutions, a process that enables the improvement of academic practices. Through a case study, they show that transformation toward ESD requires collaborative work among academic staff to redesign teaching

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methods. This effort must also include the active participation of students and promote an epistemology that acknowledges risk and uncertainty.

Nhamo and Mjimba (2020a), in their book *Sustainable Development Goals and Institutions of Higher Education*, explore how to break down disciplinary silos to integrate ESD into higher education institutions and examine the obstacles encountered through a case study in Helsinki, South Africa, New York, Italy, Zimbabwe, and Madrid, among others. Sibanda and Manik (2023) report various climate change teaching initiatives in South African universities, such as teacher training programs, professional learning communities, national-level research projects, curriculum changes, and teaching at technical and vocational colleges.

Discussion

The analyzed works reveal a transition from an instrumentalist approach to sustainability toward an intrinsic focus. Although the Sustainable Development Goals are an integrated paradigm, they offer an instrumentalist solution, as they maintain potential contradictions between economic growth and climate justice. An intrinsic approach is one that seeks to train engineers so they can reason and propose their own solutions to the environmental crisis. This requires a profound ethical instruction in engineering.

That said, there is a long tradition of teaching ethics in engineering. As early as 1947, the NSPE Code of Ethics stipulated that an engineer should “take an interest in the public welfare and be ready to apply his special knowledge, skill, and training for the benefit of mankind” (NSPE, 1947, p. 11). Today, ABET’s accreditation criteria require engineers to produce solutions that take into account the public welfare and environmental factors. Specifically, the sustainability guidelines require professionals “to contribute to the building of a sustainable society” (ABET, 2024).

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On the other hand, numerous studies point to a lack of interest in the public welfare within the context of engineering education (Cech, 2014; Lathem et al., 2011; Rottman, 2025; Leydens, 2017; Cech, 2013; Riley, 2022). This stems from a culture of depoliticization, in which ethical and social issues are considered outside the scope of engineering (Cech, 2014; Lathem et al., 2011). Moreover, historically, engineering work has been oriented toward maximizing economic benefit and scientific innovation (Rottmann, 2025). Contemporary engineering curricula in the United States have their roots in the Cold War, when the emphasis was placed on engineering sciences and basic sciences, while content related to the social sciences and the humanities was reduced (Leydens & Lucena, 2017). Additionally, engineering as a discipline emerged from the development of military technology, and today, in many countries, governments and defense organizations remain among the principal employers of engineers (Riley, 2022).

In summary, this approach to engineering, detached from the social sciences and the humanities, reflects an instrumentalist perspective. Instrumentalist education is characterized by the pursuit of external ends (for example, economic growth) rather than by the development of knowledge and the use of reason in the individual as ends in themselves (Curren, 2025, sec. 2.11). Biesta (2024) distinguishes between educating people as objects or as subjects. To subjectivize education means to cultivate individual freedom and the capacity for adulthood—that is, the ability to desire what is good both for oneself and for society.

This intrinsic approach, within engineering education for sustainability, includes systems thinking as a tool for analyzing the positive and negative societal consequences of solutions developed by industry. It also encompasses interdisciplinary collaboration with experts who can contribute diverse perspectives on a problem, both technical and human. The sustainability competencies defined by Wiek et al. (2011) are largely

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instrumentalist, as they outline a series of steps or an algorithm for progressing toward a more sustainable society; however, more recent versions of this framework include intrapersonal competence, which emphasizes certain intrinsic values (Redman & Wiek, 2021). Likewise, Kwauk and Casey (2022) propose supplementing STEM competencies with a set of transformative skills for collective action, which reflect a more intrinsic vision of education.

Conclusion

Engineering education is not a rigid discipline; rather, it must adapt to the needs of society. Just as the post-Sputnik era saw a shift toward engineering sciences and basic sciences, today it must respond to the global challenges of climate change and planetary boundaries. This involves changes across all dimensions of the curriculum. Systems thinking should be incorporated both as a core competence and as an integrative element across disciplines, connecting different branches of engineering with one another and with the social sciences.

It is necessary to transform the materialistic and waste-oriented tradition of engineering, which requires an intrinsic form of education that emphasizes the confrontation of values, decision-making, and pluralistic formation. Subjectivizing teaching is primarily a pedagogical challenge, and strategies should include project-based learning and action-oriented knowledge, among other student-centered approaches. Competencies should be extended within a green skills framework (Kwauk & Casey, 2022) that includes capacities for societal transformation, such as the ability to analyze systems of unequal power, disruptive thinking, and collective action.

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