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Sustainable Development Goals (SDGs) in Engineering Education: Definitions, Research Trends, Bibliometric Insights, and Strategic Approaches

*Risti Ragadhita, Meli Fiandini, Dwi Novia Al Husaeni, Asep Bayu Dani Nandiyanto**

Universitas Pendidikan Indonesia, Bandung, Indonesia
*Correspondence: E-mail: nandiyanto@upi.edu

A B S T R A C T

This study investigates the integration of Sustainable Development Goals (SDGs) within engineering education by providing conceptual definitions, identifying research trends, and analyzing strategic approaches. Using a systematic literature review enriched with bibliometric analysis, the study explores six key aspects: the role of SDGs in engineering education, the intersection of sustainability and technical learning, the integration of Education for Sustainable Development (ESD), core competencies required for sustainability, systems thinking as a foundational skill, and institutional challenges and opportunities. Bibliometric mapping reveals increasing global attention to SDGs in engineering, particularly in 2022 and 2024. The findings show a paradigm shift from purely technical training to holistic, interdisciplinary education that combines ethics, ecology, and social impact. Despite structural barriers and curricular gaps, strategic opportunities (such as faculty readiness, innovative pedagogies, and technological tools) support transformative learning. This review provides a comprehensive framework for aligning engineering education with the SDGs and contributes to the development of sustainability-literate future engineers.

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1. INTRODUCTION

In the era of the industrial revolution, with diverse global challenges, technical education is increasingly crucial because it supports and contributes directly to national stability [1-3]. This condition has an impact on the increasing need for educated and trained workers in the engineering field who can design, build, maintain, and develop solutions to overcome challenges amidst technological developments such as artificial intelligence, renewable energy, industrial automation, and digitalization of various sectors [4-6]. Workers in the engineering field are not only required to have technical expertise, but nowadays, they are also required to have ethical awareness and sustainable insight to be able to produce innovations that are not only functionally effective, but also socially and environmentally responsible to respond to global challenges (such as climate change, energy crises, natural disasters and social inequality) through appropriate and environmentally friendly innovations in line with the Sustainable Development Goals (SDGs) [7-10].

SDGs contain 17 universal goals (see Figure 1) agreed upon by countries in the world as an effort to create a much better and more sustainable life on earth [11]. These SDGs were born because of evidence from reality and research that the current method of development is irresponsible, such as not considering social, economic, and environmental aspects, which have the potential to produce negative impacts on society and the planet [11, 12]. Some examples of problems that arise due to a lack of consideration of SDGs aspects are global warming, air pollution due to carbon emissions, water pollution due to toxic waste, and land degradation due to the disposal of solid waste from industrial and agricultural activities. Apart from that, the use of fossil fuels as the main source of energy in power plants, as well as emissions from industrial wastewater treatment plants and the decay of biomass from industrial and agricultural waste, also worsen environmental pollution [13, 14].

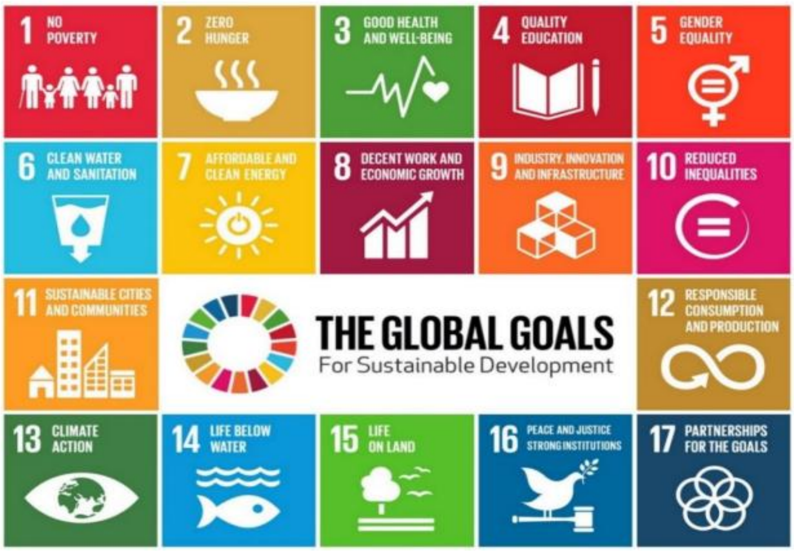

Figure 1. The 17 Sustainable development goals.

Several studies have shown that various human activities, especially in the industrial and mining sectors, make a significant contribution to environmental pollution and are not in line with the principles of the SDGs. One example is the production process in industry, which still uses a lot of fossil fuels such as coal, oil, and natural gas. Burning these fuels produces exhaust emissions containing dangerous pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and solid particles (PM), which play a major role in worsening air

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quality and accelerating global warming [15, 16]. In addition, many industries dispose of liquid and solid waste containing dangerous chemicals without going through an adequate treatment process, thereby polluting water sources and the surrounding land [17]. It is also not uncommon for chemicals used in the production process to produce emissions that have a negative impact on the environment and human health [18]. In the mining sector, operational activities such as excavation and engine burning produce waste and gas emissions, which can pollute soil, water, and air, and disrupt the balance of the ecosystem [19].

Based on the previous explanation, in facing various complex global problems, the engineering field must move in line with the SDGs principles. The SDGs emphasize the importance of solutions that are not only effective in the short term but also do not sacrifice the needs of future generations, which means there must be attention to the environmental, social, and economic impacts of every action taken [20, 21]. A holistic, sustainable, and equitable approach is the key to achieving effective and responsible development. Therefore, the SDGs are here to challenge all countries to work together to overcome various cross-border challenges [22, 23]. With cross-disciplinary collaboration and the integration of local and global knowledge, the hope of creating a more just, sustainable, and inclusive future for everyone can be realized [22, 23]. The main focus of the SDGs is not only on economic growth, but also includes dimensions of social welfare, intergenerational justice, and preserving the Earth's ecosystem [11]. Therefore, the engineering and engineering fields are required to not only be the driving force of development, but also the guardian of the balance between technological progress and the sustainability of human life and the planet.

It turns out, engineers play a vital role in achieving the SDGs because they have the knowledge and skills to design and develop technology, systems, and infrastructure that support sustainable development. However, these competencies are not enough, future engineers need to be equipped with a new set of competencies that include systems thinking skills, cross-disciplinary collaboration, awareness of social and environmental impacts, and a commitment to sustainable development principles that not only meet technical needs, but also contribute to social welfare, environmental protection, and inclusive economic development [24]. Integrating SDGs principles into the education system is a strategic step to prepare future generations who have the awareness and competence to overcome global challenges. Thus, the integration of SDGs in the education curriculum can strengthen students' capacity to contribute positively to society and the world as a whole [25].

Integrating sustainability principles into the curriculum is not just about adding topics about the environment or climate change to the lesson material, but rather includes a cross-disciplinary approach that encourages students to think critically, reflectively, and find solutions to real issues around them [25]. For example, learning can be linked through problem-based learning projects, which can be focused on local issues such as industrial waste processing, biomass utilization, or water purification with a sustainable approach. Through this approach, students are trained to think systemically, consider technical, economic, environmental, and social aspects in an integrated manner, and innovate in developing technology that supports the transition to a green industry [26]. This integration of sustainability in engineering education also means encouraging students to understand that every engineering decision has long-term consequences for the environment and society. Therefore, values such as engineering ethics, professional responsibility, and sustainability must be embedded in every learning, not just as theory, but through practical experience, industrial simulations, and engagement with the community [25].

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Even though global attention to sustainable development continues to increase, the implementation of SDGs principles in engineering education still faces various challenges. Technical education plays a key role in preparing graduates who will become decision makers in the industrial, energy, and technology sectors, which greatly influence global sustainability. Considering the strategic role of engineering education in preparing human resources who will be directly involved in the design, development, and management of industrial technology, it is important to examine the extent to which sustainability principles have been adopted in curriculum, pedagogy, and learning practices in this field. This research also aims to identify trends, challenges, pedagogical approaches, and research gaps that still exist regarding the implementation of SDGs in engineering education. The novelty of this study lies in the systematic approach that examines the relationship between education and SDGs holistically, by mapping contributions, research gaps, and directions for developing more sustainable engineering education. Thus, it is hoped that the results of this review can contribute to the development of educational strategies that are more relevant, transformative, and sustainable in facing global challenges in the industrial era and climate change.

2. METHODS

This research method is a systematic literature review (SLR) combined with bibliometric analysis to obtain a deep and comprehensive understanding of the topic being studied. SLR is carried out through systematic and transparent stages, starting from formulating research questions, determining inclusion and exclusion criteria, searching for scientific articles from various reputable databases, selecting articles based on title, abstract, and full content, to extracting and synthesizing data from selected studies. This process aims to collect relevant and high-quality empirical evidence to answer research questions objectively. As a complement, bibliometric analysis is used to identify and visualize scientific publication patterns quantitatively. This analysis includes research trends over time, document distribution by subject area (e.g., education, engineering, environment), as well as document distribution by country, which shows the global contribution to the field of study. Apart from that, network visualization was also carried out to map collaborative relationships between authors, institutions, or keywords using software such as VOSviewer. This visualization helps identify interrelated research clusters. Furthermore, overlay visualization is used to depict the dynamics of the development of keywords or topics over time, thereby providing an overview of scientific evolution and future research directions. Bibliometric analysis is focused on using the keywords: "Engineering" AND "Education" AND "SDGs" OR "Pedagogy" OR "Strategy" in the period 2020 to 2025, with document types limited to scientific articles. By combining SLR and bibliometrics, this research produces not only a comprehensive thematic synthesis but also a powerful intellectual map for understanding research developments and contributions globally.

3. RESULTS AND DISCUSSION

3.1. Definition and Dimension of SDGs

The SDGs are a global framework adopted by all United Nations (UN) member states in 2015 as part of the 2030 Agenda for Sustainable Development. The SDGs consist of 17 interconnected goals and 169 specific targets, which aim to balance the three dimensions of sustainability: economic growth, social inclusion, and environmental protection. The core philosophy of the SDGs is to “leave no one behind,” ensuring equitable development across regions, communities, and generations.

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Each goal is designed to address specific global challenges such as poverty (SDG 1), hunger (SDG 2), quality education (SDG 4), gender equality (SDG 5), clean energy (SDG 7), responsible consumption (SDG 12), and climate action (SDG 13), among others. These goals serve as both a strategic blueprint and an evaluative metric for countries, organizations, and educational institutions in aligning their policies and activities with sustainable development principles [11, 12].

In the context of engineering education, the SDGs are not only thematic content to be taught but also act as guiding principles for curriculum reform, pedagogy, and institutional strategy. Particularly, SDGs emphasize the integration of ethical reasoning, systems thinking, and social responsibility into technical education. Engineering solutions today must be designed not only for functionality, but also for socio-ecological relevance, equity, and long-term impact [22, 25].

Figure 1 illustrates the full set of 17 SDGs, which collectively define a multi-sectoral and transdisciplinary agenda. These goals have been translated into educational indicators (especially in SDG 4.7), calling for learners to acquire knowledge and skills necessary to promote sustainable development, including through education for sustainable lifestyles, human rights, gender equality, peace, and global citizenship. In short, the SDGs can be classified into 17 points:

(i) **SDG No. 1: No Poverty.** End poverty in all its forms everywhere.
(ii) **SDG No. 2: Zero Hunger.** End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
(iii) **SDG No. 3: Good Health and Well-being.** Ensure healthy lives and promote well-being for all at all ages.
(iv) **SDG No. 4: Quality Education.** Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
(v) **SDG No. 5: Gender Equality.** Achieve gender equality and empower all women and girls.
(vi) **SDG No. 6: Clean Water and Sanitation.** Ensure the availability and sustainable management of water and sanitation for all.
(vii) **SDG No. 7: Affordable and Clean Energy.** Ensure access to affordable, reliable, sustainable, and modern energy for all.
(viii) **SDG No. 8: Decent Work and Economic Growth.** Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.
(ix) **SDG No. 9: Industry, Innovation and Infrastructure.** Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
(x) **SDG No. 10: Reduced Inequalities.** Reduce inequality within and among countries.
(xi) **SDG No. 11: Sustainable Cities and Communities.** Make cities and human settlements inclusive, safe, resilient, and sustainable.
(xii) **SDG No. 12: Responsible Consumption and Production.** Ensure sustainable consumption and production patterns.
(xiii) **SDG No. 13: Climate Action.** Take urgent action to combat climate change and its impacts.
(xiv) **SDG No. 14: Life Below Water.** Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.
(xv) **SDG No. 15: Life on Land.** Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

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(xvi) **SDG No. 16: Peace, Justice and Strong Institutions.** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels.

(xvii) **SDG No. 17: Partnerships for the Goals.** Strengthen the means of implementation and revitalize the global partnership for sustainable development.

Understanding the definitional scope and interlinkages of SDGs is essential for engineering students and educators, as it frames sustainability not merely as an environmental issue, but as an integrated concern involving technology, equity, governance, and ethics. This conceptual foundation is crucial for driving transformative learning and for enabling engineers to contribute meaningfully to sustainable development on local, regional, and global scales.

3.2. SDGs Research Developments and Trends in Engineering Education

Figure 2 shows research trends on topics related to sustainable development goals in engineering education from 2020-2025. Overall, research on this topic reflects fluctuating and inconsistent developments, but shows a significant increase in interest in the integration of sustainability principles in engineering education in recent years. In 2020 and 2021, there were no documents recorded, which indicates that attention to the integration of SDGs in engineering education was still very low at that time. Most likely, in this period, the topic of SDGs has not yet become a top priority on the research agenda in the engineering field, or there have not been many initiatives that encourage the implementation of SDGs into the curriculum and practice of engineering education.

A significant increase, with more than 600 documents published, was shown in 2022. This sharp increase indicates an increase in academic and institutional awareness and commitment to the importance of integrating sustainable development principles in engineering education, which could be driven by various global and regional policies which are starting to emphasize the role of higher education in supporting the achievement of the SDGs, including in developing sustainability-based curricula, increasing the social and environmental competence of engineering students, as well as cross-disciplinary research collaboration.

However, in 2023, an extreme decline occurred to the point that no documents were recorded. This phenomenon can be caused by various factors, such as delays in the publication process, disruptions in reporting or indexing systems, or changes in research focus and funding on other topics. Another suspicion is that it is also possible that there will be a break in the collaborative initiatives that previously produced a spike in 2022.

Furthermore, 2024 again shows an even higher spike, with almost 1000 documents recorded. This shows that interest in SDGs topics in engineering education is not only continuing but is experiencing extraordinary strengthening. This increase may be influenced by the emergence of more pro-sustainability education policies, increased SDGs-based research funding, or collective awareness among academics regarding the strategic role of engineering education in facing global challenges such as climate change, environmental degradation, and social inequality.

In 2025, the trend shows zero. However, it should be noted that 2025 is still ongoing. This low value is most likely caused by incomplete published data for the current year. Therefore, this trend cannot be used as a conclusion for 2025. In general, Figure 1 shows that although it is not yet stable, there is a significant increasing trend in publications discussing SDGs in the context of engineering education, especially in even-numbered years such as 2022 and 2024. This indicates that this topic is starting to gain an important place in academic and higher

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education discourse, although the challenges of research consistency and sustainability still need to be addressed.

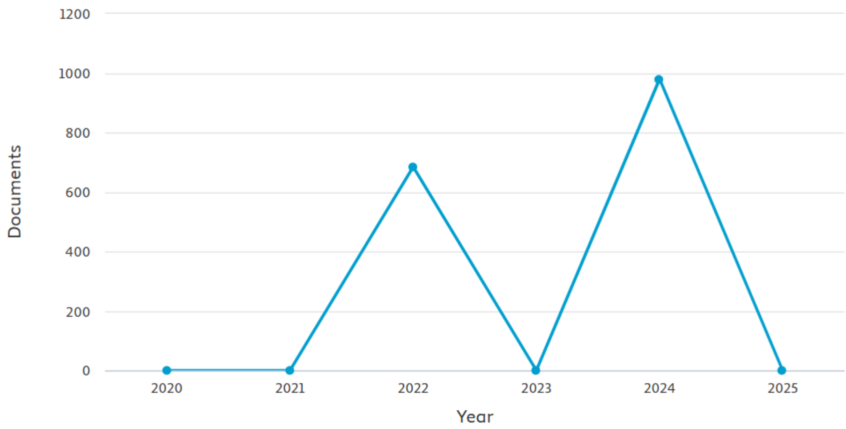

Figure 2. Research trend.

Figure 3 shows the distribution of documents based on scientific fields that discuss the topic of SDGs in Engineering Education. Interestingly, even though the main focus is on engineering education, the majority of documents come from the field of Social Sciences (30.2%), followed by Engineering (19.5%), and Computer Science (15.0%). This phenomenon shows that the integration of SDGs in engineering education is not only seen as a purely technical or curricular issue, but also as a social, cultural, and educational policy issue. The field of Social Sciences is likely to dominate because many studies explore the sociological, pedagogical, and policy aspects of implementing sustainability principles into engineering education. Topics such as curriculum transformation, education based on sustainable values, the role of educational institutions in social change, soft skills development, and community involvement in engineering projects are areas of social studies that are closely related to SDGs in the context of engineering education.

Furthermore, the dominance of social sciences also reflects the existence of a strong interdisciplinary approach, where engineering education no longer only focuses on technical competence alone, but also includes dimensions of ethics, social sustainability, and justice. For example, SDG 4 (quality education), SDG 5 (gender equality), SDG 10 (reduced inequalities), and SDG 13 (climate action) require a holistic approach that involves a deep understanding of social structure and community dynamics, which is the domain of social science.

In other words, even though "engineering education" is the center of attention, it is the social sciences that play a major role in studying, criticizing, and encouraging the transformation of the engineering education paradigm to make it more responsive to global challenges. This emphasizes that the success of SDGs integration in technical education is largely determined by the synergy between technical and social approaches, which creates education that is not only technologically smart but also socially wise and environmentally sustainable.

Figure 4 shows the number of documents related to SDGs in engineering education by country or region, with data taken from the Scopus database. From **Figure 4**, it can be seen that the United States dominates publications on this topic with a very high number of documents, approaching 1,000 documents. This indicates that the United States is very active in studying and applying SDGs principles to engineering education. This is in line with the large

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number of leading universities, progressive higher education policies, and rapidly developing cross-disciplinary research initiatives in the country.

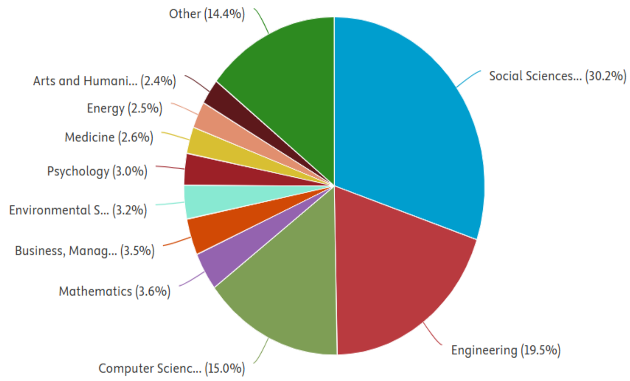

Figure 3. Distribution of documents based on scientific fields that discuss the topic of SDGs in engineering education.

In second position, China was recorded as having 629 documents. China is a country with rapid development in the engineering and technology higher education sector, and has a strong national agenda regarding sustainability. India, Spain, and the UK followed in sequence, indicating that these countries also have serious concerns about integrating sustainable development goals into their engineering education systems.

Interestingly, several countries such as Malaysia, Mexico, and Colombia, which are included in the developing country category, also appear on the list. This shows that the SDGs topic in technical education is not only a concern of developed countries, but is also an important part of the higher education development strategy in developing countries. For example, Malaysia shows a strong commitment through a national higher education policy that emphasizes the development of 21st-century skills, green technology innovation, and sustainable development.

Overall, these data reflect that the implementation of SDGs in engineering education has become a global concern across continents. Engineering education is no longer only oriented towards mastering technology alone, but is also responsible for creating future engineers who are sensitive to environmental, social, and economic issues in a sustainable manner. This approach encourages the integration of engineering curricula with the principles of ethics, sustainability, social justice, and global responsibility, in line with the spirit of the 17 Sustainable Development Goals proclaimed by the UN.

Figure 5 is a network visualization of SDGs topics in engineering education. Engineering education plays a central role in achieving the SDGs, as depicted in the conceptual network visualization that links technical, social, and sustainability dimensions. In this context, engineering education is no longer limited to mastering science and mathematics concepts, but also includes strengthening critical thinking skills, problem-solving, and the ability to design sustainability-oriented solutions. The close relationship between topics such as engineering students, classroom, and performance reflects a focus on effective, student-centered learning processes. On the other hand, the relationship with keywords such as industry, requirements, and artificial intelligence shows that engineering education is very responsive to the needs of modern industry and the latest technological developments. More importantly, the emergence of words such as sustainability, society, and sustainable development goals underscores the paradigm shift in engineering education towards sustainable and socially responsible development. Therefore, engineering education is

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currently in a strategic position to equip the younger generation not only with technical skills but also with a global vision to create innovations that have a positive impact on society and the environment.

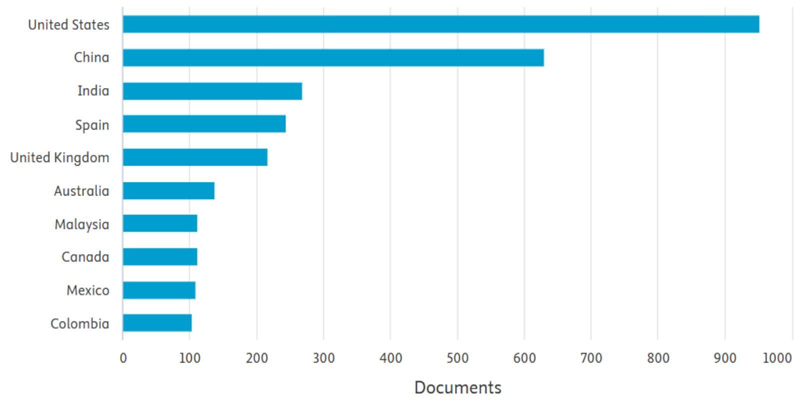

Figure 4. Number of documents related to SDGs in engineering education by country or region.

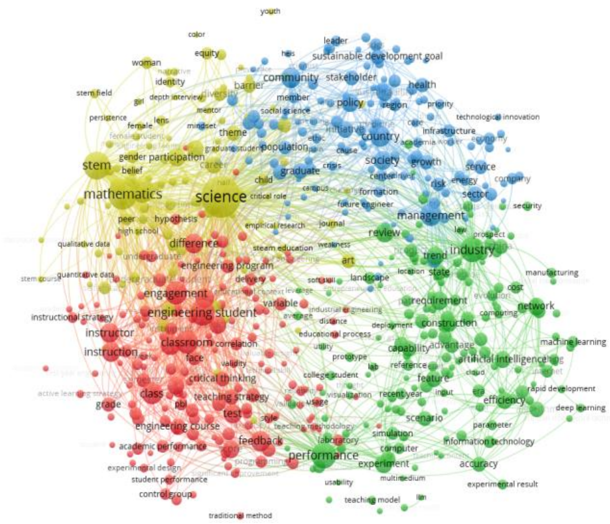

Figure 5. Network visualization of SDGs topics in engineering education.

Figure 6 is a visualization overlay in the context of engineering education research connected to the SDGs, providing a chronological overview of the development of research themes based on color. The blue color depicts themes that have been researched for a long time (around 2022), while the green color shows themes that are still active in recent years, and the yellow color indicates topics that are on the rise and becoming new trends in scientific literature (around 2023 and above). In this visualization, keywords such as "artificial intelligence", "efficiency", "requirements", "community", and "sustainable development goals" appear in yellow, indicating that these topics are starting to be widely researched and are relevant to current challenges in the field of engineering education, especially those that support the global sustainability agenda. Meanwhile, themes such as "science", "mathematics", "engagement", and "classroom", which are colored blue to green, reflect the classic foundations in engineering education, which are still maintained but are not discussed as much in the latest trends. As such, this overlay becomes an important tool in identifying new directions and cutting-edge research priorities that increasingly integrate cutting-edge technologies and sustainable development goals into engineering education curricula and practices.

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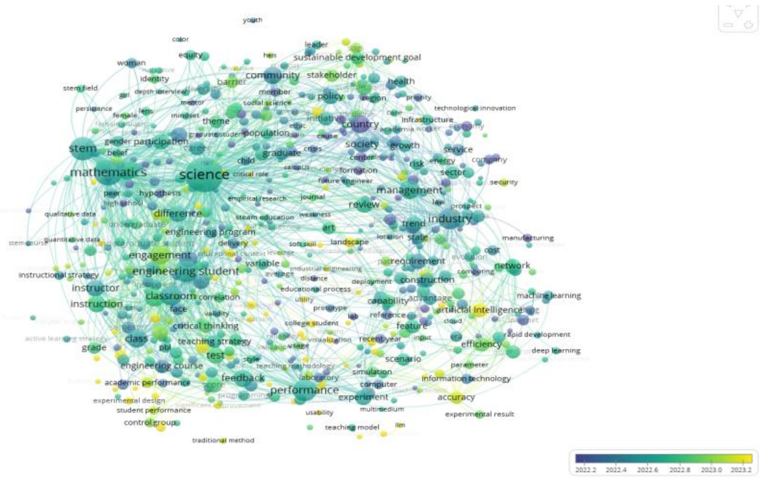

Figure 6. Overlay visualization of SDGs topics in engineering education.

3.3. Role of Engineering Educators in Promoting SDGs

Engineering educators play a pivotal role in advancing the 2030 SDGs, particularly through their influence on education quality, research innovation, community engagement, and institutional transformation [27]. Their responsibilities extend beyond delivering technical knowledge in the classroom; they act as agents of change in the pursuit of sustainable technological development, community empowerment, and inclusive economic growth.

In this context, their roles encompass various strategic domains:

(i) Curriculum Designers for Sustainable Competency. Engineering educators are instrumental in developing curricula that are not only aligned with global labor market demands but also deeply integrated with sustainability principles. Engineering education must equip students with cross-disciplinary competencies that include environmental awareness, engineering ethics, and adaptive capabilities in response to technological shifts and global crises such as climate change and pandemics [27].

(ii) Drivers of Innovation and Applied Research. In the realm of research and innovation, engineering educators foster the development of technology-based solutions to key developmental challenges. These include renewable energy systems, environmentally friendly transportation, and affordable health technologies, especially those vital in emergency situations like the COVID-19 pandemic. Applied research emerging from engineering schools serves as the backbone of local innovation, directly contributing to SDG 3 (Good Health), SDG 7 (Affordable and Clean Energy), and SDG 9 (Industry, Innovation, and Infrastructure).

(iii) Community Partners and Technology Transfer Agents. Engineering educators also play a crucial role in community engagement and technology transfer. They facilitate partnerships between universities and local communities to co-create contextually appropriate solutions, such as water-saving irrigation systems, village-level waste management tools, or community health devices based on local wisdom and affordability. Engagement in sustainability-related initiatives has been recognized as a fundamental approach to fostering real-world problem-solving [27].

(iv) Facilitators of Inclusive and Transformational Learning. They serve as facilitators of inclusive learning ecosystems by encouraging gender equity in STEM fields, promoting critical global awareness among students, and embedding values of social responsibility

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and sustainability in pedagogy. These efforts are aligned with SDG 4 (Quality Education) and SDG 5 (Gender Equality).

(v) Strategic Implementers of the SDGs Framework in Higher Education. integrating SDGs into engineering education requires a structured and comprehensive framework that supports the alignment of educational objectives with sustainability goals [28]: Engagement in sustainability-related initiatives has been recognized as a fundamental approach to fostering real-world problem-solving,

- (a) Designing SDG-aware curricula and hands-on learning practices;
- (b) Promoting active and digital learning methods;
- (c) Engaging stakeholders such as industry and communities;
- (d) Implementing real-world projects that embody sustainability;
- (e) Recommending institutional policies and professional development programs for educators.

This positions engineering educators as:

- (a) Transformational Curriculum Designers who align theory, technology, and sustainability values;
- (b) Innovation Facilitators who guide students in solving real-world challenges through project- and challenge-based learning;
- (c) Connectors between Academia, Industry, and Communities by translating research into practical, scalable applications;
- (d) Sustainability Advocates who influence policy and institutional strategies to explicitly support SDG implementation.

(iv) Institutional Contributors to Global SDG Strategies. A systematic review of 22 case studies conducted globally identified several key contributions of engineering schools in advancing sustainability within education and practice [29].

- (a) Multi-stakeholder collaboration involving academia, government, industry, and communities in curriculum co-design;
- (b) Comprehensive curriculum reform to embed sustainability, ethics, and systems thinking into engineering programs;
- (c) Diverse pedagogical strategies, such as project-based learning, challenge-based learning, simulations, and case-based discussions;
- (d) Innovative sustainability assessments, including SDG portfolios and impact rubrics;
- (e) Research and community service focused on SDG outcomes, producing tangible prototypes and social innovations;
- (f) Strategic alignment of research agendas to enhance interdisciplinary empowerment and apply global goals in local contexts.

3.4. Intersection between Engineering and Sustainability Education

The UN plays a critical role in sustainable development through the SDGs, which consist of 17 goals aimed at creating a better and more sustainable future for all. The UN is committed to supporting its member states in achieving these goals. The SDGs cover various dimensions of sustainability, including social, economic, environmental, as well as education and partnerships needed to achieve sustainable development. The more recent 2030 Agenda focuses on global implementation of the SDGs, including increasing awareness and knowledge of sustainability at all levels of society, especially in education. This relates to efforts to incorporate sustainability into the curriculum of engineering education and other disciplines in higher education, in line with the goals stated in the SDG Quality Education (#4) [30].

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In this context, engineering education plays a crucial role as one of the disciplines that is closely related to the development of technology, innovation, and solutions to global challenges. Engineering education is not only required to produce technically competent graduates, but also to be able to understand the social, ethical, and environmental implications of their engineering practices. Therefore, there has been a paradigm shift in engineering education, from merely focusing on technical efficiency to a more holistic, contextual, and transdisciplinary approach—namely at the intersection of engineering and sustainability education [31].

The concept of "intersection between engineering and sustainability education" describes the essential combination of engineering knowledge and understanding of sustainability in decision-making. This intersection is increasingly important in today's world, as engineers are at the forefront of designing and implementing technologies that directly impact people's lives and the sustainability of the planet. Engineering education integrated with sustainability principles encourages students to think systemically, consider sustainability throughout a product's life cycle, and assess the social and environmental impacts of every technical solution [32].

As part of a global effort to advance engineering's meaningful contributions to the SDGs, the National Academy of Engineering (NAE) has identified 14 Grand Challenges for Engineering, a multidimensional set of challenges rooted in the needs of tomorrow's society. These challenges encompass four broad themes: sustainability, health, security, and better lives. **Figure 7** illustrates the relationship between the 17 SDGs of the UN and the 14 Grand Challenges for Engineering from the NAE. This visualization shows that many of the global challenges addressed through the SDGs can be directly supported by engineering innovation and solutions. The connecting arrows in the figure indicate the specific contributions of each engineering challenge to the broader development goals, highlighting how educators [30, 33, 34].

Some of the most obvious connections are between SDG #3 (Good Health and Well-Being) and engineering challenges such as Engineer Better Medicines and Advanced Health Informatics, which demonstrate that advances in health technologies directly contribute to people's quality of life. Similarly, SDG #6 (Clean Water and Sanitation) is closely linked to the Provide Access to Clean Water challenge, affirming that developing engineering-based water supply systems is key to ensuring access to sanitation and safe drinking water. For SDG #7 (Affordable and Clean Energy), the Make Solar Energy Economical and Provide Energy from Fusion challenges are two key engineering approaches to creating clean, affordable, and sustainable energy sources, which also support SDG #13 (Climate Action) in climate change mitigation efforts (see **Figure 7**) [30].

Another linkage emerges between SDG #4 (Quality Education) and Advanced Personalized Learning, where educational technology plays a role in improving the quality of adaptive and inclusive learning, narrowing the gap in access to education. Meanwhile, the development of improved urban Infrastructure is an important contribution to SDG #11 (Sustainable Cities and Communities), which emphasizes the need for smart, efficient, and resilient city planning. The Secure Cyberspace challenge also emerges as an important support for SDG #16 (Peace, Justice, and Strong Institutions) because reliable digital security systems are the foundation for fair and trusted governance in modern societies (see **Figure 7**) [31].

In addition to these direct contributions, there are also broader thematic and systemic connections. For example, the Manage the Nitrogen Cycle and Develop Carbon Sequestration challenges support SDG #12 (Responsible Consumption and Production) and SDG #13 (Climate Action) by helping to reduce pollution and manage the environmental impacts of

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human activities. On the other hand, enhanced virtual Reality and Tools of Scientific Discovery contribute to SDG #9 (Industry, Innovation, and Infrastructure), as advances in simulation technology and fundamental research strengthen the innovation base of industry (see **Figure 7**) [33].

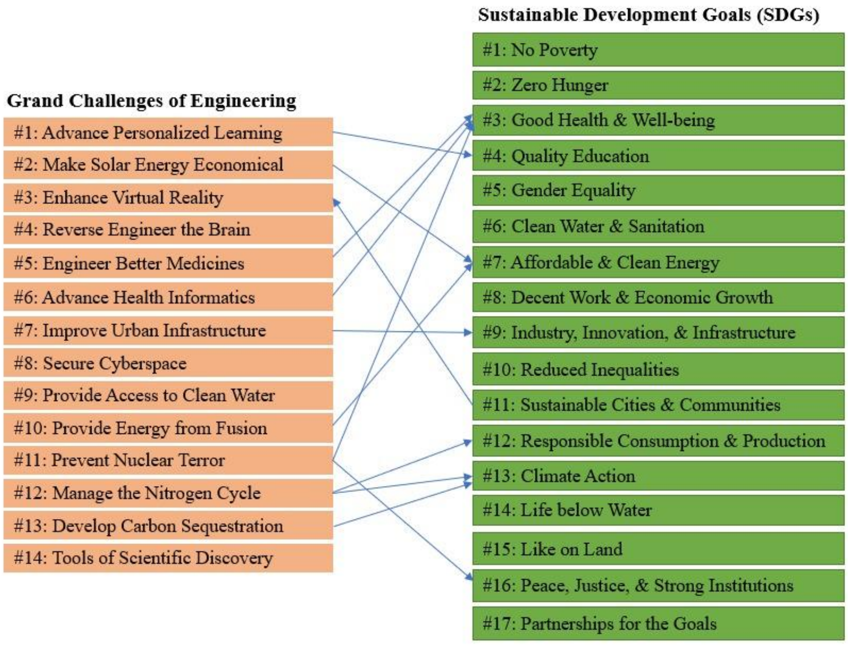

Figure 7. Intersection and strategic alignment of agenda 2030's sustainable development goals with the national academy of engineering's grand challenges.

Moreover, the integration of engineering challenges and SDGs reflects the Triple Bottom Line (TBL) principle that emphasizes the balance between the three main dimensions of sustainability: social, economic, and environmental. Engineering challenges no longer only emphasize the efficiency and reliability of technology, but now also consider aspects of social justice, community participation, and ecological responsibility. Herein lies the importance of the intersection between engineering education and sustainability education: creating engineers who are not only experts in their fields but also aware of the socio-environmental impacts of every technological action taken.

3.5. Transformative Pathways: Integration of Education for Sustainable Development (ESD) in Engineering Education

The implementation of Education for Sustainable Development (ESD) in engineering education is seen as a key element in achieving the SDGs by 2030. This process begins with designing a curriculum based on sustainability principles. The next step is to prepare teaching staff with appropriate theoretical knowledge, cognitive skills, and academic competencies. In the next stage, educational institutions need to determine program learning outcomes (Program Outcomes/PO) and prepare an integrated course learning achievement matrix (Course Outcomes/CO). The final stage includes developing laboratory facilities and supporting academic facilities, as well as establishing strategic collaboration with the industrial sector and society. The stages in integrating education based on SDGs are explained in detail as follows.

(i) Designing a sustainability-based engineering curriculum

The main foundation for integrating SDGs principles into engineering education is transforming the curriculum by not just adding environmental-themed courses, but reorganizing the entire curriculum structure so that it is able to instill a holistic, transdisciplinary, and systemic perspective. A curriculum designed with a sustainability paradigm includes several themes, as shown in **Table 1**. The transformative process of this curriculum must also be adaptive to local and global contexts and responsive to the real challenges facing the world today, such as climate change, the energy crisis, and development gaps.

(ii) Empowering educators

Educators, as the main actors in the education process, need to be empowered to become agents of change. This includes intensive and ongoing training in sustainable pedagogy, integration of socio-environmental issues in engineering teaching, as well as mastery of active and reflective learning methods. Strengthening the capacity of educators can be done through transdisciplinary workshops (on SDGs, systems thinking methods, and ecological literacy), innovative pedagogy training programs (such as problem-based learning (PBL), inquiry-based learning, and service learning), and collaboration across institutions and industry.

(iii) Outcomes-Oriented Frameworks

Study program learning outcomes (Program Outcomes/PO) and course learning outcomes (Course Outcomes/CO) must be formulated strategically to align with sustainability principles. The linkage matrix between PO and CO becomes an important tool to ensure that the entire learning process supports the development of ESD competencies, such as systems thinking, environmental ethical awareness, collaboration, and sustainability literacy. This harmonization functions as a link between the academic world and the SDGs targets directly.

Table 1. Coverage of curriculum components designed with a sustainability paradigm.

Theme	Topic	Focus
Sustainable Engineering	Life Cycle Thinking	Students are invited to think systematically about the entire product/technology life cycle (from raw material extraction, manufacturing process, distribution, use, to disposal). This is important to encourage engineering decisions that are resource-efficient and have minimal ecological impact.
	Green Design	Focus on designing industrial processes that reduce waste, emissions, and energy consumption, such as the use of low-carbon technologies, recycled materials, and biomass or waste-based production processes.
	Environmental Impact Modeling and Analysis	Students are given analytical skills with tools such as Life Cycle Assessment (LCA), Carbon Footprint Analysis, and Material Flow Analysis as a basis for making sustainable engineering decisions.
	Energy and Material Efficiency	The curriculum encourages understanding of the efficiency of thermal, electrical systems, and industrial processes, as well as circular economy principles in the management of raw materials and by-products.
Engineering Ethics and Social Justice	Professional Ethics and Social Responsibility	Build awareness that engineering decisions have a major impact on safety, the environment, and the welfare of society. Students are introduced to professional codes of ethics (such as NSPE, IEEE, or PII) as well as case studies of ethical violations in engineering practice.
	Issue of Unequal Access to Technology	Examines how technology often exacerbates social inequality and encourages students to design technology that is inclusive, affordable, and appropriate to local cultural contexts.

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Table 1 (Continue). Coverage of curriculum components designed with a sustainability paradigm.

Theme	Topic	Focus
	Value-Based Decision Making	Provides a reflective space for students to consider human values, sustainability, and impartiality in every engineering decision.
	Social and Environmental Risk Analysis	Students are trained to identify social-ecological risks from engineering projects, such as the impact of infrastructure development on vulnerable communities, land conflicts, or ecosystem damage.
Socio-Technical Systems Thinking	The Interrelationship of Technology and Society	Students study how technological change affects social structures (such as automation and unemployment), consumption culture, and societal interaction patterns.
	Public Policy and Environmental Regulation	Students are introduced to technical regulatory mechanisms that support sustainable development, such as emission standards, carbon taxes, and national/international energy policies.
	Inclusive Governance in Engineering	Explores the role of community, NGO, government, and private sector participation in the public engineering decision-making process. This is important for engineering projects to be not only technically successful, but also socially acceptable.
	Social Innovation and Appropriate Technology	Develop students' ability to create simple engineering solutions that have a big impact on improving people's quality of life, such as low-cost water purification devices, local solar energy systems, or household waste processing.

(iv) Development of supporting laboratory facilities and academic facilities

Laboratory facilities that adopt living laboratory principles are crucial in sustainable engineering education. Students should have the opportunity to apply ESD principles in real contexts, such as waste engineering projects, renewable energy modeling, or water and materials efficiency. Collaboration with industry is also important, not only for internships or collaborative research, but also for developing two-way learning systems and community empowerment.

3.6. Learning Model of ESD Integration

In facing the challenges of the 21st century, which is marked by the complexity of global crises such as climate change, resource scarcity, social inequality, and technological disruption, engineering education is required to transform into a driving force for sustainable development. Engineering education no longer just aims to produce graduates who are reliable in technical aspects alone, but must also be able to produce professionals who are ethically aware, adaptive to change, and able to respond to cross-sector challenges with responsible, innovative solutions. ESD exists as a conceptual framework that integrates environmental, social, and economic dimensions into the education system. In the context of engineering education, ESD demands a transformative pedagogical approach, cross-sector collaborative models, as well as values-based learning and real action. ESD also emphasizes the importance of strengthening sustainability literacy, systemic thinking, and 21st century skills such as critical thinking, collaboration, and innovation. Various learning models in engineering education have been developed strategically to support the achievement of SDGs as shown in **Table 2**. These models not only offer a curricular approach, but also build an

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institutional ecosystem and collaboration between universities, industry and society. Each model focuses on specific SDG outcomes and reflects how engineering education can contribute significantly to global solutions.

Tabel 2. Learning model of ESD integration.

Learning Model	Model Focus	Practice Focus	Learning Approaches	Achievements toward SDGs	Ref
Action-Oriented Sustainability Practice	This model emphasizes students' active involvement in real practice through sustainable engineering projects in laboratories, industry, and society. The focus is on implementing engineering solutions that are resource efficient, green technology, and have minimal environmental impact.	(i) Renewable energy engineering, (ii) Domestic waste processing system, (iii) Small scale biogas technology, (iv) Water conversion and energy savings, (v) Collaboration with community and industry.	(i) Project based Learning (ii) Service learning (iii) Collaborative Engineering Learning	SDG 4, SDG 12, SDG 13, ADG 17	[27]
Curriculum-Driven Sustainability Literacy	This model integrates sustainability literacy into the engineering education curriculum systematically and explicitly, so that students gain structured sustainability knowledge, skills and values from the beginning to the end of the educational process.	(i) Simulation of future city designs and sensor systems for energy efficiency, (ii) Development of bicycle lanes, electric vehicles and clean energy-based public transportation, (iii) Disaster management and resilient infrastructure, (iv) Evaluate the social and environmental impacts of engineering projects, (v) Analyze the accessibility and social impact of engineering projects.	(i) Problem based Learning (ii) System Thinking Education (iii) Case-Base Discussion (iv) Collaborative Engineering Learning	SDG 4, SDG 11, SDG 17	[35]

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Tabel 2 (Continue). Learning model of ESD integration.

Learning Model	Model Focus	Practice Focus	Learning Approaches	Achievements toward SDGs	Ref
Socio-Scientific Issue-Based Education	This model integrates scientific and social approaches in engineering learning to build students' critical awareness of the social, ethical and environmental consequences of engineering solutions.	(i) Designing cheap rainwater harvesting and filter systems on a local basis, (ii) Designing water and energy efficient automatic irrigation, (iii) Designing a participatory waste detection and processing system, (iv) Designing of cheap and renewable energy technology, (v) Social evaluation of engineering projects.	(i) Socio-Scientific Inquiry (ii) Problem-Based Learning (iii) Argumentation and Debate (iv) Role Play (v) Community-Based Project Learning	SDG 1, SDG 2, SDG 4	[36]
Holistic Engineering for Sustainable Development	Carrying a multidisciplinary approach that integrates research, theory, and engineering practice in one unit. Students are trained to develop systemic and integrated solutions, such as clean technology design, green industrial systems, and sustainable manufacturing that pay attention to aspects of health and the work environment.	(i) Human-centered which integrates civil engineering with environmental health, for example, creating healthy air circulation without additional energy, (ii) Zero-waste production, (iii) Integrated green energy system.	(i) Problem-Based Learning (ii) System Thinking Training (iii) Service Learning	SDG 3, SDG 4, SDG 12, SDG 13, SDG 17	[37]
Industrial Advisory-Integrated Curriculum	Involving industry directly in curriculum design, module development, and evaluation of learning outcomes.	(i) Joint university-industry projects, (ii) Industrial visits, (iii) Green product development, (iv) Internship for sustainability,	(i) Problem-Based Learning (ii) Problem-Based Learning (iii) Experiential learning	SDG 4, SDG 17	[38]

Tabel 2 (Continue). Learning model of ESD integration.

Learning Model	Model Focus	Practice Focus	Learning Approaches	Achievements toward SDGs	Ref.
	Students gain direct experience through real SDGs-based projects, thematic internships, and industrial case studies. This model strengthens connectivity between the needs of the world of work and the development of students' sustainability competencies.	(v) Guest lecturer and co-teaching.	(iv) Blended Industry-University Learning		

3.7. Student Competence to Achieve SDGs

To prepare engineering students to face SDGs challenges, a set of key competencies that have been identified through the results of focus group discussions from various stakeholders, namely academics, students, and the industrial world, is needed. These competencies are not only technical, but also reflect the need for a systemic, collaborative, creative, and ethical approach that is appropriate to the complexity of today's global problems, including:

(i) Systems thinking. This competency includes the ability to think analytically and holistically, namely being able to synthesize information and understand the relationships between elements in a system to see the big picture. In an engineering context, this is especially important because engineers are expected to be able to design solutions that are not only technically effective but also take into account the overall social and environmental impact. Holistic thinking is understood as the capacity to synthesize and relate various technical aspects to a broader social context, including global awareness and general knowledge [39].

(ii) Normative Competence. This competency is rooted in social responsibility and sustainability awareness. All stakeholders agree that future engineers must be equipped with strong moral values, an awareness of sustainability, and an orientation towards the common good. Academics emphasize the role of technical education institutions in forming "good citizens", which in this context means graduates who are aware of their role in society and the environment. These competencies are essential in making ethical and socially responsible engineering decisions [39].

(iii) Strategic Competence and Creativity. Strategic competence refers to the ability to innovate, think creatively, manage projects, and make strategic decisions. This competency is recognized as important by all groups. The industrial world emphasizes the importance of innovation capacity as the key to company continuity and competitiveness. Creativity is seen as a fundamental skill in engineering, as it is closely related to the ability to create new solutions. In addition, students and industry players also highlight the importance of design skills as part of implementing innovation, while decision-making that considers social and environmental impacts is of particular concern to academics and students [39].

(iv) Interpersonal Competence. Interpersonal competence includes communication skills, collaboration, teamwork, negotiation, and listening skills, all of which are very important in cross-cultural and disciplinary work contexts. All stakeholder groups agree that engineers must not only be able to solve technical problems but must also be able to communicate solutions effectively to others. Collaboration is considered important not only in engineering environments but also in the context of international partnerships involving diverse cultural backgrounds [40, 41].

(v) Interdisciplinary Work. The ability to work across disciplines allows engineers to understand various perspectives and collaborate with experts from other fields in solving multidimensional SDGs problems. This competency receives full support from all groups because the complexity of sustainability challenges requires synergy between fields [42, 43].

(vi) Critical Thinking. This competency is relevant because it plays an important role in evaluating information, considering various alternative solutions, and assessing the social and environmental impacts of an engineering decision. Critical thinking is often the basis for strategic competence and systems thinking [44, 45].

3.8. System Thinking as a Core Competency in Sustainability Engineering Education

Systems thinking is a core competency in engineering education for sustainability. In today's global context, the challenges faced by engineers, such as climate change, environmental degradation, energy crises, and socio-economic injustice, are not single problems that can be solved with technical solutions alone [46]. These problems are complex, interconnected, and dynamic, requiring a comprehensive, multidisciplinary, and multi-sectoral approach. Therefore, 21st-century engineering education needs to shift from the traditional reductionist approach to a learning paradigm that places systems as the basic framework for understanding and solving engineering problems [47, 48].

Systems thinking refers to the ability to identify and understand the interactions between various technical and non-technical components in a system. It includes the skills to see cause-and-effect relationships, manage feedback loops, and anticipate the long-term impacts of technological decisions in social, cultural, environmental, economic, and political contexts [49]. With this approach, engineering students are trained not only to master technical aspects but also to understand the positive role and potential negative impacts of engineering activities on sustainable development [46]. A reflective attitude towards social and ecological consequences is an integral part of systemic competence that needs to be developed from the beginning of education.

This holistic approach encourages students to adopt an interdisciplinary vision in designing engineering solutions. Integrating environmental, social, economic, and technical dimensions into the learning process can help predict potential conflicts or negative impacts, so that the solutions developed are more adaptive and contextual [50]. Integrating sustainability into the engineering curriculum not only increases students' awareness of the complexity of the problems but also helps them build a systemic thinking framework that is able to create more sustainable engineering projects [51]. As a core competency, systems thinking does not stop

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at theoretical understanding, but must be developed into praxis capabilities, namely the ability to design and implement system solutions in a real, dynamic, collaborative, and reflective manner. In this case, the Process Systems Engineering (PSE) approach is a concrete example of how a systems thinking framework can be operationalized in engineering practice. PSE offers a series of analytical methods and optimization tools, such as linear programming (LP), mixed-integer linear programming (MILP), nonlinear programming (NLP), and mixed-integer nonlinear programming (MINLP), which allow solving technical and nontechnical problems simultaneously [47, 48].

The application of systems thinking in PSE is visualized through the Life Cycle Sustainability Assessment (LCSA), shown in **Figure 8**. LCSA combines three main approaches: Life Cycle Assessment (LCA) to assess environmental impacts, Life Cycle Costing (LCC) for the economic dimension, and Social Life Cycle Assessment (S-LCA) for the social dimension. With a cradle-to-grave approach, this diagram illustrates a holistic sustainability evaluation system and positions PSE as a system-based decision-making tool that considers all dimensions of sustainability simultaneously [47].

Furthermore, **Figure 9** shows the spatial and temporal reach of the PSE approach, from the molecular scale (femtoseconds) to the macro scale (years and kilometers). This visualization emphasizes the ability of PSE to address cross-scale problems, whether in molecular design, reaction engineering, supply chain optimization or national energy policies. This proves that systems thinking in the context of engineering is multi-scale and multidisciplinary, and is highly relevant to addressing major challenges such as industrial decarbonization, energy transition, and sustainable waste management [47].

Thus, systems thinking is not just an additional technical skill, but a philosophical and practical foundation in future engineering education. This ability not only strengthens the mastery of systems analysis but also fosters critical awareness of the relationship between technology, society, and the environment.

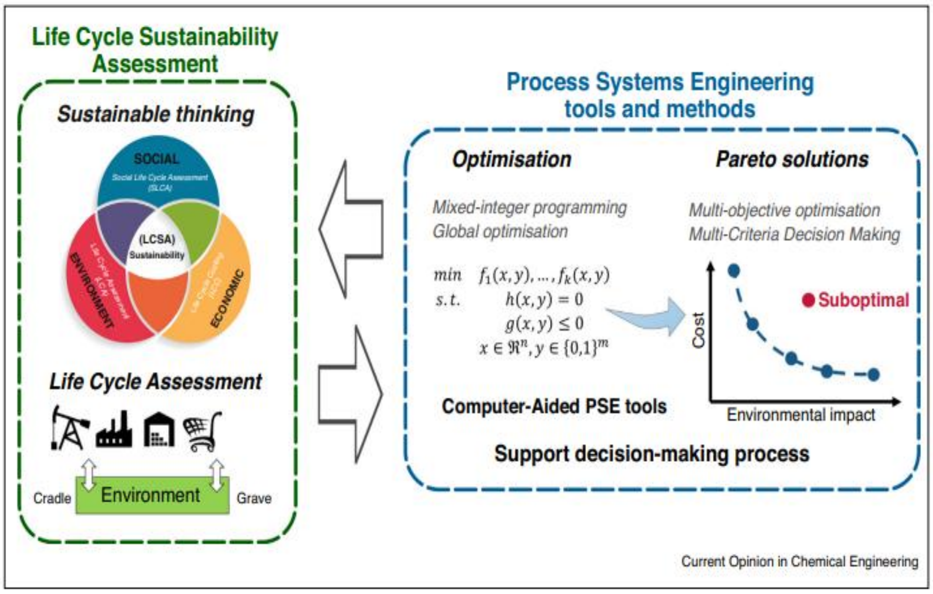

Figure 8. Concepts and tools in process systems engineering for sustainability adopted from [47].

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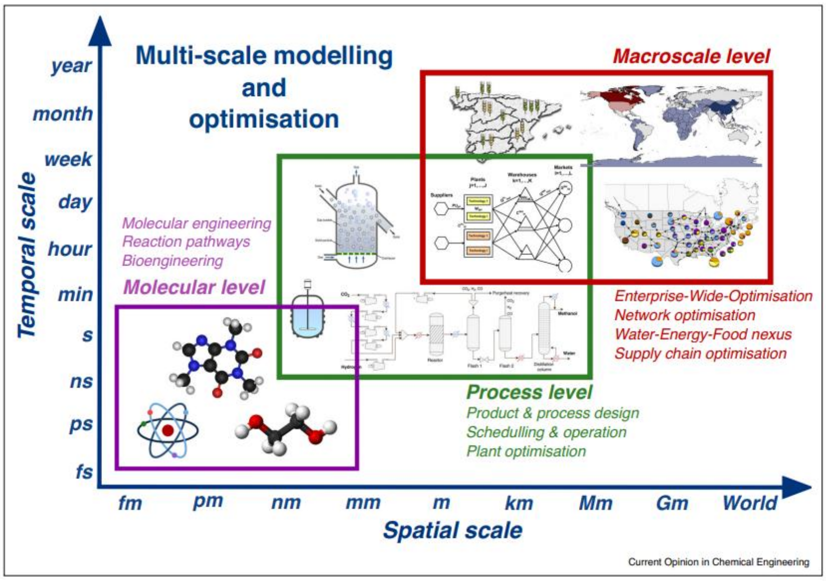

Figure 9. Time and space scales in sustainability problems in process systems engineering, adopted from [47].

3.9. Challenges and Opportunities in Integrating SDGs in Engineering Education

The integration of the SDGs into engineering education is becoming increasingly important in response to the growing complexity of global challenges facing humanity. As agents of change, engineers play a crucial role in developing sustainable solutions, which calls for a transformation in engineering education systems, particularly in curriculum development, competency formation, and pedagogical approaches. However, this transformation presents several significant challenges while also offering a range of strategic opportunities.

Challenges in Integrating SDGs into Engineering Education:

(i) Complexity in Developing Sustainability Competencies. Integrating sustainability competencies into engineering education requires a systemic approach, which has not yet been fully adopted by many institutions. The absence of practical guidelines and consistent competency standards leads to varied interpretations across institutions regarding the meaning and scope of sustainability competencies. As a result, curriculum development is often sporadic and lacks comprehensive coordination [33].

(ii) Gaps in Required Competencies. Although engineering students are expected to develop systemic, strategic, and normative competencies to address SDG-related challenges, many academic programs still focus predominantly on technical skills. Crucial competencies such as anticipatory thinking, social awareness, and reflective capacity have yet to receive adequate attention in teaching and learning processes [39].

(iii) Structural and Organizational Barriers in Academia. The siloed structure of higher education institutions poses a major barrier to interdisciplinary collaboration. Faculty members often face challenges in developing interdisciplinary learning due to time constraints, heavy workloads, and a lack of institutional support and incentives for sustainability-oriented innovation [52].

(iv) Unpreparedness of Traditional Curricula. Most engineering curricula remain rooted in conventional approaches that are insufficiently flexible and inadequately responsive to the complex issues of sustainability. These curricula do not yet support interdisciplinary

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learning, project-based learning, or the integration of social and ethical values needed to address SDGs holistically [53].

Opportunities in Integrating SDGs into Engineering Education:

(i) Growing Global Awareness and Institutional Drive. The rising global awareness of the importance of sustainability education offers an opportunity for engineering institutions to reassess their visions, missions, and development strategies. This global momentum can catalyze the adoption of more progressive academic policies aligned with the principles of the SDGs [33].

(ii) Identification of Relevant Core Competencies. There is an increasing clarity regarding the core competencies relevant to integrating SDGs into engineering education. Competencies such as systems thinking, ethical reasoning, interdisciplinary collaboration, and social awareness can serve as a foundation for designing more adaptive and contextually relevant curricula [39].

(iii) Readiness of Some Faculty Members to Innovate. Although unevenly distributed, there are educators who demonstrate a strong commitment to incorporating sustainability issues into their teaching. With adequate institutional support, professional development, and academic freedom, these faculty members have the potential to become key agents of change in advancing SDG-based innovations in engineering education [52].

(iv) Advances in Technology and Pedagogical Approaches. Technological advancements and emerging pedagogical strategies—such as project-based learning, the use of digital media, and international collaboration—enrich the learning experience. These innovations provide opportunities to design learning environments that are more practical, contextual, and aligned with real-world sustainability challenges [53].

4. CONCLUSION

This study confirms that the integration of SDGs in engineering education is not only relevant but also strategic in shaping future engineers who are able to respond to the complexity of sustainability challenges. The meeting point between engineering education and sustainability education lies in the importance of developing cross-disciplinary competencies that combine technical expertise with social, economic, and ecological understanding. The integration of ESD reflects a paradigm shift from a purely technical approach to a holistic and systemic approach.

In this context, systems thinking is identified as a core competency that enables engineering students to understand the complex interactions between technical, social, and environmental elements in the solution design process. Although there are still significant challenges, such as the complexity of developing sustainability competencies, gaps in student competencies, structural academic barriers, and the unpreparedness of traditional curricula, various strategic opportunities are also wide open. Increasing global awareness, clarity of relevant core competencies, readiness of some educators to innovate, and the development of transformative technology and pedagogy are important assets to encourage more effective ESD integration.

Thus, the integration of sustainability principles in engineering education contributes significantly to producing engineering graduates who are not only technically superior but also have high social and ecological awareness. This strengthens the role of engineering education as a strategic key in supporting the achievement of the SDGs through the development of sustainable, ethical, and multidimensional technological solutions.

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5. AUTHORS' NOTE

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