ASEAN Journal for Science and Engineering in Materials

Journal homepage: https://ejournal.bumipublikasinusantara.id/index.php/ajsem

Advancing Sustainability and Green Engineering in Mechanical Engineering Education: Concepts, Research Trends, Challenges, and Implementation Strategies

Meli Fiandini[1], Gafurdjan Israilovich Mukhamedov[2], Dustnazar Omonovich Khimmataliev[2], Asep Bayu Dani Nandiyanto[1,]*

[1]Universitas Pendidikan Indonesia, Bandung, Indonesia
[2]Chirchik State Pedagogical University, Chirchik, Uzbekistan
[*]Correspondence: E-mail: nandiyanto@upi.edu

ABSTRACT

Sustainability and green engineering are increasingly vital in mechanical engineering education as industries prioritize environmental responsibility, energy efficiency, and waste reduction. This study aims to review and synthesize current research trends, challenges, and implementation strategies concerning the integration of sustainability into mechanical engineering curricula. We used a systematic review approach using literature published between 2019 and 2024. Results indicate that although sustainability is recognized as important, its integration remains inconsistent due to curriculum gaps, limited hands-on experiences, weak industry collaboration, and insufficient faculty training. Proposed solutions include project-based learning, interdisciplinary courses, strengthened partnerships with industry, and the incorporation of green technologies such as carbon capture and circular economy practices. These strategies are essential because they bridge the gap between theory and real-world application. The findings highlight the need for standardized educational frameworks and enhanced collaboration. This review contributes to the development of curricula that prepare future engineers to address complex environmental challenges.

ARTICLE INFO

Article History:
Submitted/Received 23 Jan 2025
First Revised 20 Feb 2025
Accepted 17 Apr 2025
First Available online 18 Apr 2025
Publication Date 01 Sep 2025

Keyword:
Education,
Green engineering,
Industry collaboration,
Mechanical engineering
Renewable energy,
Sustainability.

1. INTRODUCTION

Sustainability and green engineering are critical pillars of modern technological development, particularly in mechanical engineering, where the demand for energy-efficient, low-emission, and resource-conscious technologies continues to grow. Sustainability is defined as development that meets present needs without compromising the ability of future generations by minimizing environmental, economic, and social impacts (Gao *et al*., 2021; Kaletnik & Lutkovska, 2020). Meanwhile, green engineering refers to the design and development of environmentally friendly technologies that optimize energy efficiency, carbon footprint reduction, waste minimization, and the responsible use of non-renewable resources while maintaining performance and efficiency (Rosengart *et al*., 2023; Edwards, 2021; Zhou *et al*., 2017; AL-Rawahy, 2013). Example studies relating to sustainability and green engineering are shown in **Table 1**.

Table 1. Previous studies relating to sustainability and green engineering.

No	Title	Ref
1	In-vitro analysis of antimicrobial activities of green synthesized silver oxide nanoparticles on some microorganisms found in open wound	Maryanti *et al*. (2022)
2	Leadership and organizational cultural roles in promoting sustainable performance appraisal and job satisfaction among academic staff	Abdulmaleek *et al*. (2025)
3	Machine learning-based CO_2 hydrogenation to high-value green fuels: A comprehensive review for computational assessment	Adeoye *et al*. (2023)
4	Economic policies for sustainable development: Balancing growth, social equity, and environmental protection	Ahmed *et al*. (2024)
5	Sustainability of performance of teacher-awardees' instructional competence and teaching effectiveness	Ali *et al*. (2024)
6	Application of plants extracts as green corrosion inhibitors for steel in concrete-a review	Aquino *et al*. (2024)
7	Efforts to improve sustainable development goals (SDGs) through education on diversification of food using infographic: Animal and vegetable protein	Asmara *et al*. (2018)
8	Advanced green technologies toward future sustainable energy systems	Aziz (2019)
9	Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs)	Basnur *et al*. (2024)
10	Examining the potential of sustainability marketing adoption on the performance of beverages company	Bello *et al*. 2023)
11	Assessment of student awareness and application of eco-friendly curriculum and technologies in Indonesian higher education for supporting sustainable development goals (SDGs): A case study on environmental challenges	DJirong *et al*. (2024)
12	Towards understanding the corrosion inhibition mechanism of green imidazolium-based ionic liquids for mild steel protection in acidic environments	Ech-Chihbi *et al*. (2024)
13	Students' critical thinking skills and sustainability awareness in science learning for implementation education for sustainable development	Ekamilasari *et al*. (2021)
14	Sustainable entrepreneurship as a solution to urbanization and food security challenges: A developing countries perspective	Esubalew *et al*. (2024)
15	Bibliometric analysis of research trends in conceptual understanding and sustainability awareness through artificial intelligence (AI) and digital learning media	Fiandini *et al*. (2023)
16	Sustaining students' mental health through the use of tiktok application	Gajo *et al*. (2023)

Table 1 (Continue). Previous studies relating to sustainability and green engineering.

No	Title	Ref
17	The relationship of vocational education skills in agribusiness processing agricultural products in achieving sustainable development goals (SDGs)	Gemil *et al.* (2024)
18	The mechanism of ensuring the sustainability of the development of the higher education system during the formation of a new technological order	Glushchenko (2023)
19	Green concrete: Ferrock applicability and cost- benefit effective analysis	Hadi *et al.* (2023)
20	Green skills understanding of agricultural vocational school teachers around West Java Indonesia	Handayani *et al.* (2020)
21	The influence of environmentally friendly packaging on consumer interest in implementing zero waste in the food industry to meet sustainable development goals (SDGs) needs	Haq *et al.* (2024)
22	Development of green polybag innovation products from biomass waste as planting media	Harahap *et al.* (2025)
23	Greening the internet of things: A comprehensive review of sustainable IOT solutions from an educational perspective	Jebur (2023)
24	Activated carbon films from water hyacinth waste for stable and sustainable counter-electrode application in dye-sensitized solar cells	Kamanja *et al.* (2025)
27	Analysis of student's awareness of sustainable diet in reducing carbon footprint to support sustainable development goals (SDGs) 2030	Keisyafa *et al.* (2024)
28	Effect of substrate and water on cultivation of Sumba seaworm (nyale) and experimental practicum design for improving critical and creative thinking skills of prospective science teacher in biology and supporting sustainable development goals (SDGs)	Kerans *et al* (2024)
29	Uncovering the full potential utilization of petroleum reserves residue for sustainable energy supply	Khan *et al.* (2025)
30	Eco-creative hub model as the key to integrating creativity and sustainability	Khusaini *et al.* (2023)
31	Towards sustainable wind energy: A systematic review of airfoil and blade technologies over the past 25 years for supporting sustainable development goals (SDGs).	Krishnan *et al.* (2024)
32	Conversion of green silica from corn leaf into zeolites Na A-X	Kurniawan *et al.* (2022)
33	Effects of sustained deficit irrigation on vegetative growth and yield of plum trees under the semi-arid conditions: Experiments and review with bibliometric analysis	Laita *et al.* (2024)
34	Study on economic, sustainable development, and fuel consumption	Maheshvari (2022)
35	Smart learning as transformative impact of technology: A paradigm for accomplishing sustainable development goals (SDGs) in education	Makinde *et al.* (2024)
36	Implementation of sustainable development goals (SDGs) no. 12: Responsible production and consumption by optimizing lemon commodities and community empowerment to reduce household waste	Maulana *et al.* (2023)
37	Domestic waste (eggshells and banana peels particles) as sustainable and renewable resources for improving resin-based brakepad performance: Bibliometric literature review, techno-economic analysis, dual-sized reinforcing experiments, to comparison with commercial product	Nandiyanto *et al.* (2022)
38	Domestic waste (eggshells and banana peels particles) as sustainable and renewable resources for improving resin-based brakepad performance: Bibliometric literature review, techno-economic analysis, dual-sized reinforcing experiments, to comparison with commercial product	Nurnabila *et al.* (2023)

Table 1 (Continue). Previous studies relating to sustainability and green engineering.

No	Title	Ref
39	Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs)	Nurramadhani *et al.* (2024)
40	Limestone calcined clay cement as a green construction material	Patil *et al.* (2022)
41	Efforts to enhance sustainable consciousness and critical thinking in high school students through learning projects	Purwaningsih *et al.* (2023)
42	Green route synthesis of amorphous silica from oil palm decanter cake: From literature review to experiments	Rahim *et al.* (2023)
43	Safe food treatment technology: The key to realizing the sustainable development goals (SDGs) zero hunger and optimal health	Rahmah *et al.* (2024)
44	Trends and networks in education for sustainable development (ESD): A bibliometric analysis using vosviewer	Solihah *et al.* (2024)
45	Prototype of greenhouse effect for improving problem-solving skills in science, technology, engineering, and mathematics (STEM)-education for sustainable development (ESD): Literature review, bibliometric, and experiment	Sopekan *et al.* (2024)
46	Implementing peace education concepts in early childhood curriculum: A tool for addressing violence and promoting sustainable development in Nigeria	Sridevi *et al.* (2024)
47	Microwave pyrolysis of agricultural and plastic wastes for production of hybrid biochar: Applications for greener environment	Suryani *et al.* (2021)
48	Education for sustainable development in science national exam questions of elementary school	Tarraya *et al.* (2025)
49	Emerging technologies for sustainable universities and colleges: A meta-synthesis	Theophilus *et al.* (2023)
50	Literature review for civil engineering practice and technology innovation in civil engineering and educational sustainability	Thongnop *et al.* (2021)
51	Quality sorting of green coffee beans from wet processing by using the principle of machine learning	Utama *et al.* (2023)
52	Quality sorting of green coffee beans from wet processing by using the principle of machine learning	Abd Wahab *et al.* (2023)
53	Correlation among construction, safety, accident, and the effectiveness construction industry development board (CIDB) green card training program: An initial review	D'Silva *et al.* (2022)

The application of sustainability and green engineering in mechanical engineering is particularly relevant due to the industry's responsibility to reduce environmental impact while ensuring technological efficiency and economic feasibility. Climate change, industrial pollution, and increasing energy consumption present significant challenges that require innovative solutions (Telenko *et al*., 2016). Mechanical engineers play a key role in designing systems that integrate renewable energy sources, advanced materials, and low-carbon manufacturing processes, making sustainability an essential part of modern engineering education. Many reports regarding materials science have been well-documented (Syahputra *et al*. 2021; Patil *et al*. 2022; Irwasnyah *et al*., 2024; Noviyanti *et al*., 2024).

To meet these demands, mechanical engineering education must equip students with both technical expertise and sustainability awareness. The curriculum traditionally focuses on mechanics, thermodynamics, materials science, and system design, but a stronger emphasis on sustainability is needed to prepare graduates to develop energy-efficient technologies, adopt green manufacturing practices, and address global environmental challenges (Cho *et al*., 2021). Many educational institutions are recognizing this need and have started integrating sustainability principles into their engineering programs (Bernaberi *et al*., 2023).

However, the implementation of sustainability concepts in mechanical engineering education remains inconsistent, with significant variations in how institutions embed green engineering principles into their curricula (Maulidah *et al*., 2021; Cunningham *et al*., 2020; Prasad *et al*., 2018).

Despite the growing emphasis on sustainability, several challenges hinder its full integration into mechanical engineering education:

(i) *Curriculum Gaps*: Many institutions lack standardized guidelines for embedding sustainability in mechanical engineering coursework. The focus often remains on traditional engineering principles, with sustainability treated as an elective rather than a core subject.

(ii) *Theory-Practice Disparity*: Students often learn sustainability concepts in theory, but lack hands-on experience in applying them to real-world engineering problems. Industry demands practical sustainability solutions, yet universities often fail to bridge the gap between academic learning and industrial applications.

(iii) *Limited Interdisciplinary Collaboration*: Sustainability solutions require input from environmental science, materials engineering, and digital technologies. However, many mechanical engineering programs do not integrate interdisciplinary knowledge, limiting students' ability to develop holistic solutions.

(iv) *Insufficient Research on Educational Strategies*: While many studies focus on the application of green engineering in industry, fewer explore how mechanical engineering education can contribute to sustainability. There is limited research on effective teaching methods, industry-academic partnerships, and institutional policies that support sustainability education.

This study provides a comprehensive review of research on sustainability and green engineering in mechanical engineering education, focusing on:

(i) Identifying key research trends related to sustainability integration in engineering curricula.

(ii) Exploring challenges in implementing sustainability principles in mechanical engineering education.

(iii) Proposing effective strategies to bridge the gap between academic curriculum and industrial practice.

Unlike previous studies that primarily focus on green engineering applications in industry, this research examines how mechanical engineering education itself must evolve to align with sustainable industrial practices. By analyzing current research gaps and opportunities, this study provides valuable insights for educators, policymakers, and industry leaders seeking to enhance engineering curricula with sustainability-driven solutions. With a deeper understanding of the factors influencing the integration of sustainability in mechanical engineering education, this study aims to contribute to the development of a more adaptive and future-ready curriculum, equipping the next generation of engineers with the skills to tackle global environmental challenges effectively.

2. METHODS

This study adopted a systematic review approach to examine the integration of sustainability and green engineering in mechanical engineering education. The data for this study were obtained from reputable academic databases, including Scopus and Google Scholar taken on 5 March 2025. Mainly, the search covered publications from 2019 to 2024, ensuring the inclusion of the most recent advancements in sustainability education within mechanical engineering. To retrieve relevant literature, a keyword-based search strategy was employed: "sustainability" AND "green engineering", OR "mechanical" AND "engineering education", AND "curriculum integration" AND "education". These keywords were refined based on preliminary searches to ensure that only studies directly related to the topic were included. The search results were then screened according to predefined inclusion and exclusion criteria. The review was synthesized from the findings, prioritizing of peer-reviewed journal articles, reviews, conference proceedings with a focus on research trends, challenges, and implementation strategies. Books, book chapters, non-academic sources, opinion pieces, and irrelevant studies were excluded. The selection was further refined by focusing on publications available in English and ensuring that the content directly addressed sustainability within mechanical engineering education. To support the data analysis, the concept of bibliometric analysis was adopted. Using data from reliable sources from mainly Scopus, this analysis allows researchers to see publication patterns and collaborations between researchers on a particular topic. Examples of the bibliometric analysis reports in many areas are presented in **Table 2.**

Table 2. Previous studies used bibliometric analysis.

No	Topic of Bibliometric	Ref.
1	Bibliometric analysis of nanocrystalline cellulose synthesis for packaging application research using VOSviewer	Maulidah *et al.* (2021)
2	Bibliometric analysis of engineering research using vosviewer indexed by google scholar	Nandiyanto *et al.* (2022)
3	Computational bibliometric analysis on publication of techno-economic education	Ragadhita and Nandiyanto (2022)
4	Bibliometric analysis for understanding “science education” for “student with special needs” using vosviewer	Nursaniah *et al.* (2023)
5	The role of iron oxide in hydrogen production: Theory and bibliometric analyses	Nandiyanto *et al.* (2023)
6	Trends and developments in research on adsorption in education: bibliometric analysis	Nandiyanto *et al.* (2024a)
7	Research trends from the Scopus database using keyword water hyacinth and ecosystem: A bibliometric literature review	Nandiyanto *et al.* (2024b)
8	Research trends on teachers: a bibliometric analysis	Wendi *et al.* (2024)
9	Trends and networks in education for sustainable development (ESD): A bibliometric analysis using vosviewer	Al Husaeni *et al.* (2023)
10	Literature review and bibliometric mapping analysis: Philosophy of science and technology education	Pramanik *et al.* (2023)
11	Strengthening the role of local community in developing countries through community-based tourism from education perspective: Bibliometric analysis	Nugraha *et al.* (2022)
12	Bibliometric analysis of magnetite nanoparticle production research during 2017-2021 using vosviewer	Enelund *et al.* (2013)

3. RESULTS AND DISCUSSION

3.1. Global Perspective based on Publication Trends in Sustainability and Green Engineering in Mechanical Engineering Education

Sustainability and green engineering have become critical components of mechanical engineering education, driven by the urgent need to address environmental challenges and integrate sustainable practices into engineering solutions. Research in this area has expanded significantly, focusing on key themes such as the incorporation of sustainability principles in curricula, advancements in green technologies, and the role of interdisciplinary approaches in engineering education.

Several studies, as shown in **Table 1**, emphasized the integration of sustainability concepts into mechanical engineering curricula to prepare future engineers for the challenges of sustainable development. This included the adoption of project-based learning, industry collaboration, and the development of sustainability-focused coursework, combining engineering principles with environmental and social considerations. Additionally, recent research highlighted the role of digital tools and computational modeling in enhancing sustainable engineering education. Technologies such as computer-aided design (CAD), finite element analysis (FEA), and computational fluid dynamics (CFD) are being used to optimize energy efficiency, material selection, and system performance in engineering design.

The implementation of sustainability and green engineering principles in mechanical engineering education varies across different regions, influenced by policy regulations, research funding, and institutional priorities. Developed countries such as the United States, United Kingdom, Germany, and China have made significant progress in embedding sustainability into engineering programs, supported by government policies, research funding, and industry partnerships. These nations focus on cutting-edge research in renewable energy systems, energy-efficient manufacturing, and sustainable materials. In developing countries, the adoption of green engineering education is growing, although at a slower pace due to challenges such as limited research funding, infrastructure constraints, and the lack of standardized sustainability curricula, which will be explained in the next sections. However, there is increasing awareness of the need for sustainable engineering solutions, leading to collaborative initiatives between universities, industries, and government agencies to promote green technology education.

3.2. Interdisciplinary Approaches in Sustainable Mechanical Engineering Education

A variety of research methodologies have been employed to study and improve sustainability and green engineering in mechanical engineering. This is confirmed by the type of publications for this area (**Fig. 1(a)**). Most common approaches include:

(i) Experimental and Simulation-Based Studies: Many research efforts focus on developing and testing energy-efficient mechanical systems, renewable energy prototypes, and sustainable materials through laboratory experiments and computational simulations.
(ii) Case Studies and Best Practices: Several studies analyze real-world implementations of sustainability in mechanical engineering education, providing insights into effective teaching methods, curriculum development, and industry collaborations.
(iii) Survey and Qualitative Research: Researchers have conducted surveys and interviews with educators, students, and industry professionals to assess the effectiveness of sustainability education and identify areas for improvement.
(iv) Comparative Analysis of Educational Frameworks: Some studies compare different sustainability education frameworks across institutions and countries, highlighting best

practices and challenges in integrating green engineering into mechanical engineering curricula.

In general, sustainability in mechanical engineering is inherently multidisciplinary, requiring knowledge from fields such as environmental science, energy systems, materials engineering, and social sciences. As shown in **Table 1**, the studies mostly emphasized the importance of integrating multiple disciplines into mechanical engineering programs to provide students with a holistic understanding of sustainability challenges. This is also confirmed by the analysis of the disciplines involved in the publication (see **Figure 1(b)**). For example, sustainable materials research explores the development of biodegradable polymers, recycled metals, and energy-efficient composites that reduce the environmental impact of manufacturing processes. Similarly, the incorporation of renewable energy technologies into engineering curricula (such as solar, wind, and bioenergy systems) equips students with the knowledge needed to design energy-efficient systems. Moreover, social sciences and policy studies are playing an increasingly important role in mechanical engineering education, helping students understand the broader economic, environmental, and social impacts of engineering decisions. This multidisciplinary approach ensures that future engineers are equipped to design solutions that are not only technically sound but also environmentally and socially responsible.

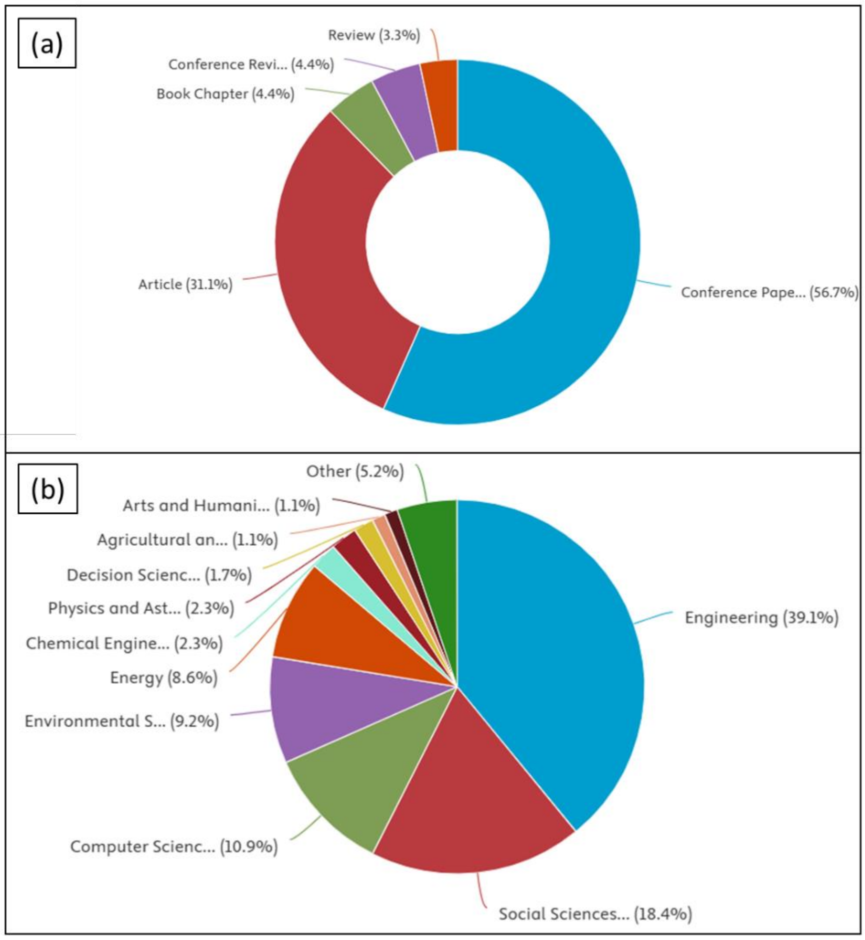

Figure 1. Documents obtained from the Scopus database taken on March 2025 regarding sustainability and green engineering in mechanical engineering education: (a) Documents by publication type; (b) documents by subject.

3.3. Research Trends in Sustainability and Green Engineering

Sustainability and green engineering have become integral to mechanical engineering education, as the field plays a crucial role in addressing global challenges such as climate change, resource depletion, and environmental pollution (Okokpujie *et al*., 2019; Ramanujan *et al*., 2019; Lozano *et al*., 2018). Research in this area has gained significant momentum, with studies focusing on renewable energy applications, sustainable materials, and industry-academia collaboration to develop an environmentally responsible engineering workforce (Krzywanski *et al*., 2023). Several examples are presented in **Table 1**.

At its core, sustainability in mechanical engineering involves developing technologies and practices that meet present societal needs without compromising the ability of future generations to do the same (Gao *et al*., 2021). This principle aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure), which emphasize the need for energy-efficient solutions and sustainable industrial development (Okokpujie *et al*., 2019).

A key approach to achieving sustainability in mechanical engineering is through Green Engineering, which focuses on designing and implementing technologies that reduce environmental impact throughout a product's life cycle (Ramanujan *et al*., 2019). This includes minimizing energy consumption, optimizing material use, reducing waste, and improving industrial process efficiency. As industries increasingly prioritize sustainability, the integration of green engineering principles into mechanical engineering curricula is essential to prepare future engineers for the transition to energy-efficient systems, sustainable manufacturing, and innovative environmental solutions (Lozano *et al*., 2018).

Table 3 summarizes the current research trends, key challenges, and future directions in sustainable mechanical engineering education. **Figure 2** illustrates the interconnections between major research themes, showing how sustainability initiatives in mechanical engineering education are evolving. Based on **Table 3** and **Figure 2**, Key research themes in green engineering education include:

(i) Applications of Renewable Energy in Mechanical Engineering. The integration of solar, wind, biomass, and other renewable energy systems into engineering curricula has expanded rapidly. Research explores energy-efficient designs for mechanical systems, such as Solar-powered mechanical devices for industrial and domestic applications (Barbosa *et al*., 2022), Hybrid energy systems that integrate wind and solar power to improve efficiency (Kettune *et al*., 2022), and Biomass energy systems as alternative fuel sources in sustainable manufacturing (Gatto *et al*., 2015). These innovations are crucial for reducing dependency on fossil fuels while enhancing students' hands-on learning experience.

(ii) Green Materials and Sustainable Design. Sustainable materials research emphasizes eco-friendly manufacturing and waste reduction strategies in mechanical engineering (Barbosa *et al*., 2022), including: Biodegradable polymers and recycled composites are replacing conventional materials, Additive manufacturing (3D printing) is enabling more efficient material usage, and Life Cycle Assessment (LCA) tools are being incorporated into curricula to analyze environmental impacts of mechanical products (Tangwanichagapong *et al*., 2017).

(iii) Industry-Academia Collaboration for Sustainability. Growing cooperation between universities and industry aims to align mechanical engineering curricula with sustainable industry needs [70], including: Internship programs with green technology companies provide hands-on experience, University-industry joint research initiatives foster innovation in sustainable engineering, and Certification-based courses enhance student knowledge of environmental standards.

Table 3. Research trends, challenges, and future directions in green engineering education.

Research Trend	Key Focus Areas	Challenges	Future Directions
Renewable Energy Applications	Solar, wind, biomass integration in curricula	High initial cost, need for hands-on training	AI-driven energy optimization models
Green Materials & Design	Eco-friendly materials, sustainable manufacturing	Lack of scalability in real-world applications	Advancements in 3D printing for sustainable materials
Industry-Academia Collaboration	Internships, certification-based courses	Limited industry partnerships, funding constraints	Expansion of research-industry consortia

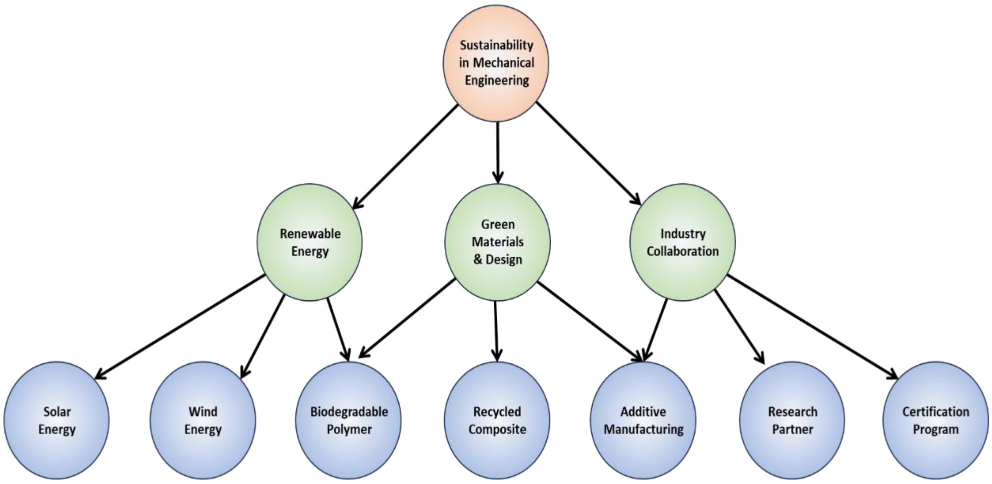

Figure 2. Interconnections between research trends in green engineering education.

3.3.1. Key components of sustainability in mechanical engineering education

Figure 3 illustrates the integration of sustainability concepts into mechanical engineering education, highlighting key themes and their application in engineering coursework. This is important to ensure that future mechanical engineers develop the necessary expertise Sustainability education must incorporate several fundamental elements:

(i) Sustainable Materials and Manufacturing: Use of biodegradable polymers, recycled metals, and composites to reduce material waste; Adoption of additive manufacturing (3D printing) for material efficiency; and Implementation of life cycle assessment (LCA) in design processes.

(ii) Energy Efficiency and Renewable Technologies: Integration of solar, wind, and biomass energy into mechanical systems; Use of energy-efficient motors, heat recovery systems, and regenerative braking; and Application of computational fluid dynamics (CFD) for optimizing energy usage.

(iii) Environmental Impact Reduction: Development of low-emission transportation technologies, including electric and hybrid vehicles; Application of carbon capture and storage (CCS) systems in industrial processes; and Reduction of water and energy consumption in manufacturing facilities.

(iv) Industry Collaboration and Practical Applications: Inclusion of real-world case studies and partnerships with industries adopting green engineering; Encouragement of internships and research projects focused on sustainability; and Promotion of certifications such as LEED (Leadership in Energy and Environmental Design) in engineering curricula.

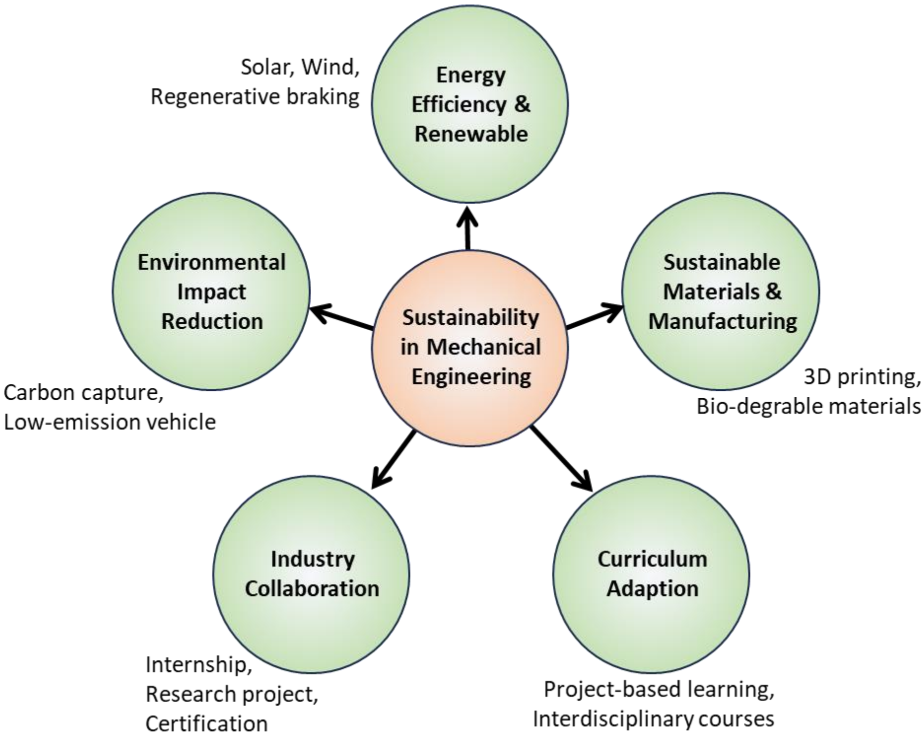

Figure 3. Framework for integrating sustainability in mechanical engineering education.

3.3.2. Curriculum adaptation for sustainability

The successful incorporation of sustainability into mechanical engineering curricula requires curricular modifications to ensure students develop both conceptual knowledge and practical skills. These curriculum enhancements bridge the gap between theoretical knowledge and real-world applications, preparing graduates to contribute to sustainable engineering solutions effectively. These adaptations may include:

(i) Project-Based Learning (PBL): Hands-on projects where students design and prototype sustainable engineering solutions (e.g., energy-efficient devices, green building materials).

(ii) Interdisciplinary Courses: Integration of environmental science, policy studies, and materials engineering to provide a holistic understanding of sustainability challenges.

(iii) Simulation and Modeling Tools: Use of FEA, CFD, and life cycle assessment software to assess the environmental impact of engineering designs.

(iv) Industry Collaboration: Partnering with green technology companies for internships, case studies, and research opportunities.

3.3.3. Future directions in sustainability and green engineering in mechanical engineering education

While significant advancements have been made, several gaps remain in research and implementation. Future studies should focus on the following areas to strengthen them in mechanical engineering education:

(i) Integration of AI and IoT in Sustainability Education. AI-driven analytics and IoT-based monitoring systems can enhance energy efficiency, predictive maintenance, and resource optimization in mechanical engineering applications. Research should explore how these technologies can be embedded in engineering curricula to improve sustainability education.

(ii) Scalability of Renewable Energy Labs. Expanding access to solar, wind, and biomass energy labs is essential for providing hands-on experience in sustainable energy systems. Future studies should investigate cost-effective models for integrating renewable energy infrastructure into engineering education

(iii) University-Industry Collaboration. Stronger partnerships between academia and industry are needed to bridge knowledge gaps and align curricula with real-world sustainability challenges. Research should focus on effective frameworks for industry-led projects, internships, and joint research initiatives.

(iv) Circular Economy Approaches. The mechanical engineering curriculum should emphasize design-for-recycling principles, waste reduction strategies, and sustainable product lifecycle management. Future studies should evaluate how these concepts can be effectively incorporated into engineering education.

(v) Policy and Regulatory Compliance. Engineers must be trained in carbon neutrality commitments, emissions regulations, and environmental policies to develop sustainable solutions that meet global standards. Research should explore the integration of sustainability policy education into mechanical engineering programs.

By addressing these areas, future research will drive the evolution of mechanical engineering education, ensuring that graduates are equipped with the skills needed for sustainable industrial transformation and the challenges of a green economy.

3.4. Implementation Strategies for Sustainability and Green Engineering in Mechanical Engineering Education

Tables 4 and **5** summarizes these implementation strategies, including their applications, benefits, and challenges. **Figure 4** illustrates the interconnection between these strategies, emphasizing how they collectively enhance sustainability education in mechanical engineering. Based on **Tables 4** and **5** as well as **Figure 4**, To effectively integrate sustainability into mechanical engineering education, multiple strategies must be implemented to bridge the gap between theoretical knowledge and practical application.

These strategies ensure that students gain hands-on experience, collaborate with industry, adopt multidisciplinary approaches, and benefit from infrastructure that supports green technologies (Kettunen *et al*., 2022).

(i) Project-based Learning (PjBL) for Practical Experience. PjBL allows students to apply sustainability concepts in real-world scenarios, fostering problem-solving skills and innovation (Kettunen *et al*., 2022). Examples include: Designing solar water heating systems or small wind turbines as part of coursework; Developing energy-efficient mechanical components using computational simulations; and Conducting waste reduction projects in university laboratories.

(ii) Strengthening Industry Collaboration. University-industry partnerships help ensure that curricula remain relevant to sustainability challenges in the workforce (Gatto *et al*., 2015). Collaborations include Internships with companies specializing in green technology and renewable energy; Joint research projects focused on sustainable materials and energy-efficient designs; and Industry-led guest lectures and workshops to expose students to real-world sustainability applications.

(iii) Multidisciplinary Approach to Sustainability. Sustainability in mechanical engineering requires knowledge from environmental science, materials engineering, and policy studies (Tangwanichagapong *et al.*, 2017). Successful interdisciplinary strategies include: Joint courses between mechanical engineering and environmental science; Collaborations with materials science to explore sustainable manufacturing techniques; and Integration of AI and IoT in sustainability-based engineering projects.

(iv) Development of Green Infrastructure on Campus. Upgrading university infrastructure with sustainable technologies encourages experiential learning (Saleet *et al.*, 2023). Best practices include Installation of solar panels and electric vehicle charging stations; Rainwater harvesting and recycling systems for engineering labs; Sustainable building designs as demonstration models for students.

For future considerations for sustainability implementation, while these strategies significantly enhance sustainability education, additional steps are needed:

(i) Increased government and industry funding to support green initiatives.
(ii) Development of AI-driven sustainability simulations for hands-on learning.
(iii) Stronger collaboration between policymakers and academia for standardized curricula.

By addressing these challenges, mechanical engineering education can fully integrate sustainability principles, equipping graduates with the skills needed for a green future.

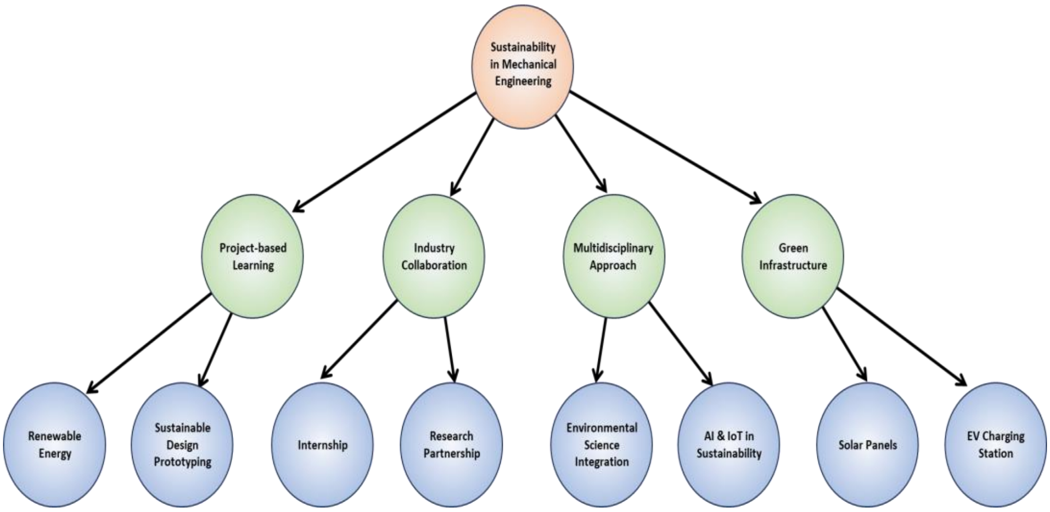

Figure 4. Integrated implementation strategies for sustainability education.

Table 4. Implementation, description, and curriculum application example of sustainability in mechanical engineering education.

Implementations	Description	Curriculum application example
Project-Based Learning	Students have the chance to work on practical projects that use sustainability concepts.	Create initiatives for the development of solar water heating systems or tiny wind turbines.
Industry Collaboration	Working together with businesses to make sure the curriculum meets their needs	Industrial internships with companies focused on green technology.
Multidisciplinary Approach	Integrating several fields to tackle sustainability issues comprehensively.	Cooperation between environmental science, material science, and mechanical engineering.
Green Infrastructure Development	Improving campus facilities with green technologies and renewable energy systems.	Utilizing electric vehicles and putting up solar panels on campus.

Table 5. Implementation strategies for sustainability in mechanical engineering education.

Strategy	Application	Benefits	Challenges
Project-Based Learning	Development of solar water heating systems, wind turbines	Hands-on experience, innovation, real-world skills	Requires funding and specialized faculty support
Industry Collaboration	Internships, joint research on green technology	Real-world exposure, networking, career readiness	Industry participation may be limited
Multidisciplinary Approach	Courses integrating engineering, environmental science	Broader perspective, cross-disciplinary innovation	Coordination across departments is needed
Green Infrastructure	Campus solar panels, EV charging, recycling programs	Demonstrates sustainability, long-term cost savings	High initial investment costs

3.5. Applications and Impacts of Sustainable and Green Technologies on Mechanical Engineering Education

Green technologies are relevant to mechanical engineering education (**Table 6**). As many industries transition to green technologies, they are currently confronted with formidable obstacles in mitigating their environmental impact. The mechanical engineering curriculum needs to take into account the technologies that industries are adopting, such as green materials, renewable energy, and efficient production techniques (Prasojo *et al*., 2025). The following are some examples of green technologies used in mechanical engineering education:

(i) Renewable energy systems: Prioritizing the design and development of industrial-use solar, wind, and biomass energy systems.

(ii) Green materials: The application of recyclable and more effective materials in manufacturing and design processes (Gao *et al*., 2021).

(iii) Green Manufacturing: The use of technology that lowers industrial waste and energy usage (Gao *et al*., 2021).

Table 6. Green technologies in industry and their impact on mechanical engineering education.

Green Technology	Description	Curriculum application example
Renewable Energy	The utilization of renewable energy sources such as sun, wind, and biomass.	Teaching about solar panel technologies, wind turbines, and bioenergy systems.
Green Materials	The use of environmentally friendly materials that can be recycled to reduce carbon footprint.	Teaching about biodegradable materials and recyclable materials.
Green Manufacturing Processes	Technologies that reduce waste, energy consumption, and carbon footprint during production.	Case studies of manufacturing processes that use low energy and green materials.

The impact can be directly received several years after the education is implemented. It plays a crucial role in the development and application of green technologies (**Figure 5**). These technologies are designed to reduce environmental impact, improve energy efficiency, and enhance the sustainability of industrial processes.

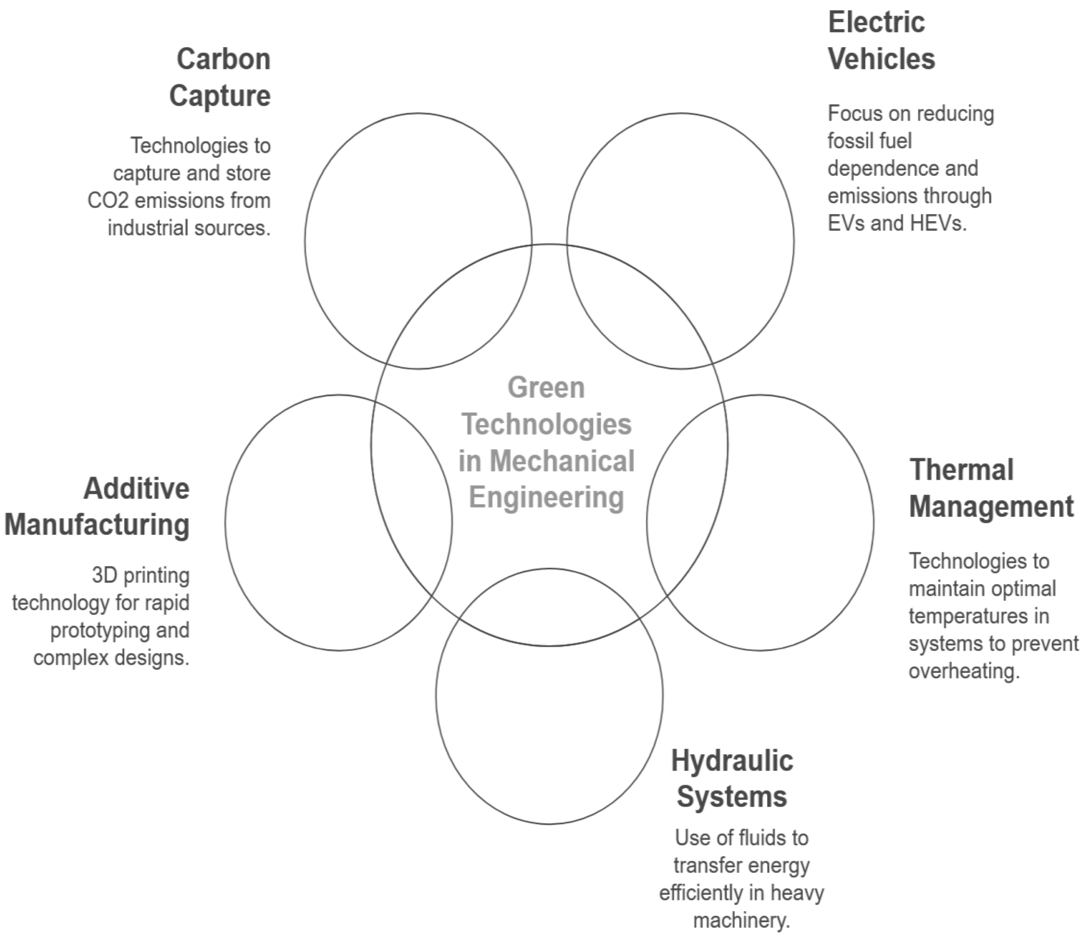

Figure 5. Innovative green solutions in mechanical engineering.

Several examples of key green technologies that are reshaping the mechanical engineering landscape are:

(i) *Electric and Hybrid Vehicles (EVs and HEVs).* Electric vehicles (EVs) and hybrid vehicles (HEVs) are breakthroughs in the automotive industry, focused on reducing dependence on fossil fuels and reducing greenhouse gas emissions. EVs are powered entirely by electric motors that are driven by energy stored in rechargeable batteries (Nykvist *et al.*, 2019). EVs produce no exhaust emissions, making them a more environmentally friendly option compared to fossil fuel-powered vehicles. However, challenges faced by electric vehicles include limited range, relatively long charging times, and high battery costs (Miao *et al.*, 2019). Recent advances in battery technology, particularly lithium-ion batteries, have improved energy storage capacity and faster charging times, although research is ongoing to improve battery performance and reduce costs. HEVs, on the other hand, combine an internal combustion engine (ICE) with an electric motor, allowing for more efficient use of fossil fuels and reducing exhaust emissions (Hannan *et al.*, 2014). HEVs have two power sources: an internal combustion engine that operates at high speeds and an electric motor that functions at low speeds or during acceleration. The regenerative braking system in hybrid vehicles also allows the energy lost during braking to be recovered and converted into electricity for storage in the battery (Dhand *et al.*, 2013; Gauto *et al.*, 2023). Further developments in this sector include research into pure electric vehicles (BEVs) that use 100% electric energy, as well as the development of plug-in hybrid vehicles (PHEVs) that allow battery charging from an external source, providing more flexibility in energy use (Jixiang *et al*., 2021).

(ii) *Thermal Management Technologies.* Thermal management is becoming increasingly important in the design and operation of various engine systems, especially those involving systems that generate high heat, such as internal combustion engines, electric vehicles, and industrial electronics. Thermal management technologies aim to maintain temperatures at safe and optimal levels to avoid component damage due to overheating (Liang *et al*., 2021). In electric vehicles, the battery cooling system is a crucial aspect because excessively high temperatures can reduce the battery's lifespan or even damage it. Cooling technologies using water-based fluids or active refrigeration technologies are used to keep the battery temperature within a safe range (Prakash *et al*., 2016). In the automotive sector, engine cooling systems use radiators that work by circulating coolant to absorb heat from the engine and release it into the air. In addition, heat recovery technologies such as regenerative braking systems used in hybrid and electric vehicles can convert the kinetic energy wasted during braking into electrical energy that can be stored back in the battery. In the industrial sector, heat recovery systems from machines that generate excess heat, such as turbines or fossil fuel power plants, can improve overall energy efficiency by capturing and converting heat into reusable energy (Oró *et al*., 2012). In addition, the use of advanced thermal materials, such as phase change materials (PCMs), which absorb and release energy in the form of heat when a phase change occurs (e.g. from solid to liquid) is increasingly being applied to regulate the temperature inside heat-sensitive components or devices (Oró *et al*., 2012).

(iii) *Hydraulic and Pneumatic Systems.* Hydraulic and pneumatic systems are used in various engineering applications to transfer mechanical energy using fluid media or pressurized air. Hydraulic systems work by using fluids (usually hydraulic oil) to transfer power (Gao *et al*., 2024). The working principle of this system is to flow pressurized fluid to various components that require power, such as heavy equipment (eg excavators, bulldozers), printing machines, and various other industrial machines. Hydraulic systems are very efficient in producing large power with a relatively small size and are very suitable for use in applications that require precision control and high strength (Kosova *et al*., 2023). On the other hand, pneumatic systems use compressed air as a medium to move mechanical components. Pneumatic systems are generally simpler, cheaper, and lighter than hydraulic systems. This technology is widely used in industrial automation equipment, such as packaging machines, assembly machines, and robotic systems for processes that require high speed and precision, but with lower loads. The main advantages of pneumatic systems are their cleanliness (because they use air) and lower operating costs. However, this system has disadvantages in terms of strength, when compared to hydraulic systems (Jiménez *et al*., 2019).

(iv) *Additive Manufacturing (3D Printing).* Additive manufacturing, more commonly known as 3D printing, is a production method that turns digital designs into physical objects by gradually adding material, layer by layer. This technology is very useful in prototyping with faster time and lower cost and allows for more complex designs and product personalization that were previously difficult to achieve with conventional manufacturing techniques. 3D printing can use a variety of materials, from plastics to metals to ceramics (Salmi, 2016). 3D printing is primarily used in the automotive, aerospace, and medical industries, where components with complex and special shapes are needed. For example, in the automotive industry, 3D printing is used to create custom parts or vehicle prototypes. Likewise, in the aerospace industry, 3D printing allows the creation of lighter but still strong aircraft engine components. In the medical world, 3D printing allows the creation of implants or prosthetics that are customized to the needs of patients (Osman *et al.,* 2021).

(v) *Carbon Capture and Storage (CCS).* Carbon Capture and Storage (CCS) is a technology that aims to reduce the concentration of carbon dioxide (CO_2) in the atmosphere by capturing CO_2 emissions produced by power plants and heavy industry, and then storing them underground or in safe storage (Vijayan *et al*., 2024). This technology is very relevant in climate change mitigation efforts, especially in sectors that are difficult to reduce emissions directly, such as the fossil fuel power generation industry, cement factories, and steel factories (Capocelli *et al*., 2022). The CCS process consists of three main steps: carbon capture, carbon transportation, and carbon storage. The captured CO_2 is then pumped through pipes and stored in safe geological formations, such as depleted oil and gas reservoirs or underground rock layers that are deep and stable enough (Leung *et al*., 2014). CCS development also faces challenges related to high costs, potential gas leaks, and the readiness of long-term storage infrastructure. However, this technology is still considered one of the potential solutions to reduce CO_2 emissions in the long term (Blocken *et al*., 2012).

(vi) *Fluid Mechanics and Dynamics.* Fluid mechanics is a branch of physics that studies the behavior of fluids (liquids and gases) in static and dynamic states. Fluid dynamics studies the forces acting on fluids and how fluids move (Sarkar *et al*., 2019). In mechanical engineering, a good understanding of fluid mechanics is essential in a variety of applications, such as the design of heat transfer systems, turbine engines, pumps, and hydroelectric power plants. Fluid dynamics also plays a major role in the aerodynamic design of vehicles, both for land vehicles and air vehicles. For example, the aerodynamic design of a car or plane can reduce air resistance, which in turn reduces fuel consumption (Xu *et al*., 2017). In industry, the use of Computational Fluid Dynamics (CFD) is a very useful tool for simulating fluid flow under various conditions, allowing engineers to design more efficient and optimal systems without having to conduct expensive physical experiments. CFD is used in the design of combustion engines, and ventilation systems, and in the analysis of air movement around building structures or vehicles (Chen, 2024).

3.6. Challenges in Integrating Sustainability into Mechanical Engineering Education

The identification of the main challenges in the integration of sustainability and green engineering is presented in **Table 7**. Although mechanical engineering programs have made great strides toward sustainability, there are still several key obstacles to overcome, especially when facing to developing countries (Prasojo *et al*., 2025; Nandiyanto *et al*., 2020):

(i) *Theory-Practice Gap*: Although a lot of theoretical information regarding sustainability is presented in the classroom, there is frequently a significant lack of industry-relevant practical application (Okokpujie *et al*., 2019).

(ii) *Faculty and Educator Readiness*: Since many faculty members lack a solid understanding of sustainability or green engineering, the instruction they give may not always be up to date with the newest or most useful ideas (Gao *et al*., 2021).

(iii) *Absence of Consistent Curriculum Guidelines*: Teaching and implementing sustainability generally is inconsistent due to the many methods that different educational institutions include sustainability (Lozano *et al*., 2018).

(iv) *Lack of Resources and Infrastructure*: Some educational institutions lack the resources and infrastructure needed to successfully incorporate sustainability subjects, such as facilities for renewable energy that can be used as teaching aids (Lozano *et al*., 2018).

Table 7. Challenges in integrating sustainability in mechanical engineering education.

Challenges	Description	Proposed solution
The gap between Theory and Practice	Theories taught in class often do not align with real practices in the industry.	Applying a project-based approach to link theory with industry practice.
Readiness of Faculty	A large number of faculty members are not well-versed in green engineering and sustainability.	Establishing training and development initiatives for teachers to expand their understanding of sustainability.
Lack of Consistent Curriculum	Every educational establishment uniquely incorporates sustainability.	Establishing uniform curricular requirements for mechanical engineering that incorporate sustainability.
Lack of Infrastructure	Some institutions lack the facilities required to support actual sustainability instruction.	On-campus renewable energy facilities and green technology are being implemented.

4. CONCLUSION

This study provides a comprehensive review of research trends, challenges, and implementation strategies in sustainability and green engineering within mechanical engineering education. The findings emphasize the growing role of sustainability in engineering curricula, focusing on energy efficiency, waste reduction, and responsible resource management to prepare future engineers for environmentally conscious industrial practices. Research in sustainability and green engineering education has shown significant growth, particularly after the disruptions caused by the COVID-19 pandemic. This resurgence reflects an increasing global commitment to integrating sustainability into mechanical engineering. Key areas of focus include renewable energy technologies, sustainable materials, and industry-academia collaboration, which are essential for developing engineering solutions that align with environmental and industrial needs. Despite progress, challenges persist, including gaps between theoretical knowledge and practical application, faculty preparedness, inconsistent curricula, and inadequate infrastructure. To overcome these barriers, this study highlights four key implementation strategies:

(i) Project-Based Learning (PBL).
(ii) Industry Collaboration.
(iii) Multidisciplinary Approaches.
(iv) Infrastructure Development.

Additionally, green technologies such as renewable energy systems, sustainable materials, additive manufacturing, and carbon capture are becoming integral to mechanical engineering education, reinforcing the shift toward sustainable industrial practices. Moving forward, further research is needed to:

(i) Enhance AI and IoT applications in sustainable mechanical engineering education.
(ii) Expand interdisciplinary sustainability programs through global collaboration.
(iii) Develop scalable models for integrating sustainability into core engineering courses.

By addressing these aspects, mechanical engineering education can play a pivotal role in shaping the next generation of engineers who will lead the transition toward a more sustainable, energy-efficient, and environmentally responsible future.

5. ACKNOWLEDGMENT

This study is supported by Universitas Pendidikan Indonesia.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

7. REFERENCES

Abd Wahab, N., Mahmood, N. H. N., and Minghat, A. D. (2023). Correlation among construction, safety, accident, and the effectiveness construction industry development board (CIDB) green card training program: An initial review. *ASEAN Journal of Science and Engineering*, *3*(2), 139-146.

Abdulmaleek, R. O., Okon, I. E., Ndukwe, G. I., Adamma, P., and Ekwumemgbo, E. (2025). In-vitro analysis of antimicrobial activities of green synthesized silver oxide nanoparticles on some microorganisms found in open wound. *ASEAN Journal for Science and Engineering in Materials*, *4*(1), 43-54.

Adeoye, M. A., Jimoh, H. A., and Abdulkareem, H. B. (2023). Leadership and organizational cultural roles in promoting sustainable performance appraisal and job satisfaction among academic staff. *ASEAN Journal of Economic and Economic Education*, *2*(2), 115-124.

Ahmed, M., Latif, R., Seher, S., Sajjad, R., Hussain, T., Islam, M. R., and Waleed, A. (2024). Machine learning-based CO_2 hydrogenation to high-value green fuels: A comprehensive review for computational assessment. *ASEAN Journal for Science and Engineering in Materials*, *3*(2), 195-216.

Al Husaeni, D. F., and Munir, M. (2023). Literature review and bibliometric mapping analysis: Philosophy of science and technology education. *Indonesian Journal of Multidiciplinary Research*, *3*(2), 219-234.

Ali, M. A., Kamraju, M., and Sonaji, D. B. (2024). Economic policies for sustainable development: Balancing growth, social equity, and environmental protection. *ASEAN Journal of Economic and Economic Education*, *3*(1), 23-28.

Al-Rawahy, K. H. (2013). Engineering education and sustainable development: The missing link. *Procedia-Social and Behavioral Sciences*, *102*, 392-401.

Aquino, P. M. M. (2024). Sustainability of performance of teacher-awardees' instructional competence and teaching effectiveness. *ASEAN Journal of Educational Research and Technology*, *3*(3), 205-214.

Asmara, Y. P., Kurniawan, T., Sutjipto, A. G. E., and Gafar, J. (2018). Application of plants extracts as green corrosion inhibitors for steel in concrete-A review. *Indonesian Journal of Science and Technology*, *3*(2), 158-170.

Aziz, M. (2019). Advanced green technologies toward future sustainable energy systems. *Indonesian Journal of Science and Technology*, *4*(1), 89-96.

Barbosa, F. V., Lobarinhas, P. A., Teixeira, S. F., and Teixeira, J. C. (2022). Project-based learning in a mechanical engineering course: A new proposal based on student's views. *International Journal of Mechanical Engineering Education*, *50*(4), 767-804.

Basnur, J., Putra, M. F. F., Jayusman, S. V. A., and Zulhilmi, Z. (2024). Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs). *ASEAN Journal for Science and Engineering in Materials*, *3*(1), 51-58.

Bello, K. B., and Abubakar, J. (2023). Examining the potential of sustainability marketing adoption on the performance of beverages company. *ASEAN Journal of Economic and Economic Education*, *2*(1), 35-46.

Bernabei, M., Colabianchi, S., Falegnami, A., and Costantino, F. (2023). Students' use of large language models in engineering education: A case study on technology acceptance, perceptions, efficacy, and detection chances. *Computers and Education: Artificial Intelligence*, *5*, 100172.

Blocken, B., and Gualtieri, C. (2012). Ten iterative steps for model development and evaluation applied to Computational Fluid Dynamics for Environmental Fluid Mechanics. *Environmental Modelling and Software*, *33*, 1-22.

Capocelli, M., and De Falco, M. (2022). Generalized penalties and standard efficiencies of carbon capture and storage processes. *International Journal of Energy Research*, *46*(4), 4808-4824.

Chen, S. (2024). Advancing sustainability in mechanical engineering: Integration of green energy and intelligent manufacturing. *Applied and Computational Engineering*, *66*, 150-155.

Cho, H. J., Zhao, K., Lee, C. R., Runshe, D., and Krousgrill, C. (2021). Active learning through flipped classroom in mechanical engineering: Improving students' perception of learning and performance. *International Journal of STEM Education*, *8*, 1-13.

Cunningham, C. M., Lachapelle, C. P., Brennan, R. T., Kelly, G. J., Tunis, C. S. A., and Gentry, C. A. (2020). The impact of engineering curriculum design principles on elementary students' engineering and science learning. *Journal of Research in Science Teaching*, *57*(3), 423-453.

D'Silva, T. C., Verma, S., Magdaline, R. M., Chandra, R., and Khan, A. A. (2022). Environmental resilience and sustainability through green technologies: A case evidence from rural coastal India. *Environmental Engineering Research*, *27*(5), 1-11.

Dhand, A., and Pullen, K. (2013). Review of flywheel based internal combustion engine hybrid vehicles. *International Journal of Automotive Technology*, *14*, 797-804.

Djirong, A., Jayadi, K., Abduh, A., Mutolib, A., Mustofa, R. F., and Rahmat, A. (2024). Assessment of student awareness and application of eco-friendly curriculum and technologies in Indonesian higher education for supporting sustainable development goals (SDGs): A case study on environmental challenges. *Indonesian Journal of Science and Technology*, *9*(3), 657-678.

Ech-Chihbi, E., El Hajjaji, F., Titi, A., Messali, M., Kaya, S., Serdaroğlu, G., andTaleb, M. (2024). Towards understanding the corrosion inhibition mechanism of green imidazolium-based ionic liquids for mild steel protection in acidic environments. *Indonesian Journal of Science and Technology*, *9*(2), 395-420.

Edwards, M. G. (2021). The growth paradox, sustainable development, and business strategy. *Business Strategy and the Environment*, *30*(7), 3079-3094.

Ekamilasari, E., and Pursitasari, I. D. (2021). Students' critical thinking skills and sustainability awareness in science learning for implementation education for sustainable development. *Indonesian Journal of Multidiciplinary Research*, *1*(1), 121-124.

Enelund, M., Knutson Wedel, M., Lundqvist, U., and Malmqvist, J. (2013). Integration of education for sustainable development in the mechanical engineering curriculum. *Australasian Journal of Engineering Education*, *19*(1), 51-62.

Esubalew, A. A., and Adebisi, S. A. Sustainable entrepreneurship as a solution to urbanization and food security challenges: A developing countries perspective. *Indonesian Journal of Multidiciplinary Research*, *4*(2), 363-376.

Fiandini, M., Nandiyanto, A. B. D., and Kurniawan, T. (2023). Bibliometric analysis of research trends in conceptual understanding and sustainability awareness through artificial intelligence (AI) and digital learning media. *Indonesian Journal of Multidiciplinary Research*, *3*(2), 477-486.

Gajo, A. G. E., Gaisen, E. M. P., Franz Von King, R. L., Edaṅo, L. B., and Calixtro Jr, V. L. (2023). Sustaining students' mental health through the use of tiktok application. *Indonesian Journal of Community and Special Needs Education*, *3*(1), 11-20.

Gao, M., Wang, Q., Shan, X., Li, Q., and Zhang, L. (2024). Application of hydraulic energy-saving technology in the teaching, research, and practice of mechanical engineering. *Sustainability*, *16*(3), 1315.

Gao, M., Wang, Q., Wang, N., Ma, Z., and Li, L. (2021). Application of green design and manufacturing in mechanical engineering: Education, scientific research, and practice. *Sustainability*, *14*(1), 237.

Gatto, A., Bassoli, E., Denti, L., Iuliano, L., and Minetola, P. (2015). Multi-disciplinary approach in engineering education: Learning with additive manufacturing and reverse engineering. *Rapid Prototyping Journal*, *21*(5), 598-603.

Gauto, M. A., Carazzolle, M. F., Rodrigues, M. E. P., de Abreu, R. S., Pereira, T. C., and Pereira, G. A. G. (2023). Hybrid vigor: Why hybrids with sustainable biofuels are better than pure electric vehicles. *Energy for Sustainable Development*, *76*, 101261.

Gemil, K. W., Na'ila, D. S., Ardila, N. Z., and Sarahah, Z. U. (2024). The relationship of vocational education skills in agribusiness processing agricultural products in achieving sustainable development goals (SDGs). *ASEAN Journal of Science and Engineering Education*, *4*(2), 181-192.

Glushchenko, V. V. (2023). The mechanism of ensuring the sustainability of the development of the higher education system during the formation of a new technological order. *ASEAN Journal of Educational Research and Technology*, *2*(2), 153-162.

Hadi, A. M., Hasan, K. F., Ahmed, I. M., Meteab, M. A., and Hasan, Q. F. (2023). Green concrete: Ferrock applicability and cost-benefit effective analysis. *ASEAN Journal for Science and Engineering in Materials*, *2*(2), 119-134.

Handayani, M. N., Ali, M., Wahyudin, D., and Mukhidin, M. (2020). Green skills understanding of agricultural vocational school teachers around West Java Indonesia. *Indonesian Journal of Science and Technology*, *5*(1), 20-29.

Hannan, M. A., Azidin, F. A., and Mohamed, A. (2014). Hybrid electric vehicles and their challenges: A review. *Renewable and Sustainable Energy Reviews*, *29*, 135-150.

Haq, M. R. I., Nurhaliza, D. V., Rahmat, L. N., and Ruchiat, R. N. A. (2024). The influence of environmentally friendly packaging on consumer interest in implementing zero waste in the food industry to meet sustainable development goals (SDGs) needs. *ASEAN Journal of Economic and Economic Education*, *3*(2), 111-116.

Harahap, H., Nasution, H., Manurung, R., Yustira, A., and Rashid, A. A. Development of green polybag innovation products from biomass waste as planting media. *Indonesian Journal of Science and Technology*, *10*(1), 145-158.

Irwansyah, F. S., Amal, A. I., Diyanthi, E. W., Hadisantoso, E. P., Noviyanti, A. R., Eddy, D. R., and Risdiana, R. (2024). How to read and determine the specific surface area of inorganic materials using the Brunauer-Emmett-Teller (BET) method. *ASEAN Journal of Science and Engineering*, *4*(1), 61-70.

Jebur, T. K. (2023). Greening the internet of things: A comprehensive review of sustainable iot solutions from an educational perspective. *Indonesian Journal of Educational Research and Technology*, *3*(3), 247-256.

Jiménez, M., Romero, L., Domínguez, I. A., Espinosa, M. D. M., and Domínguez, M. (2019). Additive manufacturing technologies: An overview about 3D printing methods and future prospects. *Complexity*, *2019*(1), 9656938.

Jixiang, W. A. N. G., Yunze, L. I., Xiangdong, L. I. U., Chaoqun, S. H. E. N., Zhang, H., and Xiong, K. (2021). Recent active thermal management technologies for the development of energy-optimized aerospace vehicles in China. *Chinese Journal of Aeronautics*, *34*(2), 1-27.

Kaletnik, G., and Lutkovska, S. (2020). Innovative environmental strategy for sustainable development. *European Journal of Sustainable Development*, *9*(2), 89-89.

Kamanja, R., Wongrerkdee, S., Rungsawang, T., Wongrerkdee, S., Krobthong, S., Pimpang, P., and Manatura, K. Activated carbon films from water hyacinth waste for stable and sustainable counter-electrode application in dye-sensitized solar cells. *Indonesian Journal of Science and Technology*, *10*(1), 133-144.

Keisyafa, A., Sunarya, D. N., Aghniya, S. M., and Maula, S. P. (2024). Analysis of student's awareness of sustainable diet in reducing carbon footprint to support sustainable development goals (SDGs) 2030. *ASEAN Journal of Agriculture and Food Engineering*, *3*(1), 67-74.

Kerans, G., Sanjaya, Y., Liliasari, L., Pamungkas, J., and Ate, G. Y. (2024). Effect of substrate and water on cultivation of sumba seaworm (nyale) and experimental practicum design for improving critical and creative thinking skills of prospective science teacher in biology and supporting sustainable development goals (SDGs). *ASEAN Journal of Science and Engineering*, *4*(3), 383–404.

Kettunen, Petri, Janne Järvinen, Tommi Mikkonen, and Tomi Männistö. (2022). Energizing collaborative industry-academia learning: A present case and future visions. *European Journal of Futures Research*, *10*(1), 8.

Khan, M. A., Hakeem, L., Ali, M. J., and Hussain, M. S. (2025). Uncovering the full potential utilization of petroleum reserves residue for sustainable energy supply. *ASEAN Journal for Science and Engineering in Materials*, *4*(1), 13-22.

Khusaini, M., Finuliyah, F., and Lestari, A. M. (2023). Eco-creative hub model as the key to integrating creativity and sustainability. *Indonesian Journal of Multidiciplinary Research*, *3*(2), 435-444.

Kosova, F., and Unver, H. O. (2023). A digital twin framework for aircraft hydraulic systems failure detection using machine learning techniques. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *237*(7), 1563-1580.

Krishnan, A., Al-Obaidi, A. S. M., and Hao, L. C. (2024). Towards sustainable wind energy: A systematic review of airfoil and blade technologies over the past 25 years for supporting sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *9*(3), 623-656.

Krzywanski, J., Kijo-Kleczkowska, A., Nowak, W., and De Souza-Santos, M. L. (2023). Technological and modelling progress in green engineering and sustainable development: Advancements in energy and materials engineering. *Materials*, *16*(22), 7238.

Kurniawan, T., Satria, D., Saputra, J. B., Bilad, M. R., Nordin, N. A. H. M., and Abdullah, H. (2022). Conversion of green silica from corn leaf into zeolites Na AX. *Indonesian Journal of Science and Technology*, *7*(2), 171-186.

Laita, M., Sabbahi, R., Elbouzidi, A., Hammouti, B., Messaoudi, Z., Benkirane, R., and Aithaddou, H. (2024). Effects of sustained deficit irrigation on vegetative growth and yield of plum trees under the semi-arid conditions: Experiments and review with bibliometric analysis. *ASEAN Journal of Science and Engineering*, *4*(2), 167–190.

Leung, D. Y., Caramanna, G., and Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, *39*, 426-443.

Liang, K., Wang, M., Gao, C., Dong, B., Feng, C., Zhou, X., and Liu, J. (2021). Advances and challenges of integrated thermal management technologies for pure electric vehicles. *Sustainable Energy Technologies and Assessments*, *46*, 101319.

Lozano, F. J., Lozano, R., Freire, P., Jiménez-Gonzalez, C., Sakao, T., Ortiz, M. G., and Viveros, T. (2018). New perspectives for green and sustainable chemistry and engineering: Approaches from sustainable resource and energy use, management, and transformation. *Journal of Cleaner Production*, *172*, 227-232.

Maheshvari, R. (2022). Study on economic, sustainable development, and fuel consumption. *ASEAN Journal of Economic and Economic Education*, *1*(1), 41-46.

Makinde, S. O., Ajani, Y. A., and Abdulrahman, M. R. (2024). Smart learning as transformative impact of technology: A paradigm for accomplishing sustainable development goals (SDGs) in education. *Indonesian Journal of Educational Research and Technology*, *4*(3), 213-224.

Maryanti, R. I. N. A., Rahayu, N. I., Muktiarni, M., Al Husaeni, D. F., Hufad, A., Sunardi, S., and Nandiyanto, A. B. D. (2022). Sustainable development goals (SDGs) in science education: Definition, literature review, and bibliometric analysis. *Journal of Engineering Science and Technology*, *17*, 161-181.

Maulana, I., Asran, M. A., and Ash-Habi, R. M. (2023). Implementation of sustainable development goals (SDGs) no. 12: Responsible production and consumption by optimizing lemon commodities and community empowerment to reduce household waste. *ASEAN Journal of Community Service and Education*, *2*(2), 141-146.

Maulidah, G. S., and Nandiyanto, A. B. D. (2021). A Bibliometric analysis of nanocrystalline cellulose synthesis for packaging application research using VOSviewer. *International Journal of Research and Applied Technology*, *1*(2), 330-334.

Miao, Y., Hynan, P., Von Jouanne, A., and Yokochi, A. (2019). Current Li-ion battery technologies in electric vehicles and opportunities for advancements. *Energies*, *12*(6), 1074.

Nandiyanto, A. B. D., Al Husaeni, D. N., Al Husaeni, D. F., Raghadita, R., and Fiandini, M. (2024a). Trends and developments in research on adsorption in education: Bibliometric analysis. *Indonesian Journal of Educational Research and Technology*, *4*(3), 331-344.

Nandiyanto, A. B. D., and Al Husaeni, D. F. (2022). Bibliometric analysis of engineering research using vosviewer indexed by google scholar. *Journal of Engineering Science and Technology*, *17*(2), 883-894.

Nandiyanto, A. B. D., Biddinika, M. K., and Triawan, F. A. R. I. D. (2020). Evaluation on research effectiveness in a subject area among top class universities: A case of Indonesia's academic publication dataset on chemical and material sciences. *Journal of Engineering Science and Technology*, *15*(3), 1747-1775.

Nandiyanto, A. B. D., Fiandini, M., and Al Husaeni, D. N. (2024b). Research trends from the scopus database using keyword water hyacinth and ecosystem: A bibliometric literature review. *ASEAN Journal of Science and Engineering*, *4*(1), 33-48.

Nandiyanto, A. B. D., Ragadhita, R., Fiandini, M., Al Husaeni, D. N., and Aziz, M. (2023). The role of iron oxide in hydrogen production: Theory and bibliometric analyses. *Moroccan Journal of Chemistry*, *11*(04), 897-1318.

Nandiyanto, A. B. D., Ragadhita, R., Fiandini, M., Al Husaeni, D. F., Al Husaeni, D. N., and Fadhillah, F. (2022). Domestic waste (eggshells and banana peels particles) as sustainable and renewable resources for improving resin-based brakepad performance: Bibliometric literature review, techno-economic analysis, dual-sized reinforcing experiments, to comparison with commercial product. *Communications in Science and Technology*, *7*(1), 50-61.

Noviyanti, A.R., Adzkia, Q.A.A., Novella, I., Kurnia, I., Suryana, S., Ma'Amor, A.B., and Irwansyah, F.S. (2024). Hydroxyapatite as delivery and carrier material: Systematic literature review with bibliometric analysis. *ASEAN Journal of Science and Engineering*, *4*(2), 191-206.

Nugraha, A. S. (2022). Bibliometric analysis of magnetite nanoparticle production research during 2017-2021 using VOSviewer. *Indonesian Journal of Multidiciplinary Research*, *2*(2), 327-332.

Nurnabila, A. T., Basnur, J., Rismayani, R., Ramadhani, S., and Zulhilmi, Z. (2023). Analysis of the application of mediterranean diet patterns on sustainability to support the achievement of sustainable development goals (SDGs): Zero hunger, good health and well beings, responsible consumption, and production. *ASEAN Journal of Agriculture and Food Engineering*, *2*(2), 105-112.

Nurramadhani, A., Riandi, R., Permanasari, A., and Suwarma, I. R. (2024). Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *9*(2), 261-286.

Nursaniah, S. S. J., and Nandiyanto, A. B. D. (2023). Bibliometric analysis for understanding “science education” for “student with special needs” using vosviewer. *ASEAN Journal of Community and Special Needs Education*, *2*(1), 45-54.

Nykvist, B., Sprei, F., and Nilsson, M. (2019). Assessing the progress toward lower priced long range battery electric vehicles. *Energy policy*, *124*, 144-155.

Okokpujie, I. P., Fayomi, O. S. I., and Oyedepo, S. O. (2019). The role of mechanical engineers in achieving sustainable development goals. *Procedia Manufacturing*, *35*, 782-788.

Oró, E., De Gracia, A., Castell, A., Farid, M. M., and Cabeza, L. F. (2012). Review on phase change materials (PCMs) for cold thermal energy storage applications. *Applied Energy*, *99*, 513-533.

Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., and Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: A review. *Environmental Chemistry Letters*, *19*(2), 797-849.

Patil, S. S., Jadhav, V. S., Nalavade, S. S., and Maske, M. M. (2022). Limestone calcined clay cement as a green construction material. *ASEAN Journal of Science and Engineering*, *2*(2), 157-166.

Prakash, R. P. L., Selvam, M., Pandian, A. A. S., Palani, S., and Harish, K. A. (2016). Design and modification of radiator in IC engine cooling system for maximizing efficiency and life. *Indian Journal of Science and Technology*, *9*(2), 1-2.

Pramanik, P. D., and Rahmanita, M. (2023). Strengthening the role of local community in developing countries through community-based tourism from education perspective: Bibliometric analysis. *Indonesian Journal of Multidiciplinary Research*, *3*(2), 331-348.

Prasad, J., Goswami, A., Kumbhani, B., Mishra, C., Tyagi, H., Jun, J. H., and Das, S. K. (2018). Engineering curriculum development based on education theories. *Current Science*, 1829-1834.

Prasojo, L.D., Yuliana, L., and Prihandoko, L.A. (2025). Research performance in higher education: A PLS-SEM analysis of research atmosphere, collaboration, funding, competence, and output, especially for science and engineering facilities in Indonesian universities. *ASEAN Journal of Science and Engineering*, *5*(1), 123-144.

Purwaningsih, W., Arrifa, F. H., and Riandi, R. (2023). Efforts to enhance sustainable consciousness and critical thinking in high school students through learning projects. *Indonesian Journal of Teaching in Science*, *3*(1), 33-44.

Ragadhita, R., and Nandiyanto, A. B. D. (2022). Computational bibliometric analysis on publication of techno-economic education. *Indonesian Journal of Multidiciplinary Research*, *2*(1), 213-222.

Rahim, N. A., Harun, N. Y., Saeed, A. A. H., and Bilad, M. R. (2023). Green route synthesis of amorphous silica from oil palm decanter cake: From literature review to experiments. *Indonesian Journal of Science and Technology*, *8*(2), 141-156.

Rahmah, F. A., Nurlaela, N., Anugrah, R., and Putri, Y. A. R. (2024). Safe food treatment technology: The key to realizing the sustainable development goals (SDGs) zero hunger and optimal health. *ASEAN Journal of Agriculture and Food Engineering*, *3*(1), 57-66.

Ramanujan, D., Zhou, N., and Ramani, K. (2019). Integrating environmental sustainability in undergraduate mechanical engineering courses using guided discovery instruction. *Journal of Cleaner Production*, *207*, 190-203.

Rasuman, M. A., Nandi, N., Astari, A. J., and Ashie, A. B. (2024). Trends and networks in education for sustainable development (ESD): A bibliometric analysis using vosviewer. *Indonesian Journal of Multidiciplinary Research*, *4*(1), 109-126.

Rosengart, A., Granzotto, M., Wierer, R., Pazzaglia, G., Salvi, A., and Dotelli, G. (2023). The green value engineering methodology: A sustainability-driven project management tool for capital projects in process industry. *Sustainability*, *15*(20), 14827.

Saleet, H., Aldamsah, A., Banikhaled, M., Abu-Baker, A., Damseh, R. A., Al-Smadi, M. M., and Hassouneh, K. (2023). Importance and barriers of establishing educational/training programs in electric vehicles/hybrid-electric vehicles in Jordan. *World Electric Vehicle Journal*, *14*(9), 232.

Salmi, M. (2016). Possibilities of preoperative medical models made by 3D printing or additive manufacturing. *Journal of Medical Engineering*, *2016*(1), 6191526.

Sarkar, S., Thummar, K., Shah, N., and Vagrecha, V. (2019). A review paper on aerodynamic drag reduction and CFD analysis of vehicles. *International Research Journal of Engineering and Technology*, *6*(1), *231*-235.

Solihah, P. A., Kaniawati, I., Samsudin, A., and Riandi, R. (2024). Prototype of greenhouse effect for improving problem-solving skills in science, technology, engineering, and mathematics (STEM)-education for sustainable development (ESD): Literature review, bibliometric, and experiment. *Indonesian Journal of Science and Technology*, *9*(1), 163-190.

Sopekan, O. S. (2024). Implementing peace education concepts in early childhood curriculum: A tool for addressing violence and promoting sustainable development. *Indonesian Journal of Multidiciplinary Research*, *4*(2), 259-266.

Sridevi, V., Hamzah, H. T., Jweeg, M. J., Mohammed, M. N., Al-Zahiwat, M. M., Abdullah, T. A., and Abdullah, O. I. (2024). Microwave pyrolysis of agricultural and plastic wastes for production of hybrid biochar: Applications for greener environment. *Indonesian Journal of Science and Technology*, *9*(3), 791-820.

Suryani, L., and Hamdu, G. (2021). Education for sustainable development in science national exam questions of elementary school. *ASEAN Journal of Science and Engineering Education*, *1*(1), 1-6.

Syahputra, M. E., Salam, H., and Sasmita, A. H. (2021). optimization of the oxy-acetyline gas cutting process on Aisi 1045 Steel material to produce minimum width Kerf. *ASEAN Journal of Science and Engineering*, *1*(3), 207-212.

Tangwanichagapong, S., Nitivattananon, V., Mohanty, B., and Visvanathan, C. (2017). Greening of a campus through waste management initiatives: Experience from a higher education institution in Thailand. *International Journal of Sustainability in Higher Education*, *18*(2), 203-217.

Tarraya, H. O., Camposano, C. E., Rojo, S. G., Dolorica, M. C. C., Polon, J. H., and Digo, G. S. (2025). Emerging technologies for sustainable universities and colleges: A meta-synthesis. *ASEAN Journal of Educational Research and Technology*, *4*(1), 11-22.

Telenko, C., Wood, K., Otto, K., Rajesh Elara, M., Foong, S., Leong Pey, K., and Frey, D. (2016). Designettes: An approach to multidisciplinary engineering design education. *Journal of Mechanical Design*, *138*(2), 022001.

Theophilus, A. A. (2023). Literature review for civil engineering practice and technology innovation in civil engineering and educational sustainability. *ASEAN Journal of Science and Engineering Education*, *3*(2), 183-192.

Thongnop, T., Perpaman, T., Kansiri, P., Nuchda, W., and Peungsungwan, S. (2021). Quality sorting of green coffee beans from wet processing by using the principle of machine learning. *ASEAN Journal of Science and Engineering*, *1*(2), 63-66.

Utama, D. M., Santoso, I., Hendrawan, Y., and Dania, W. A. (2023). Sustainable Production-inventory model with multimaterial, quality degradation, and probabilistic demand: From bibliometric analysis to a robust model. *Indonesian Journal of Science and Technology*, *8*(2), 171-196.

Vijayan, D. S., Gopalaswamy, S., Sivasuriyan, A., Koda, E., Sitek, W., Vaverková, M. D., and Podlasek, A. (2024). Advances and applications of carbon capture, utilization, and storage in civil engineering: A comprehensive review. *Energies*, *17*(23), 6046.

Wendi, H. F., Komaro, M., and Widaningsih, L. Research trends on teachers: A bibliometric analysis. *Indonesian Journal of Multidiciplinary Research*, *4*(1), 171-180.

Xu, G., Luxbacher, K. D., Ragab, S., Xu, J., and Ding, X. (2017). Computational fluid dynamics applied to mining engineering: a review. *International Journal of Mining, Reclamation and Environment*, *31*(4), 251-275.

Zhou, Z., Alcalá, J., and Yepes, V. (2021). Optimized application of sustainable development strategy in international engineering project management. *Mathematics*, *9*(14), 1633.