THE ROLE OF INDUSTRIAL ENGINEERING AND ITS IMPACT ON SUSTAINABILITY: A SYSTEMATIC REVIEW APPROACH

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ABSTRACT

Increasing global awareness of environmental problems has propelled sustainable engineering into a pivotal discipline that is crucial for harmonising technological advancements with ecological responsibility. The purpose of industrial engineering (IE) is to improve processes, systems, and designs, placing an increased responsibility on industrial engineers to drive sustainable solutions. The *International Journal for Sustainable Engineering* (IJSE) provides cross-disciplinary information to promote sustainable practices in engineering. Drawing from the IJSE corpus, this paper analyses the alignment of sustainable development goals (SDGs) with IE topics. A framework is presented to map IE-related topics, derived from the Handbook of IE and IE undergraduate curricula in South Africa. A literature review was conducted on the relationship of each IE topic to sustainable engineering. The resulting analysis emphasised the current and potential incorporation of the SDGs into each IE topic, thus mapping out the present and potential roles of industrial engineers in achieving the SDGs.

OPSOMMING

Toenemende wêreldwye bewustheid van omgewingsprobleme het volhoubare ingenieurswese tot 'n deurslaggewende dissipline gedryf wat deurslaggewend is vir die harmonisering van tegnologiese vooruitgang met ekologiese verantwoordelikheid. Die doel van bedryfsingenieurswese (IE) is om prosesse, stelsels en ontwerpe te verbeter, en plaas 'n groter verantwoordelikheid op bedryfsingenieurs om volhoubare oplossings te dryf. Die International Journal for Sustainable Engineering (IJSE) verskaf kruisdissiplinêre inligting om volhoubare praktyke in ingenieurswese te bevorder. Met behulp van die IJSE-korpus ontleed hierdie artikel die belyning van volhoubare ontwikkelingsdoelwitte (SDG's) met IE-onderwerpe. 'n Raamwerk word aangebied om IE-verwante onderwerpe te karteer, afgelei van die handboeke van IE en IE voorgraadse kurrikulums in Suid-Afrika. 'n Literatuuroorsig is gedoen oor die verhouding van elke IE-onderwerp tot volhoubare ingenieurswese. Die gevolglike analise het die huidige en potensiële inkorporering van die SDG's in elke IE-onderwerp beklemtoon, en sodoende die huidige en potensiële rolle van bedryfsingenieurs in die bereiking van die SDG's uitgestippel.

1. INTRODUCTION

With today's rapidly evolving technological advancements, the intersection of industry and sustainability, combined with escalating economic, environmental, and social challenges, has become a focal point for progress, innovation, business viability, and societal impact [1]. As industries strive to meet the demands of a growing population while minimising their environmental footprint, the green transformation of industries is paramount. In this context, industrial engineering is crucial in driving sustainable development, aligning with global goals, and fostering economic growth [2]. This article explores the intricate relationship between industrial engineering curricular topics and the sustainable development goals (SDGs), and highlights how the principles and practices of industrial engineering could significantly enhance sustainability in various sectors.

The capabilities of the industrial engineering profession are significantly linked to technological and managerial methodologies that drive sustainable manufacturing [3]. Sustainable value creation is a core component of industrial engineering. In developing a framework for achieving sustainable value creation through transformed industrial engineering principles, Bilge *et al.* [3] argue that industrial engineers are instrumental in driving innovative technological and managerial methodologies that promote economic, environmental, and social sustainability. The industrial engineering profession is interwoven with the progression of industrial revolutions [4], including the Fourth Industrial Revolution, which is associated with advancing the SDGs. In addition, the profession is dedicated to the integration and optimization of processes, systems, and resources into cohesive strategies and structures to enhance efficiency and effectiveness in the production of quality goods and services [5].

The SDGs are 17 interconnected goals that have been adopted by the United Nations to guide global efforts towards sustainable development by 2030 [6]. These goals are an urgent call for global action, as they encompass a wide range of social, economic, and environmental objectives, including poverty eradication, climate action, responsible consumption, and sustainable production [6]. Achieving the SDGs requires concerted efforts from various stakeholders, including governments, businesses, academia, and civil society, to address systemic problems and to create inclusive and sustainable pathways for development. Industrial engineering professional principles and methodologies potentially drive the achievement of the SDGs in various aspects. From supply chain management to production optimisation, industrial engineers play a pivotal role in streamlining operations while reducing waste and environmental impact. This aligns seamlessly with SDG 9 (industry, innovation, and infrastructure), which emphasises the importance of sustainable industrialisation and fostering innovation for sustainable development.

The ECSA criteria and graduate attributes (GAs) for BEng/BSc(Eng) programmes [7] now place a stronger focus on sustainability. Graduates are required to solve complex engineering problems with sustainability and environmental impacts in mind (GA 1); design solutions must be environmentally responsible and resource-efficient (GA 3); and effective communication of the sustainability aspects of engineering activities is also essential (GA 6). Engineering managers must integrate sustainability and environmental considerations into their work, along with understanding the ethical implications, particularly concerning sustainability (GA 11 and GA 7).

Furthermore, industrial engineering encompasses a range of topics that contribute directly to achieving other SDGs. For instance, topics such as energy management and renewable resources align with SDG 7 (affordable and clean energy), while waste reduction strategies and circular economy principles resonate with SDG 12 (responsible consumption and production). By integrating these curricular topics into education and practice, industrial engineering professionals would be empowered to drive meaningful change and to contribute to a more sustainable future.

Throughout this article we examine specific industrial engineering topics and how they intersect with key sustainability issues as outlined in the SDGs through the use of the *International Journal for Sustainable Engineering*. By understanding and leveraging the synergies between industrial engineering and sustainability, we could unlock innovative solutions and pave the way to a more resilient and environmentally conscious society.

2. SUSTAINABLE ENGINEERING AND INDUSTRIAL ENGINEERING DISCIPLINES

Galvic [8] defined sustainable engineering as "the integration of social, environmental, and economic considerations into product, process, and energy system design methods". Product and process lifecycle is emphasised from the design phase to minimise adverse environmental effects while enhancing social benefit and economic prosperity. The NAL Thesaurus's [9] definition of sustainable engineering underscored that the design of processes and products must be economically feasible and must minimise the risk to human health and pollution control from the source. Sustainable engineering principles rest on the three pillars of sustainability: economic, environmental, and social sustainability [8, 10]. From the work of Gagnon *et al*. [10] and Galvic [8], Table 1 highlights the sustainable engineering principles and what they rest on.

Table 1: Sustainable engineering principles [8, 10]

	Focus	**Sustainable engineering principles**
Environment	Engineers' processes use systems analysis holistically and integrate environmental impact assessment tools.	Preserve biodiversity and respect all life forms, regardless of how useful they are to humankind. Stay within the ecosystem's carrying capacity in respect of resource development and waste elimination.
Social	Engineers seek stakeholder involvement while respecting local subsidiarity and cultures.	Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible. Offer individuals and communities the opportunity to increase their capabilities. Put the primary focus on achieving the needs of a larger number of individuals.
Economic	Engineers incorporate all costs in the value of goods and services.	Stimulate innovation to facilitate the adoption of more efficient and greener technologies. Maintain a positive and genuine long-term investment that considers all types of capital. Allocate fairly the benefits and costs related to economic activity and public policies.

Additional sustainable engineering principles that are not listed in Table 1 include looking "beyond your locality and the immediate future" and "preserv[ing] access to ecosystem services essential to health and well-being", both of which are at the intersection of environmental and social sustainability [8, 10]. Principles that are at that intersection include "offset[ting] the use of non-renewable resources by investments in renewable substitutes" and "developing closed cycles of operation and consumption to minimize waste" [8, 10].

As described above, sustainable engineering aims to balance economic, environmental, and social needs, and to create solutions that are viable in the long term and that promote the health and well-being of both current and future generations. This defines the work associated with industrial engineers and achieving the SDGs. Industrial engineers are uniquely trained and equipped to incorporate sustainability concepts into their line of work, owing to their focus on systems and observing these systems at an elevated level [2]. Industrial engineering as a framework may be grouped into the following topics [4]:

- Operations management,
- Engineering management,
- Design and manufacturing engineering,
- Facility engineering,
- Supply chain management,
- Operations research,
- Project design and development,

- Systems design and engineering,
- Information engineering,
- Work design and measurement,
- Quality and reliability engineering,
- Engineering economics analysis, and
- Ergonomics and human factors

Looking closely at these topics and at their focus and the content they cover, they contribute holistically to the three pillars of sustainability: environmental, social, and economic. The literature [11] points to a growing interest in mapping industrial engineering to contribute to achieving the SDGs.

3. SUSTAINABLE ENGINEERING AND THE SUSTAINABLE DEVELOPMENT GOALS

The SDGs correspond to goals in a universal agreement, formed by the United Nations, that seeks to address the empirical and scientific evidence that the world needs a more sustainable approach to its development actions [6]. The importance of innovation is in turn emphasised in successfully responding to the professional challenges of Industry 4.0, in line with the commitments of the SDGs. These innovation characteristics that are incorporated into the context of Industry 4.0 and SDGs are to consider soft skills and technological competencies from the perspective of the management and integration of people on the one hand to the actual knowledge and mastery of digital tools on the other [12]. The global engineering industry has established distinctive characteristics for the innovative engineer: adaptable, constantly searching for solutions, able to experiment and integrate, possessing extensive knowledge and leadership qualities, curious and communicative, responsible, persistent, enthusiastic, collaborative, creative, visionary, challenging, and with strong business intelligence and a user focus [13, 14]. Although there is evidence of the industry's demands on its professional engineers in the face of these new challenges (digital competencies, sustainability education, skills for Industry 4.0) [15], the vision of the training environments for the formation of these competencies in university engineering students has not been widely studied. In particular, no mechanisms have been established to define the competencies in which to train future engineers to respond to the SDGs and to Industry 4.0 [16]. Galvic [8] performed a comprehensive study in which the relationship between sustainable engineering and the SDGs was delineated. In this study, the relationship between the three pillars of sustainability was mapped to the 17 SDGs. In some instances, some engineering principles overlapped to cover the three aspects of sustainable development. Table 2 summarises the work of Galvic [8].

Table 2: Sustainable engineering principles mapped to SDGs [8]

Sustainability dimension	Sustainable engineering principles	Related SDGs
Triple dimensional	Holistic approach, systems thinking, and management	16
	Precautionary and preventive approaches	13
	Annual sustainability reporting using GRI	4
Environmental	Circular economy, waste minimisation, sustainability hierarchies	13
	Efficient use of resources, and increased share of renewables	6, 7
	Sustainable consumption and production	12
Social	Equalities within and between generations	5, 10
	Engagement of communities and all stakeholders	11
	Corporate social responsibility and decent work	1 -3, 8
Economic	Human capital, innovations, and creativity	4, 9
	Cost–benefit analysis using life cycle assessment	3, 13
	Internalising externalities – polluters must pay	13, 9

The sustainable engineering principles mapped to the 17 SDGs are common principles that support the industrial engineering profession. Table 3 presents the key industrial engineering principles derived from the *Handbook of industrial engineering* [17]. Although not exhaustive, the principles give an overview of what drives industrial engineering. Comparing Table 2 and Table 3, sustainable engineering and industrial engineering intersect significantly, showing the important role played by industrial engineers in driving the SDGs.

Table 3: Industrial engineering principles mapped to SDGs

Industrial engineering principles	**Description**	**Related SDGs**
Systems thinking and integration [17]	Integration of people, processes, and technology to build sustainable and resilient production and service systems. Using systems thinking in various applications such as business process reengineering	7, 9
Process improvement and optimisation [18, 19]	Apply various tools and principles such as lean thinking to eliminate waste and ensure efficient resource use.	8, 12, 13
Productivity improvement [18, 20]	Use various techniques and tools such as Six Sigma, Toyota Production Systems, and continuous improvement tools to reduce variability, increase efficiency, and improve processes.	8, 12, 13
Human-centred design [17]	Focus on holistic interaction of people, processes, and technology in designing systems and products that improve quality of work and life and improve safety and performance.	3, 8
Data and statistical thinking-oriented [17]	Make decisions informed and supported by data. Use mathematical models, statistics, and algorithms in designing and optimisation, resulting in resilient and sustainable industrial processes and energy systems.	7,8, 9, 12, 13
Quality-driven [17]	Use various tools and methods such as statistical process control, total quality management, and various international standards to enhance quality and promote zero defects in various processes.	6, 9, 12, 13
Holistic supply chain and logistics [17]	Use various tools to analyse and improve supply chain processes to ensure efficient flow of materials, information, and finance, focusing on customer satisfaction. Promote green and sustainable supply chain operations.	2, 3, 6, 7, 11, 12, 13
Integration of management principles [17]	Integrate management principles with technical skills to optimise productivity and profitability. Make economically sound decisions based on cost financial analysis.	2, 3,8, 12, 13

The link between sustainable engineering and the SDGs is inherently strong, as the sustainable engineering principles align directly with the objectives outlined in the SDGs. Sustainable engineering focuses on designing, developing, and implementing solutions that minimise negative environmental impacts, promote social equity, and ensure economic viability [8, 10]. Similarly, the SDGs provide a framework for addressing global problems, including poverty, inequality, climate change, and environmental degradation. Industrial engineering topics, such as process optimisation, resource efficiency, and supply chain management, are integral to achieving many of the SDGs. This intricate interplay underscores the intrinsic connection between sustainable engineering and industrial engineering topics, illustrating how advancements in industrial engineering could support progress towards the SDGs and foster a more sustainable global landscape.

4. METHODOLOGY

Drawing from the *International Journal for Sustainable Engineering*'s (IJSE) corpus, this paper has analysed the alignment of the SDGs with the typical IE disciplines. A framework is presented to map IE-related topics, derived from the *Handbook of industrial engineering* [17], the paper on the development of an Industry 4.0 competency maturity model in the *SAIEE Africa Research Journal* [4], and a comparison of IE curricula from South African universities with the SDGs. The development has two dimensions: the SDGs, and industrial engineering topics. The study adopted a qualitative research design by conducting a comprehensive literature review [21] of articles published in the *International Journal for Sustainable Engineering* (IJSE) between 2021 and 2023. The journal was selected because it publishes engineering cross-disciplinary information for promoting sustainable practices in engineering; thus, its content could be mapped to the SDGs. A total of 217 articles were initially identified for potential inclusion in the study. The selection process for these articles was guided by specific criteria to ensure relevance and quality:

- **Keyword selection:** The articles were filtered based on the presence of the following keywords: "sustainable engineering", "sustainable development", "sustainable development goals", "industrial engineering", and "sustainability". This ensured that the focus remained on the intersection of industrial engineering and sustainable practices.
- **Inclusion and exclusion criteria:**
  Inclusion: The articles that directly addressed the SDGs (SDGs) and their integration with industrial engineering were prioritised.
  Exclusion: The articles that did not explicitly discuss the SDGs were excluded from the analysis. This step was crucial to maintain the relevance of the data to the research objectives.
- **Selection process:** Of the initial 217 articles, 133 met the inclusion criteria and were used to formulate the results section. These articles were carefully reviewed and analysed to extract pertinent information related to the alignment of the SDGs with industrial engineering topics.
- **Framework development:** To analyse the data systematically, a framework was developed that mapped the industrial engineering (IE) topics derived from the *Handbook of IE* and from South African IE undergraduate curricula to sustainable engineering principles.
- **Data analysis:** Each IE topic was examined for its relationship to sustainable engineering through a detailed literature review. The analysis highlighted the current and potential incorporation of the SDGs into each IE topic, providing insights into the role of industrial engineers in achieving these global goals.

This rigorous methodology ensured that the findings presented in the article are based on a robust and focused review of the relevant literature, providing a clear understanding of how industrial engineering practices could contribute to sustainable development. Deductive thematic analysis [22] was used in the data analysis, allowing the mapping of identified industrial engineering themes to industrial engineering topics and the SDGs. This design was appropriate for exploring the extent to which current IE disciplines incorporate sustainability principles that are aligned with the SDGs. Using a two-dimensional framework – the industrial engineering topics and the SDGs – the identified themes were first systematically mapped against each IE curriculum topic, followed by the relevant SDGs.

To ensure rigour and credibility, we ensured researcher triangulation in the coding and analysis process to reduce bias. All the data sources were publicly available documents, ensuring that there were no ethical concerns about confidentiality or consent.

5. STUDY'S FINDINGS

Table 4 shows the relationship between the various SDGs and the industrial engineering topics. The columns in Table 4 represent the different SDGs, from SDG1 to SDG17, while the rows represent the different industrial engineering topics. The numbers in each cell represent the frequency of a specific theme under an industrial engineering topic mapped to a particular SDG. The table provides a clear overview of how the industrial engineering topics aligned with and contributed to various SDGs, highlighting areas of strength and potential growth.

Table 4: Industrial engineering topics mapped to SDGs

	SDG1	SDG2	SDG3	SDG4	SDG6	SDG7	SDG8	SDG11	SDG12	SDG13	SDG14	SDG15	SDG17
	0	0	0	0	0	0	0	0	0	0	0	0	0
Design and manufacturing engineering	0	0	0	1	0	6	0	3	23	4	0	5	0
Engineering economics analysis	0	0	0	0	0	1	6	1	0	1	0	0	0
Engineering management	0	0	0	0	2	1	0	0	1	0	0	0	0
Ergonomics and human factors	0	0	0	0	0	1	0	2	1	0	0	0	0
Facility engineering	0	0	0	0	1	0	0	0	0	0	0	0	0
Information engineering	0	1	0	1	0	1	0	0	1	0	0	0	0
Operations management	0	0	0	0	1	5	1	9	9	0	2	1	0
Operations research	0	1	0	1	0	3	1	3	5	1	0	2	0
Project design and development	0	0	0	0	0	2	0	7	1	1	0	1	0
Quality and reliability engineering	0	0	0	0	0	2	0	2	6	3	1	3	0
Supply chain management	0	1	0	1	0	7	1	5	16	1	1	1	1
Systems design and engineering	0	0	0	0	3	7	1	1	3	0	1	0	0
Work design and measurement	0	0	1	0	0	0	2	0	1	0	0	0	0
Grand total	0	3	1	4	7	36	12	33	67	11	5	13	1

Figure 1 provides insights into the frequency of the references to each SDG in the context of the industrial engineering topics. The information gathered from this graph could help to guide educational institutions and industry practitioners to enhance the relevance of industrial engineering for the global sustainability goals, and its impact on them.

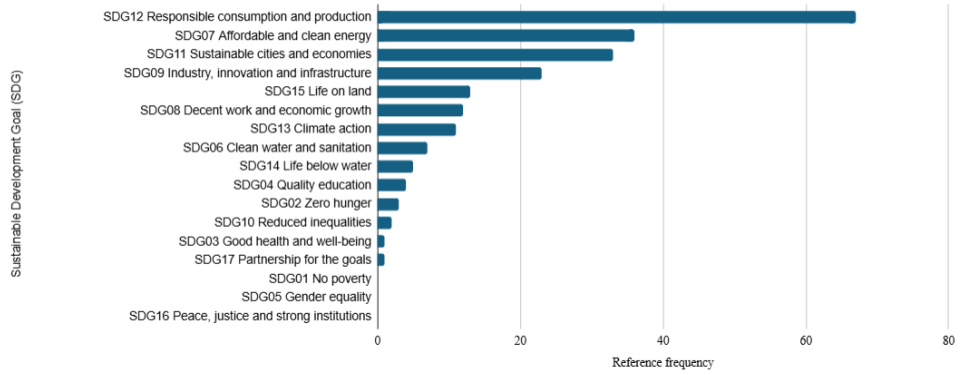


Figure 1: Reference frequency of SDGs

Figure 2 shows the reference frequency of the various industrial engineering topics, indicating how often each topic was referenced or discussed.

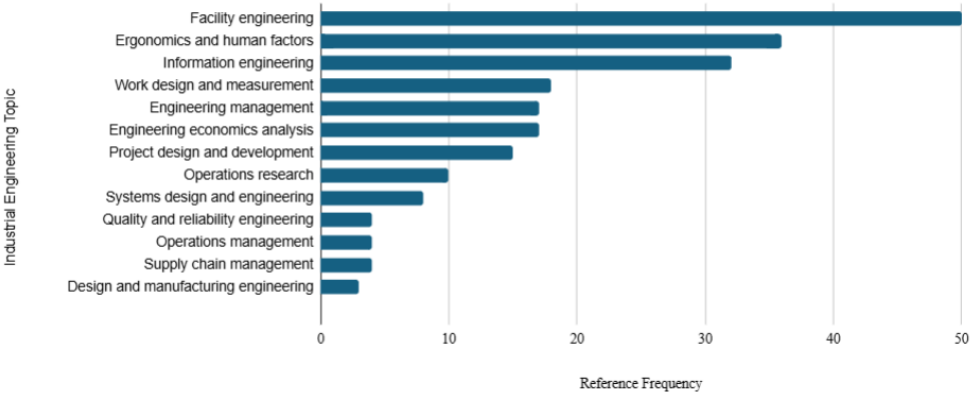


Figure 2: Frequency of various industrial engineering topics

In addition to the industrial engineering concepts, more detailed concepts were also extracted from the *Journal for Sustainable Engineering*, from which the word clouds in Figure 3 were created. Using the Pareto principle, the three SDGs with the most frequent industrial engineering references were selected for these word clouds.

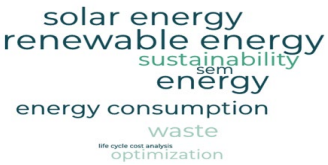
SDG12: Responsible consumption and production	SDG7: Affordable and clean energy	SDG11: Sustainable cities and economies
		

Figure 3: Word clouds of sustainable engineering concepts linked to the most frequently referenced SDGs

6. DISCUSSION

6.1. Industrial engineering topics mapped to SDGs

The key topics with a high relevance included project design and development, which linked strongly to SDG12 with 23 instances, emphasising sustainable consumption and production. Supply chain management was notable for its relevance to SDG12 (16 instances) and SDG8 (seven instances), highlighting sustainable practices and economic growth. Operations management showed equal relevance to SDG8 and SDG12 (nine instances each), indicating its importance in economic and sustainable operations. Systems design and engineering also connected significantly to SDG12 with seven instances, underscoring its role in sustainable systems.

Moderate relevance was found in design and manufacturing engineering (linked to SDG9 and SDG12), engineering management (SDG9), and quality and reliability engineering (SDG8 and SDG12). Topics with low relevance included engineering economics analysis, facility engineering, information engineering, ergonomics, human factors, and work design and measurement. Focusing on the SDGs, SDG12 (67 instances) was most frequently addressed, reflecting a primary focus on sustainability. SDG8 (36 instances) emphasises economic growth and employment, while SDG9 (33 instances) is critical for innovation and infrastructure. Other SDGs, such as 1, 2, 5, 14, 15, and 17, were less frequently addressed, suggesting areas for potential increased focus.

6.2. Reference frequency of SDGs

The graphs highlighted a strong focus on specific SDGs in industrial engineering. SDG 12 (responsible consumption and production) was the most emphasised, reflecting a priority focus on sustainable and efficient production processes. SDG 7 (affordable and clean energy) and SDG 11 (sustainable cities and communities) were also significant, indicating attention to energy efficiency and urban sustainability. SDG 9 (industry, innovation, and infrastructure) underscored the role of innovation.

Moderately emphasised were SDG 15 (life on land) and SDG 8 (decent work and economic growth), showing a concern for terrestrial ecosystems and sustainable economic practices. SDG 13 (climate action) and SDG 6 (clean water and sanitation) were noted for climate and water management. Less emphasis was placed on SDGs 14, 4, 2, 10, and 3, suggesting that these areas were less integrated into the curriculum. SDGs 17, 1, 5, and 16 were the least referenced, indicating they might not have been primary focuses in current industrial engineering topics. Overall, the emphasis on SDGs 12, 7, and 11 showed an alignment with sustainability objectives, while the lesser focus on some SDGs suggested potential areas for future curriculum enhancement to achieve a more comprehensive approach to sustainability.

7. CONCLUSION

Industrial engineering is central to sustainable engineering, offering solutions to complex problems through optimisation, innovation, and collaboration, and aligning with ECSA's graduate attributes that emphasise sustainability. It also plays a crucial role in fostering sustainability in various sectors by reducing waste and enhancing efficiency. Through the implementation of innovative technologies, the adoption of sustainable practices, and interdisciplinary collaborations, industrial engineers contribute significantly to mitigating the impact on the environment while fostering economic growth. However, the integration of the SDGs into industrial engineering practices would be paramount to achieving global sustainability targets; and, in conjunction, true sustainability would require continuous efforts, including further research, education, policy support, global cooperation, and advocacy in order to integrate sustainability principles into the core of industrial processes, supply chains, and decision-making frameworks.

To advance the integration of sustainability into industrial engineering, future work could include, first, expanding research on innovative technologies that enhance sustainable production and reduce environmental impacts – for example, developing renewable energy systems and advanced materials that are both efficient and eco-friendly. In addition, revising engineering curricula to incorporate a stronger emphasis on the SDGs would prepare graduates better to tackle sustainability challenges. Finally, continuous professional development for engineers, including training in the latest sustainable technologies and practices, would ensure that the workforce remained capable of driving progress towards a more sustainable future.

Achieving global sustainability would require integrating the SDGs into engineering practices, ongoing research, education, policy support, and collaboration. By embracing a holistic and interdisciplinary approach, industrial engineering could lead the way to a sustainable and equitable future.

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