Green Production and Sustainable Manufacturing: A Comprehensive Review

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ABSTRACT

This paper provides a comprehensive foundation for green production and sustainable manufacturing topics. It starts with exploring the historical motives behind the emergence of this field, then traces its evolution through literature and defines key terms that are most associated with it. This is followed by the most significant assessment tools of sustainable manufacturing, its challenges and barriers, and finally the gaps and the suggested solutions based on the latest research trends. The article also highlights the most significant concepts related to sustainable manufacturing and goes through their definitions, history, and tools. This paper does not only present a historical background about the field but is also supported with statistics and numbers of the most recent advancements in the areas of the evolution of sustainable manufacturing, its drivers, assessment tools, challenges, gaps, and future recommendations. It aims to provide a clear foundation for scholars and to serve as a starting point that is built on the latest literature to save time and effort.

Keywords: Sustainability, Green manufacturing, Sustainable production, Triple bottom line, TBL, Recycling, Lean manufacturing, Green supply chain management, Environment, Life cycle analysis, Industry 4.0, I4.0

Introduction

Manufacturing is the backbone of modern society and the driving motive of growth for other economic sectors. It is responsible for producing around 21% of all goods around the globe and provides jobs for a wide variety of blue- and white-collar sectors in addition to enhancing the living standards of many in society.[1] Based on the data shown in Figure 1 collected from the World Bank Group,[2] although there is a general decline in the value-added percentage GDP of manufacturing, it still contributes with a high percentage to the countries' economies.

"Manufacturing" and "production" have been assumed to give the same meaning and have been used interchangeably in the literature; however, they have different meanings with different key concepts.[3,4] In the large supply chain between suppliers and customers, while "production" involves only the value-adding processes (fabrication and assembly), "manufacturing" involves both the value-adding processes in addition to the organizational processes (planning, control, etc.).[4]

Although manufacturing is vital for providing basic human needs (food industry, clothes, water delivery systems, etc.) and is responsible for human development, unsustainable manufacturing is also accountable for most of the environmental problems such as resource depletion, marine life toxication, the rise of greenhouse gas (GHG) emissions, waste accumulation, and many more. These ecological problems not only affect the quality of living of individuals but are also responsible for the rising temperature on Earth that causes heat waves and rising sea levels, which may eventually lead to the extinction of human life on Earth.

To name a few, the increasing depletion rate of natural resources is one of the major global problems.[1] For instance, there are an estimated 2 trillion barrels of oil reserves in the world. With the current approximate daily consumption of 75 million barrels worldwide, the oil supply is estimated to last for another 40 years. This applies to all the natural resources available on planet Earth.

Another problem is the increasing rate of solid waste with no effective solution for complete recycling yet, and the remaining wastes end up eventually in landfills. In 1997, Basaly et al.[5] reported that the average daily waste amount per person in the United States is around 2 kg (4.5 pounds), which equals 180 million tons of waste that are sent to landfills each year. The manufacturing sector alone is responsible for 60% of these annual non-hazardous wastes.[1] With the increase in population rate, Basaly predicted that this number may reach 400 billion tons of waste by 2030, which is "enough to bury Los Angeles 100 meters deep".

On the environmental side, Ahmad et al.[6] mentioned that the industrial sector was responsible for 36% of the CO2 emissions in the USA in 2012 and was the largest contributor of particulate matter pollution in Malaysia in 2015 and the second largest source of water pollution in 2010 in the same country. In China, the wastewater resulting from manufacturing reached 16.67 billion tons. On the social side, around 150 million children in 2016 were used as labor worldwide which negatively impacted their health.

Realizing the seriousness of the problem, 196 parties in 2015 signed a legally binding international treaty at the United Nations Climate Change Conference (COP 21) in France, Paris. The treaty demanded to keep "the increase in the global average temperature to well below 2 °C above pre-industrial levels" while pursuing efforts to "limit the temperature increase to 1.5 °C above pre-industrial levels."[7] However, recently, the UN's Intergovernmental Panel on Climate Change realized that going beyond the 1.5 °C threshold will cause way more severe impacts than anticipated, and to limit the effect of global warming, the intensity of the GHG emissions should be declining starting in 2025 and should be reduced by 43% by 2030.[7] Despite that, the global mean temperature rise has already been reported to reach 1.1 °C in 2023 and is expected to rise to 1.5 °C by 2035 according to the UN's report.[8]

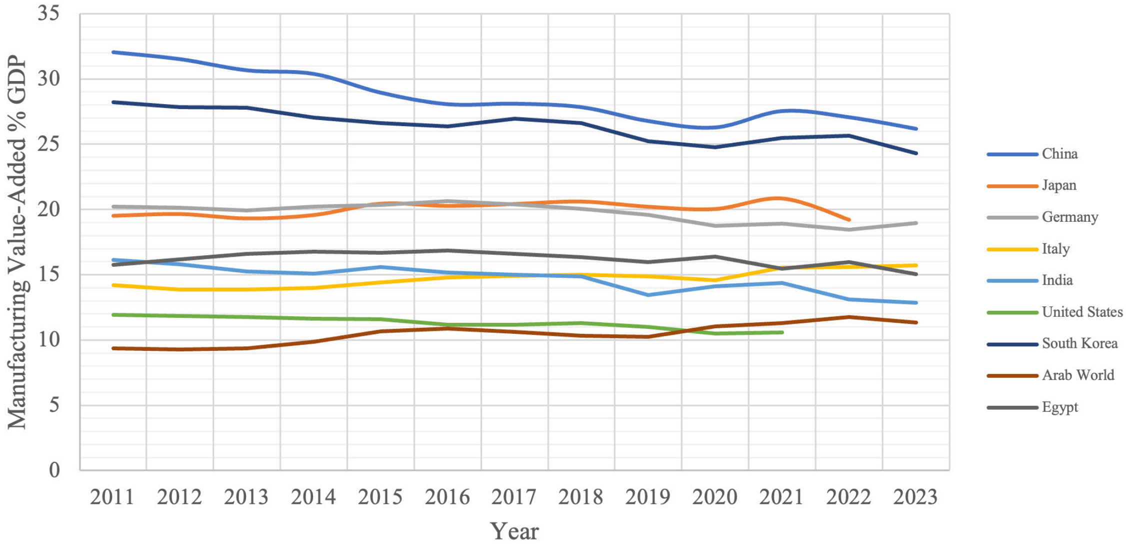

Fig 1 | Manufacturing value-added % GDP for sample countries

Catastrophise all around the globe have already started spreading including intensive heat waves, rising sea levels, floods, droughts, and species extinction, and 17 million metric tons of plastic pollutants are already in the oceans. To mitigate the crisis and limit the global warming effect to 1.5 °C by 2030, regulations on the national level have been created around the globe to support sustainable developments and urge all parties including the industrial sector to make sustainability their top priority.[8,9]

To sum up, on one side, manufacturing is vital for the economic growth and social development of the current generation, and on the other side, unsustainable manufacturing negatively and significantly affects the environmental, societal, and economic aspects and the ability of future generations to fulfill their needs due to natural resource depletion, pollution, climate change, social injustice, unstable economic status, etc.[10]

Definitions and Scope

Green Manufacturing (GM) term was founded in 1977, and it incorporates approaches in manufacturing specifically that are environmentally friendly throughout the stages of the product's lifecycle, starting with raw material extraction to production, use, and end of life and including middle processes such as distribution, etc. GM is also concerned with waste minimization, pollution control, and the conservation of energy and natural resources.[11]

The term "sustainability," on the other hand, emerged between the 70s and 80s of the last century and was motivated further by the rising environmental issues.[10] Sustainable development is a broad term that covers the ability to achieve today's demands without compromising those of future generations as explained in the Brundtland report in The World Commission on Environment and Development.[12] Meanwhile, the term "sustainable manufacturing" is defined by the U.S. Environmental Protection Agency and Lowell Centre for Sustainable Production as the process of creating goods and/or providing services by implementing processes and systems that involve minimal negative effects, are energy efficient, conserve natural resources, are safe for employees, communities, and consumers, and are economically rewarding. They also defined three pillars of sustainable manufacturing, namely: environmental, social, and economic.[13–15]

Pursuing the three sustainability pillars is known as the Three Bottom Line (TBL) approach. It was first introduced by John Elkington in the late 1990s and aimed for equal and simultaneous consideration of these three dimensions.[9,16] The development of this term _as stated by its author_ was a way of achieving the 1987s Brundtland Report[12] and to develop a term that goes with business brains to explain that sustainability does not conflict with business.

The sustainability environmental side focuses on maintaining a clean environment (air, water, and soil), eco-balance, wise and efficient consumption of natural resources, regulation implementation, and environmentally conscious manufacturing processes in general. On the social side, it focuses on improving health, safety, quality of life, and ethics, especially for those directly engaged in these systems. On the economic side, sustainability is mainly focused on the appropriate balance between cost and profit to guarantee business stability and continuity. This includes processes related to product and process development and business opportunities.[3,17]

As a general rule, a system is considered unsustainable when resource consumption and waste production are higher than nature's ability to recover and provide new nutrients and resources as explained by Paul et al.[10]

United Nations (UN), in a recent report released in 2023,[18] has set 17 goals to urge all responsible parties to contribute to achieving sustainability by 2030. Many of them are related to manufacturing in one way or another, such as clean water and sanitation, affordable

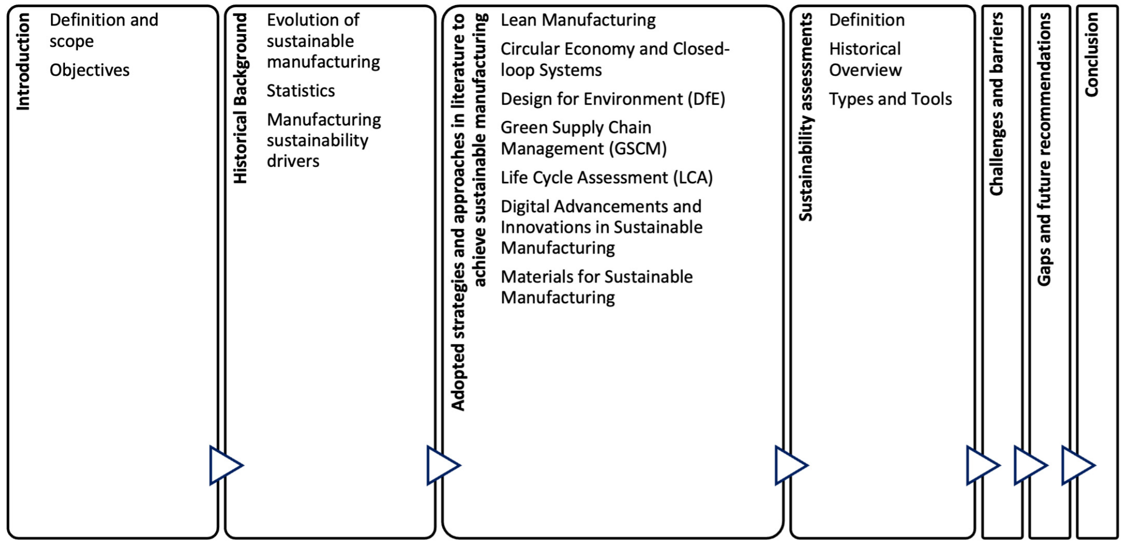

Fig 2 | Flow of the research review

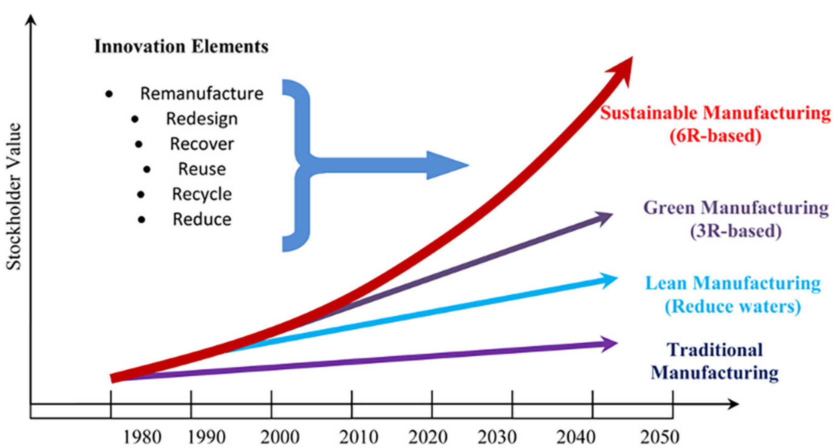

Fig 3 | Evolution of sustainable manufacturing[1]

and clean energy, decent work and economic growth, industry innovation and infrastructure, sustainable cities and communities, responsible consumption and production, climate action, etc. These goals cover all three main sustainability dimensions: economical, environmental, and social.

To sum up, the goal of green production focuses only on minimizing the environmental footprint of manufacturing processes such as waste reduction, energy efficiency, pollution control, eco-friendly materials, and performing lifecycle assessment (mostly cradle-to-grave type). On the other hand, sustainable manufacturing is a broader expression that seeks achieving a balance between economy, environment, and social well-being on the full lifecycle (cradle-to-cradle type).

Objectives

After introducing the current global problem related to sustainability and manufacturing followed by the main terms' definitions in Section 1, this article aims to study different aspects of sustainable manufacturing distributed in the sections as follows: In Section 2, a historical background is provided including information regarding the stages the manufacturing went through before sustainability, enhanced with some statistics, in addition to the most significant factors and elements of sustainable manufacturing, then followed by the motives for sustainability. Section 3 then talks about some of the most significant approaches adopted to achieve sustainability, their definitions, significance, recent trends from literature, and real-life applications. Section 4 talks about the sustainability assessment, its definition, significance, history, and its most common types and tools. Section 5 is focused on the challenges and barriers facing the full implementation of sustainable solutions in the manufacturing sector and covered their history, types, causes, and examples of real-life challenges. Research gaps are then included in Section 6 in addition to the future directions and recommendations inspired by literature. A summary of the research review is illustrated in Figure 2.

Historical Background

Evolution of Sustainable Manufacturing

From the sustainability point of view, the evolution of sustainable manufacturing has gone through four main phases, namely, traditional manufacturing, lean manufacturing that targeted only waste reduction, GM which implemented the 3R strategy (reduce, reuse, and recycle), and finally sustainable manufacturing implementing the 6R strategy (reduce, reuse, recycle, recover, redesign, and remanufacture).[1,19] Jaafar et al.[20] and Jayal et al.[21] explained each of the 6R terms as follows: The term "Reduce" is associated with the first stages of the product's life cycle and is concerned with the activities related to simplifying the product's design and reducing the materials and resources used to facilitate post-use utilization. This may include the reduced use of resources, energy, materials, waste, etc. "Reuse" refers to the reuse of the same product or its components for a new lifecycle after the end-of-life of the first one. This minimizes the

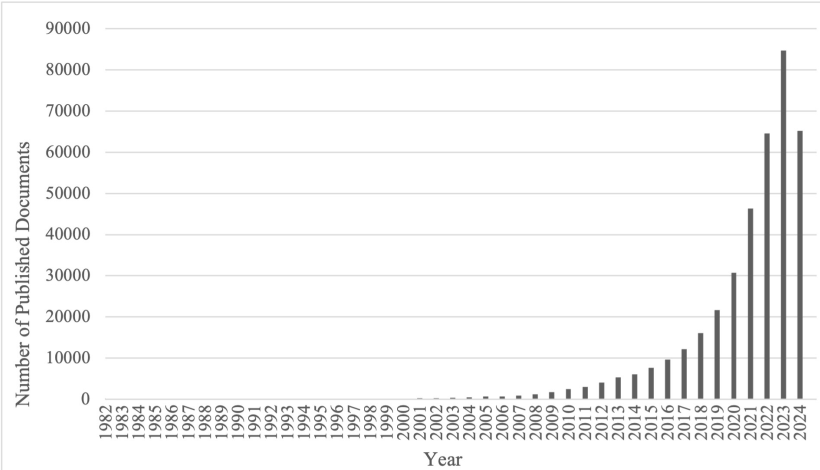

Fig 4 | Number of documents published per year covering the topic of GM and sustainable production

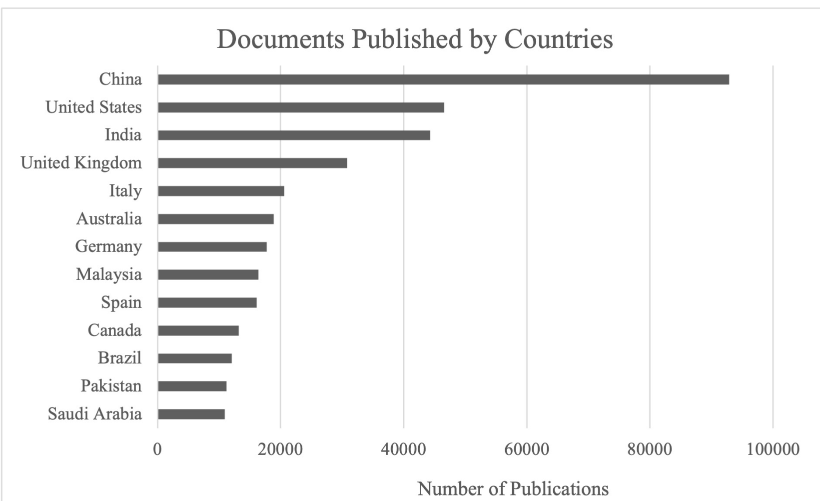

Fig 5 | Top countries based on the number of publications

use of new raw materials and is considered an activity with the lowest environmental impact as it involves fewer processes. "Recycle" is a term that refers to the activities implemented to convert the current products or components that would otherwise be thrown away into new useful products (e.g., shredding, smelting, and separating). "Recover" refers to the activities of dismantling, collecting, and preparing the components at their end-of-life to be part of subsequent lifecycles of another product. "Redesign" is more related to "Reduce" where it targets redesigning products to simplify future uses after their end-of-life. One of the techniques that apply the redesign concept is the Design for Environment, or DfE. "Remanufacture" is the manufacturing that is not performed for the first time on the same material to restore the material or product to its original state. Implementing the 6R strategy in the product's life cycle was predicted to help keep the continuous flow of raw materials for a longer time and minimize the environmental footprint.[20] The 6R system involved in sustainable manufacturing is also believed to maximize the value of a product which enhances the potential for better profit.[1] Figure 3 illustrates how the 6R approach increases the product's value and enhances the benefits for stakeholders compared to GM (which is based on only 3Rs) and the earlier approaches.

In 2018, Kishawi et al.[17] further extended the sustainable manufacturing concept and required it to also include the interaction among three levels to cover the required sustainability target; those levels are product, process, and system. The product level involves the 6R approach instead of the 3R approach to cover multiple lifecycles and to achieve the closed-loop paradigm. The process level focuses on reducing energy consumption and eliminating hazards and wastes via effective process planning. Finally, the sustainable system is achieved by using an efficient supply chain system that covers all the stages of the lifecycle.

Statistics

Recently, research in the field of green production and sustainable manufacturing has been increasing dramatically. The following Figure 4 shows the number of published documents covering this field from the year 1982 to the year 2024, with China coming on top based on the number of publications as shown in Figure 5 and with approximately double the number of publications of the following country (the United States).

Figure 6 displays the number of published documents related to green production and sustainable manufacturing per subject area, an information that was extracted from the Scopus Database using keywords *("Sustainability" AND "Green" AND "Technology" AND "Manufacturing" OR "Production").*[22]

It shows Environmental Engineering coming ahead with 18% of all publications followed by Engineering with 12%, and then Energy with 11%.

Manufacturing Sustainability Drivers

Under the umbrella of sustainability's three pillars, Jaafar et al. and Sartal et al.[20,23] defined some of the stockholders' drivers of sustainable manufacturing including the reduced time that a product takes to be ready for the market, minimized raw materials and manufacturing costs, the less regulatory constraint and reduced liabilities, the increased demand for sustainable products that result from increasing sustainability public awareness, the idea of delivering value-added products to customers, and enhancing better employee health and safety. All these previous reasons are believed to increase tangible and intangible corporate profit. Continuous efforts are given to improve the process of identifying, managing, and measuring these factors to better enhance the process.

In addition to the previous drivers, part of the governments' and global organizations' efforts to force sustainability applications into action is adding legislations that require the conformance of the product to

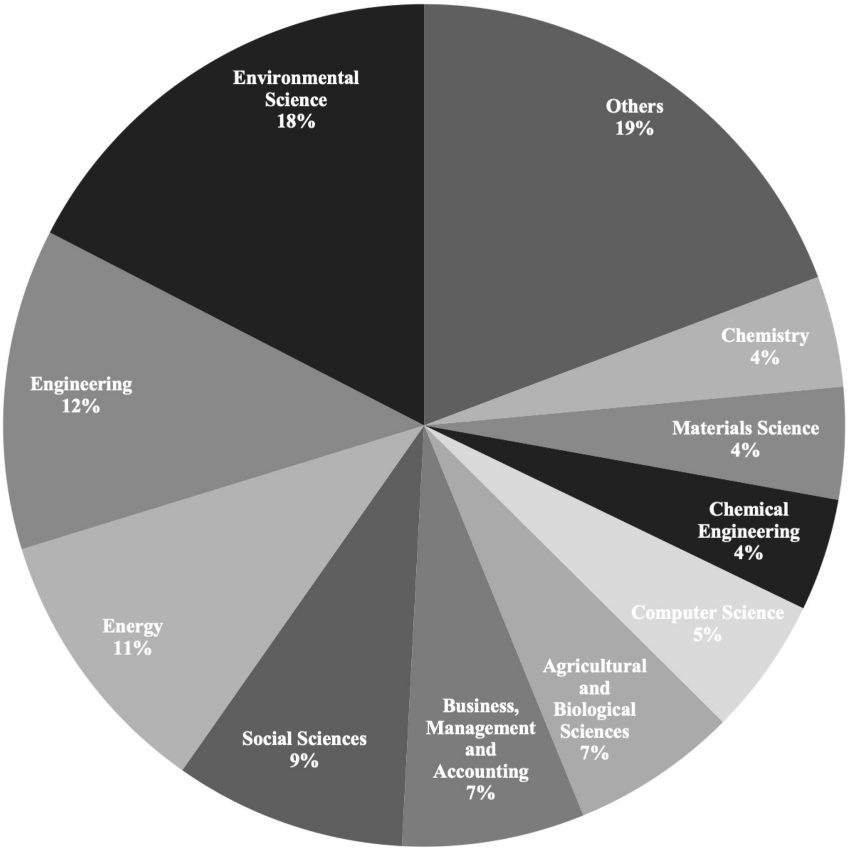

Fig 6 | Number of published documents per subject area

certain sustainability targets over its different lifecycle stages.[20] Examples of these legislations are:

- The Waste Electrical and Electronic 2002/96/EC (WEEE) Directive
- The Restriction of Hazardous Substances 2002/95/EC (RoHS) Directive
- The End-of-Life Vehicles (ELVs) Directive
- The Energy Using Product (EuP) Directive

In 2006, 80%–90% of companies had already recognized the importance of the environmental cause with many of them starting to implement environmentally-friendly operations mechanisms.[1,24] With the recent international environmental awareness, stakeholders (including owners and stockholders of companies, in addition to customers, regulators, and employees) have been pushing towards considering the environmental interest during the designing process. Responding to this pressure, manufacturing companies have declared responsibility for some commitments including complying with the legislation, financial liabilities on products causing environmental damage, behaving ethically towards the environment, etc.[25]

Adopted Strategies and Approaches in Literature to Achieve Sustainable Manufacturing

This section discusses some of the previously adopted strategies in the literature that aim to achieve sustainable manufacturing. It shows that these strategies are not isolated efforts, but parts of integrated efforts of different community sectors to achieve sustainability via exploring, developing, and adopting intelligent technologies. It also shows that sustainable manufacturing is not a passive effort, but a practical and dedicated to finding a smarter, eco-friendly, and sustainable future.[11]

Lean Manufacturing

Lean manufacturing was first introduced by the Toyota production system,[26] which adopted the strategy of constant improvement. The term "Lean" implies eco-efficiency as well as circularity. Lean management paradigm focuses on maximizing efficiency and improving working conditions, which eventually results in minimizing waste and improving operational performance.[26,27] It divides activities inside an organization into either value-adding activities that customers are willing to pay for or non-value-adding activities that are considered waste as the customers are not interested in.[26] Lean manufacturing is simply "use less of everything," which by necessity means minimum materials, labor, space, and investments in machinery and tools.[23] Recent updates to lean manufacturing include enhanced product quality along with reducing cost and lead time.[28]

Circular Economy and Closed-Loop Systems

Circular economy is a business model that involves reusing, repairing, remanufacturing, and recycling technologies to enhance sustainability.[3] Circular economy is also opposite to linear economy that encompasses a make-use-dispose strategy. Circular economy points out a manufacturing system that adopts the idea of having no waste, which means that a product's waste is another product's raw material.[3,10]

In the closed-loop manufacturing system, Jaafar et al.[20] involved all the 6R elements: reuse, recover, recycle, redesign, reduce, and remanufacture to cover all the phases of a product's lifecycle. The author explained the closed-loop system approach in the following Figure 7. It can be noticed that the circular economy and closed-loop manufacturing system are targeting the same thing and applying almost the same strategies.

Closed-loop manufacturing system targets solving the rising problem of waste by dealing with them as raw materials for other products. Chowdhury et al.[29] discussed the serious issue of untreated plastic waste that will eventually lead to "a grave pollution crisis." Tomic and Schneider,[30] on the other hand, emphasized the possibility and opportunity of turning plastic waste into energy in a process that may acquire more profit gains than the traditional manufacturing paths. For example, one of the innovative approaches of implementing the closed-loop principal is turning waste plastics into hydrocarbon fuel in a process known as upcycling.[11]

Challenges accompanying circular economy and closed-loop systems involve complexity and short lifecycle of products, abundance of materials, and the inconsistent conditions of the end product.[3]

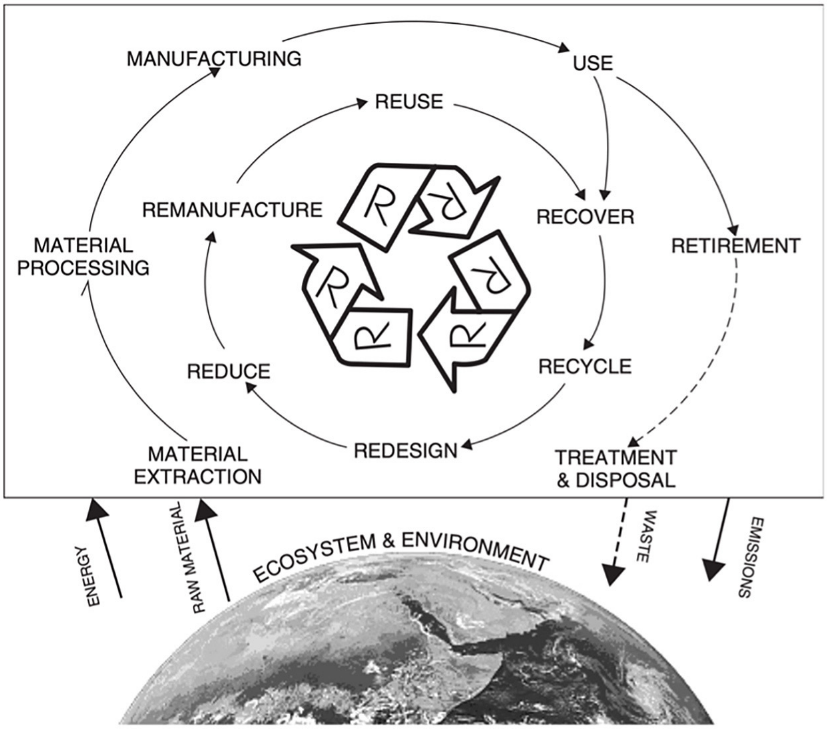

Fig 7 | The closed-loop product lifecycle system[20]

Design for Environment (DfE)

Myer Kutz[25] defines the Design for Environment (DfE) as "*the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle*". DfE focuses on the design aspects associated with the impact on health and safety, hazardous materials minimization, disassembly, waste, compliance with regulations, recycling, and recovery. Tools that can be useful in the application of the DfE include guidelines and checklists, design matrices for each product, environmental effect analysis, and lifecycle analysis.[25] In their research, Kudz pointed out Black & Decker as a successful example of applying and benefiting from the DfE. It is noted that the DfE approach covers only one aspect of the TBL, that is the environment.

Green Supply Chain Management (GSCM)

Traditional supply chain management is the systematic process of converting raw materials into final products in addition to the following processes including delivery to consumers.[11] GSCM, on the other hand, is a concept that integrates environmental concerns with supply chain management and focuses on two main targets: mitigating environmental impact and eliminating adverse effects on public health.[31] GSCM is sometimes known in literature by different names such as Green Logistics, Environmental Logistics, Supply Chain Environmental Management, and Sustainable Supply Network Management.[11] GSCM covers a wide range of operations starting from the early lifecycle stages such as sustainable procurements and vendor management across all the other phases to waste management, market distribution, marketing, and green outbound logistics. It interconnects economic success and environmental responsibility.[11]

The research by Ahmad et al.[32] is considered one of the successful attempts that study the significance of GSCM on the sustainability performance of 384 organizations covering three different industries (i.e., textiles, automobiles, and tobacco). The study focused on five dimensions of the GSCM, namely: GM, green purchasing, cooperation with customers, eco-design, and green information systems. It confirmed the significant positive impact on sustainable performance in all dimensions except for the cooperation with customers, which had no impact. In their research, the authors concluded that the incorporation of GSCM practices in the manufacturing organizations will enhance the environmental performance along with the economic performance.

Hijazi et al.,[33] on the other hand, confirmed the significance of eco-design and enriched the landscape of the GSCM by adding corporate environmental management and customer participation as additional significant dimensions.

Life Cycle Assessment (LCA)

LCA is an evaluation process that measures and analyzes the environmental performance along different stages of a product's lifecycle.[25,34] Traditional LCA usually covered only the cradle-to-grave lifecycle phases. The cradle-to-cradle lifecycle, however, implements recycling, recovery, and reuse and is formally known as the Design for Sustainability DfS concept.[20] This approach is a systematic way to analyze and mitigate the manufacturing process impact on the TBL dimensions at the lifecycle's early stages. It has already been promoted through educational and training programs in a step to be fully implemented in the near future.[20] Although LCA is a time-consuming process and cannot be used to improve the environmental impact of current products, it might be a good tool to measure the improved environmental performance of a current product when redesigned to be more environmentally benign.[25]

Digital Advancements and Innovations in Sustainable Manufacturing

Lee et al.[35] performed a thorough review research analysis and confirmed that the growing trends in sustainable manufacturing are following the digital revolution, which resulted in the fourth industrial revolution, or what is known as Industry 4.0 (I4.0). In their review, they predicted that deep learning and big data, with their huge processing capabilities, will be utilized in the digital transformation and the creation of decision-making algorithms in the field of sustainable manufacturing. They also anticipated that technologies with older trends such as additive manufacturing and electronic devices will most likely continue to strengthen.

According to Sartal et al.,[23] I4.0 has emerged as a new trend during the last decade and was associated with sustainable manufacturing as a way of enhancing the industrial value. ElMaraghy et al.[3] confirmed the information and added the Internet of Things (IoT) as another trend and added that both of them are capable of extending the product's lifecycle which can boost its value and support a sustainable economy.

Bag and Pretorius[36] integrated the concept of sustainable manufacturing with I4.0 and circular economy. Their study extended the theoretical model created by Dobey et al.[37] in several of their previous studies to cover not just the significant role of implementing big data and predictive analysis in improving organizational performance, but also how they take part in sustainable manufacturing and integrate circular economy. For instance, the cyber-physical system (CPS) is one of the embedded systems that are used to control physical devices in a system using digital communication and is one of the system examples that is mainly networked with IoT.[38] The integration of such systems can assist in job scheduling and will help in cost and resource minimization.[36] I4.0 is based on some principles including interoperability, decentralization, virtualization, real-time capabilities, modularity, and service orientation.[36]

In literature, CPS, I4.0, Industrie 4.0, and smart manufacturing systems (SMS) are sometimes used interchangeably as they share many similar features.[3]

Materials for Sustainable Manufacturing

Research for sustainable materials has always been one of the most important steps toward achieving sustainability. An example is the utilization of biodegradable materials, which has emerged as one of the effective approaches for attaining sustainability. Rice husk, for example, is one of the extensively studied materials for sustainable materials due to its abundance, good mechanical properties, and richness of useful compounds such as cellulose, lignin, and silica that can be extracted and utilized in other useful applications.[39] According to Morimoto et al.,[39] in 2020, the global rice production reached 756 million tons, which means a huge yield of rice husk. Utilizing this huge amount of byproduct material in industry instead of burning, as it is the case in some countries, is indeed a huge step forward towards achieving sustainability.

Sustainable composites are another example of materials derived to support sustainable manufacturing and sustainability in general. For example, for several years scientists have been working on developing sustainable solutions for construction composite materials. In their research, Hegyi et al.[40] offered a promising development of raw-clay-based construction material. The developed material offers several advantages such as minimized environmental impact, improved indoor air quality, high capacity of heat storage and release, and improved energy efficiency in addition to other qualities.

Sustainability Assessments

Sustainability assessments help in testing and monitoring sustainability across the different phases of manufacturing lifecycle activities. This is an important step in monitoring the environmental, economic, and social influences to facilitate solving problems and the continuous improvement process. Despite the efforts done in this area, research in the past two decades has mostly focused on the evaluation tools of only the environmental aspect.[6] However, with the rising awareness of the TBL, more researchers started covering the three sectors simultaneously. This section addresses the topic of sustainability assessment and covers its definition, historical overview, common tools and types, and challenges.

Definition

Ahmad et al.[6] defined the Sustainability Assessment (SA) as the process that evaluates the sustainability performance based on the environmental, social, and economic impact. SA can be applied to a product, process, or organization to guide the planning and the decision-making processes towards achieving sustainability goals (i.e., resource efficiency, waste reduction, etc.) and is done by identifying potential impacts and trade-offs on the environment, society, and economy.

SA is a complex process that has recently become the main industry focus as it supports the global decisions and policy-making in the context of environment, economy, and society. As a result of the increased public awareness and legislation, it is now considered as a competitive advantage for manufacturing entities to enhance their pros and market shares. As a result, companies are continuously looking for more advanced and comprehensive methods, tools, and methodologies to enhance their sustainability evaluation process.[6]

Bi et al.[1] pointed out that assessment is one of the three main and most important elements in a sustainable manufacturing system, along with the creation and application of a thorough, transparent, and repeatable lifecycle and a system design that targets cost reduction and environmental impact minimization.

Historical Overview

The work related to sustainability assessment officially started in 1992 when the program of the United Nations Statistics Division (UNSD) realized the importance of addressing the adverse effects of unsustainable lifestyles and was then followed by the proposal of the first lifecycle assessment model.[34,41]

A study by Ahmad et al.,[6] in 2023, investigated a decade of research on sustainability dimensions. The review analysis revealed that in 32 research studies, the environmental dimension was the most popular and was included in all the reviewed studies, followed by the economic dimension (21 out of 32) and then the social dimension (18 out of 32). They summarized that, although the TBL concept has gained significant popularity during the past decade, the assessment analysis of the social dimension in manufacturing activities is still in need of more attention and investigation. Despite the growing research and implementation of sustainability in the different manufacturing aspects, there is still a lack of clear frameworks followed to identify the actions required in the sustainable manufacturing field.[9]

Types and Tools

Based on literature,[42–44] manufacturing sustainability assessment is done on several levels, i.e., product, process, facility, national, etc.[42–44] Depending on the lifecycle phases included, the boundaries of the assessment are defined (e.g., Cradle-to-Grave: where all lifecycle phases are included from raw material to end-of-life, while Cradle-to-Entry: covers only from the raw material extraction phase till the entry to the manufacturing facility, etc.). In addition, the complexity of the assessment increases with increasing the number of phases included.

Ahmad et al.[6] covered the most studied methods and tools of sustainable manufacturing over the last decade from 2010 to 2020. They found that out of 32 used methods, the majority were developed to assess sustainability at the process level (15 out of 32), followed by the assessment methods at the product level (10 out of 32), and finally the assessment at the facility or plant level (9 out of 32). They also emphasized that the evaluation of higher levels (i.e., national) will require more data, time, and resources. The most used assessment methods based on their review included Lifecycle Assessment (LCA) (11 out of 32), Analytic Hierarchy Process (AHP), and Fuzzy Analytic Hierarchy Process (FAHP) (8 out of 32), in addition to Sustainable Analysis and Value Evaluation (SAVE) and others.

In another research by the same author,[44] they noted that, from the manufacturing viewpoint, the higher the assessment level, the better the evaluation of sustainability. This means that the assessment on the facility level gives a more comprehensive view than the unit level as it considers all the processes at the same time which enables effective decision-making.

Challenges and Barriers

Despite the recent wide and intensive research during the past decades, until the year 2012, the U.S. Federal Trade Commission listed "sustainability" as one of the concepts that would not be addressed in the "Green Guide" due to the unavailability of a clear perception about the term and that the "Commission lacks sufficient evidence on which to base general guidance" as stated in their report.[45] The number of interpretations related to sustainability has increased, and there has not been a unified definition yet. This acted as a hurdle that delayed implementing sustainability in organizations due to the lack of a clear image and practices related to sustainable manufacturing.[23]

In addition, despite the recent research clearing the vision regarding the issue of sustainability, the potential risks of the lack of effective activation, and the emergence of potential practical tools, there are still some barriers impeding the full application. For example, challenges associated with the full implementation of a circular economy involve high initial investment costs, weak cooperation between businesses, a complex supply chain, inaccurate information about the product's design and manufacturing processes, a lack of competent talents, compromised quality, and a long and expensive disassembly process.[36]

Regarding sustainability assessments, challenges are usually characterized by several complexities (such as the different values of the decision-makers), in addition to uncertainties, vagueness, and the inclusion of many factors which make them challenging to manage.[46]In real life, sustainability indicators are affected by several uncertainties and randomness, and it was found that the majority of researchers overlooked both of them.[6]

Gaps and Future Recommendations

The guidelines for the social sector evaluation of the TBL were only provided by the United Nations Environment Programme in the year 2009,[47] which means that earlier developed research did not include the social dimension in the assessment methods, which was confirmed by several researchers.[11,48] This has led to most of the researched sustainable manufacturing assessment tools not including the three dimensions of the TBL and being limited to the energy analysis or lifecycle assessment and the environmental impact assessment methods. This resulted in a limited number of assessment indicators that lacked experts' validation.[6]

Scharmer et al.[9] were able to spot several other gaps including the lack of a holistic sustainability view where most of the developed models were limited to focusing on specific parts, layers, or industries, which was confirmed by this research author. They concluded that the previous research often: (a) overlooked one or more aspects of the TBL approach, especially the social sustainability aspect; (b) lacked details covering sustainability factors in manufacturing; (c) disconnected the shop floor from the company's overall sustainability; and (d) missed the concept of cross-sector sustainability.

Regarding the existing sustainable manufacturing approaches, lean manufacturing, for example, targets only waste reduction and creating value. It focuses on producing small lot sizes which in turn increases the amount of GHG emissions. GM, on the other hand, targets minimizing the exploitation of natural resources and the minimization of environmental wastes and thus implementing large lot size strategy which requires a large storage spaces.

To enhance the integration and implementation of the best-mixed strategy, organizations are recommended to be aware of the complementary and conflicting natures. In addition, integrated tools and strategic steps are required to be considered such as targeting lead-time reduction, people engagement in the decision-making process, and organizational and supply chain relationships.[26]

To have a convenient application of sustainability with all its dimensions (environmental, social, and economic), Lin and Hao[49] also recommended going in three directions to achieve sustainable manufacturing: (a) public awareness: where the ideas of traditional manufacturing are gradually replaced with the environmental protection ideas that are represented by sustainable manufacturing; (b) solving current products' environmental problems; and (c) activation of legal penalties and promoting good management and improved personnel quality.

It is also recommended by Punj et al.[11] that the new concept of modern eco-designs has evolved and broadened to cover not only technological advancements but also to implement relationships across suppliers, customers, recyclers, and government entities. And in order to overcome the gap in the sustainable manufacturing assessment tools that occurred due to the limited resources available covering all the sustainability dimensions, Ahmad et al.[6] suggested some future directions to enhance current methods and to make them more inclusive. These directions include adding extra effort in integrating the economic and social dimensions, in addition to employing weighted, validated, and applicable indicators.

Finally, there is an increasing need for a gradual empirical validation of the proposed assessment tools and indicators mentioned in the literature to extract the most useful and convenient ones and to provide credibility and variability to these tools across various sectors and industries. It is recommended to perform a comprehensive study on the human-machine interaction to enhance the operability, minimize the information asymmetries, and boost the overall organizational performance when integrating the revolutionizing I4.0 tools.[50] On the governmental level, to enhance the effective adoption of sustainable manufacturing technologies, especially in critical fields such as water, energy, and food resources, effective tools such as environmental certificates, stringent ecological regulations, and penalties against violations can be of great help.[51]

Conclusion

In a step towards achieving sustainability, the focus in the sector of manufacturing has shifted recently from a process-oriented approach to a more product-oriented approach. This means that during the manufacturing process, the focus is directed towards product optimization in a way that has minimal effect on the environment during all the stages of its lifecycle, is economically viable, and achieves its goal of serving human needs without causing them harm during manufacturing.

This paper has provided a thorough exploration of the green production and sustainable manufacturing topics and underlined the significance of sustainability in today's life, especially in the manufacturing sector. It started with a historical background of the topic, its significance, and its evolution enhanced with statistics and numbers. It then went on to clarify the motivations driving the movement towards sustainability, defining the key terms associated with it. The paper has also highlighted the significance of recent laws and public awareness among the most important catalysts for positive change toward the future. It emphasized the fact that for sustainable manufacturing to evolve, it is crucial to keep focusing on preserving natural resources and ensuring that the industrial practices align with the sustainability goals. By implementing the right measures, stakeholders will be able to provide environmentally responsible practices that serve the industry and the environment alike.

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