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Review Article

Assessing the role of circular economy principles in reducing waste by sustainable manufacturing practices: A review

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ABSTRACT

The goal of this research is to assess the potential of circular economy principles in reducing waste through the identification of sustainable manufacturing practices. By focusing on the symbiotic net, the re-manufacturing layer, and waste prevention through recycling, the following aims are addressed: to identify sustainable waste prevention practices within manufacturing companies and classify sustainable practices related to the pre-manufacturing layer, symbiotic net, re-manufacturing layer, and waste prevention through recycling; to explore and assess the potential of established sustainable practices to foster Circularity by using Wasted controller, Redirector, Re-producer, and Recycling processes; and to analyze the impact of identified sustainable practices on waste reduction. To achieve these aims, exploratory multiple case studies are employed, focusing on both manufacturing companies and non-manufacturing companies perceived as sustainable. Qualitative interviews with key informants from each company are utilized, followed by a qualitative content analysis. By identifying a set of sustainable practices within the manufacturing industry, companies can better understand the potential of established strategies to be applied and integrated into the company's business model. This understanding can help bridge the gap between the Circular Economy and the Manufacturing industry and clarify the often ambiguous concept of the Circular Economy. The generation of waste is very much correlated to industrial activities and has a significant environmental impact. It is a key target in many countries to focus on the manufacturing sector to achieve more reasonable waste management and to open up markets for recycled goods. An effective and efficient approach to this end is to integrate the principles of sustainable manufacturing based on a circular economic standpoint. Therefore, the objective of this manuscript is to review the existing work carried out in this regard. We have reviewed many previous papers related to implementing different strategies of a circular economy in manufacturing. Our findings show that there is no systematic review available in the literature that explores the implementation of the principles of circular economy in the manufacturing system.

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INTRODUCTION

Sustainable manufacturing practices, driven by concerns over climate change, resource depletion, and ecosystem degradation, are gaining prominence in manufacturing sectors [1]. The rapid growth of the world's population, combined with increased consumption patterns, is leading to environmental degradation, threatening the planet's well-being and longevity. Industrial waste, notably from the manufacturing sector, is a significant contributor to climate change and resource depletion. Currently, 92% of materials used in consumer products aren't recycled or reused, resulting in the production of 92 billion tons of waste and threatening resource and natural capital depletion [2]. This crisis has brought attention to sustainable manufacturing practices, with the Circular Economy (CE) as an emerging alternative to prevent resource depletion, pollution, and environmental crises.

The circular economy proposes designing resource-efficient products with closed-loop life cycles achievable through a deep, up-front evaluation of production and manufacturing processes. Although products designed for Circular Economy principles have advantages over conventionally manufactured products, the associated costs and complexity currently preclude their wide adoption in manufacturing industries. Organizations face difficulties in assessing the influence of CE principles on product life cycles holistically and precisely evaluating gains and constraints at different life cycle stages. This paper aims to fill this gap by quantitatively investigating the influence of "circularity" on a product's life cycle in terms of waste generation allowed in manufacturing systems and sustainably on relocating the CE concept to existing manufacturing systems. Factors that influence Sustainable Manufacturing Systems unable to adopt CE principles are also considered.

Background and Rationale

Manufacturing still represents around 16 percent of the world's economic activity, though its growth has recently slowed due to many factors, including COVID-19 [3]. Some global manufacturers have been especially impacted, such as global land and sea transportation firms, managing every day the movement of over ten million transport containers throughout the world. Another example is global automotive manufacturers, which, facing a semiconductor supply scarcity, are likely to produce 11 million fewer vehicles in 2021 than in 2020. Industry 4.0 technologies, for example, big data and deep learning, can facilitate the development of new intelligent industrial systems capable of maintaining and developing manufacturing competitiveness under unexpected environmental scenarios as showed figure 1. The introduction of new intelligent technologies to manufacturing firms, simulating the information processing capabilities of the human brain, can foster manufacturing capabilities dependent on correlated data processing at exponential speeds and volumes.

Waste manufacturing can happen inadvertently, as manufacturing systems run under a combination of global uncertainties and several coupling variables, generating non-intended event chains, called emergent behavior. Recent studies show how these factors can create parallel scenarios ranged from a slow and sub-optimized system to a chaotic and failed system. A solution to avoid unexpected

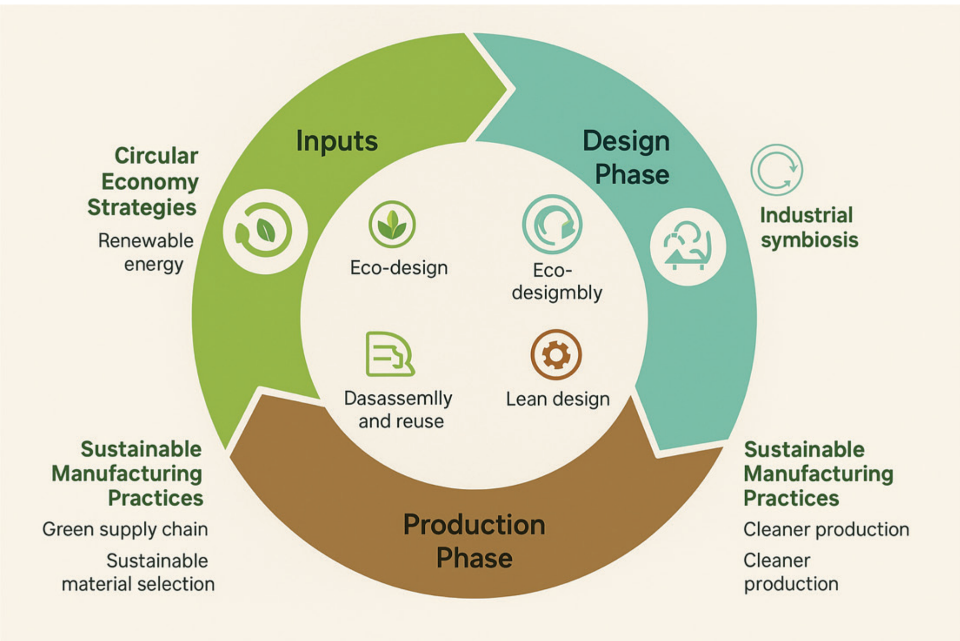

Figure 1. Framework and circular strategy loops. Adapted and redrawn from [4].

waste generation is to monitor those systems, develop explanatory models of knowledge of the factor correlations behind those emergent behaviors, and use that knowledge to pre-empt those unexpected events through decision-making systems. In this regard, methods of artificial intelligence used to infer knowledge models from data—can be useful, especially neuro-fuzzy systems, which mix knowledge of the process with models inferred from data, creating systems interpretable by humans that can be relevant to detect hazards [4].

Understanding Sustainable Manufacturing

The paradigm of sustainable manufacturing has been derived from the well-known phrase 'sustainable development' in order to overcome the environmental challenges created by all nations as a result of rapid growth in industrialization and mass production 1. Sustainable manufacturing has already been recognized as a general concept worldwide, with the aim of framing the definition, need, and different principles governing sustainable manufacturing in manufacturing industries. Sustainable manufacturing practices recognized under policies frame a sustainable future by remaining competitive in industrial markets. Sustainable manufacturing is essential to eliminate waste discharged from factories, which have created a dangerous situation in the present world by polluting water and air, and threatening the existence and health of plants, animals, and the human race.

The principles on which the paradigm of sustainable manufacturing is based are significantly utilized by industries to mitigate the harmful impacts of the manufacturing sector on the environment. An analysis of different models of sustainable manufacturing and their focus assists in understanding the importance of sustainability among industries. Continuous climate change has created a demand for reducing greenhouse gas emissions due to industrial production and hence, industries have empirical needs to limit their carbon footprint on the environment. Proponents have been increasingly advocating that sustainable manufacturing should go hand-in-hand with circular economy principles in design, manufacture, use, and reuse [5].

Definition and Concepts

Sustainable manufacturing refers to the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources. The sustainability of a product depends on its whole life cycle, including the extraction of raw materials, processing, distribution, use, and disposal. Manufacturing is a key industry segment that contributes significantly to economic growth by providing jobs, wealth, and quality of life. However, the manufacturing sector's share of GDP in many developed countries has declined due to globalization, with industries moving to developing nations where resources and labor are more abundant and less expensive. Rapid industrialization has caused environmental deterioration around the world, leading to the emergence of environmental regulations and compliance issues. The introduction of the ISO 14000 series of environmental management standards has been an effective way to address environmental issues and improve competitiveness in countries where such regulations are a concern. In developing countries, significant progress has been made in establishing environmental management systems based on ISO 14000, as well as compliance with regulatory requirements. However, there is a need to improve environmental management and economic viability for the manufacturing sector to strengthen competitiveness in the global economy [1]. Sustainable manufacturing and processing technologies should be developed to minimize the negative impacts of manufacturing on the environment and improve overall sustainability performance. Sustainable technologies are those that use renewable materials and energy sources with non-toxic chemicals and processes, minimizing waste generation, while maintaining the economic viability of the business. The move from local to global competition in the manufacturing sector has forced companies to rethink operations. Increasing global competition due to the globalization of markets and innovations in transportation and information technologies has intensified competition [6].

IMPORTANCE IN THE CURRENT INDUSTRIAL LANDSCAPE

At present, "sustainability" is considered essential in every discipline, including manufacturing and its technologies [1]. Sustainability drives a company's outlook toward profit and future. Sustainable development is defined in many ways, but a clear and widely accepted definition is: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains two key concepts: the concept of "needs," in particular, the essential needs of the world's poor, to which overriding priority should be given, and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

In manufacturing and its technologies, sustainable manufacturing is the idea of manufacturing that meets the needs without compromising the need of future generations [7]. It can be defined clearly as "the creation of manufactured products that use processes that are non-polluting, socially responsible, and economically viable." It can also be interpreted as designing, producing, using, and recycling manufactured products in such a way that there is the least environmental impact, the least social impact, and the most profitability to the manufacturer. Sustainable manufacturing is the most trending topic in today's world.

Circular Economy Principles

The principles of the circular economy (CE) are outlined to highlight its significance in sustainable manufacturing. The elaborated understanding of CE principles is important in the context of this research. It provides foundational knowledge regarding key principles underlying CE initiatives in the context of manufacturing. The extensive findings of the literature review are described as subthemes or principles of the CE. Broadly, CE principles drive circular initiatives through proficient product design, sustainable sourcing of materials and services, and end-of-life product recovery [8]. Resource efficiency and waste reduction through recycling and recovery (regenerative approaches) is an alternative or supplementary approach.

Brief descriptions of the principles of the CE as showed table 1. Product design for longevity and recovery highlights the importance of product design in driving circular initiatives in manufacturing. This may include shorter life cycle product designs, designs that enable disassembly and innovation in remanufacturing components. Sustainable sourcing of materials and services is another principle under CE that closely mirrors a green initiative. Using ethically sourced materials, developing local supply chains and developing synergies between industries to exchange by-product materials are allowed. Recovery of end-of-life products discusses approaches to establish backward supply chains for the recovery of products after the consumer end of product life. Product take-back policies, establishing by-product exchanges assisted by third parties and innovative recycling solutions to product diversion from landfills fall under this principle.

OVERVIEW AND KEY PRINCIPLES

The industrial production pattern followed by most countries worldwide can be classified as linear, which violates certain ecological principles. Therefore, to reduce waste and strive for sustainable growth, circular economy principles have been proposed for industrial production, as commonly done in nature. The basic principles of a circular economy are that after product uses all resources, including material and energy, should either be returned to the same production system for the same use (reuse) or separated and returned to a different production system for different use (recycling). Generally, resource use should be minimized and resources should be kept in production as long as possible [9].

In addition to the circularity principles, four ease-of-implementation principles have been proposed. These easy-to-implement principles are a minimum requirement for compliance with the circularity principles. Under the ease-of-implementation principles, no resource-comprehensive actions or advanced technology innovations are required. The number of inputs to a product design must not increase and other changes to the core components must also not occur. Anything that could decrease product durability must also be avoided. There must be no other major technical redesigns or

Table 1. Circular economy integration in solid waste management Data extracted and tabulated from [9]

Stage	Focus area	Circular economy strategies (loops)	SWM practices
Waste prevention	Source reduction, eco-design	- Product redesign - Lightweighting - Avoid single-use	- Eco-packaging - Green procurement
Collection & sorting	Waste segregation & logistics	- Separate at source - Smart bins - Reverse logistics	- Recycling centers - Digital monitoring
Recycling & recovery	Material and resource recovery	- Mechanical & chemical recycling - Upcycling - Material cascading	- MRFs (Material Recovery Facilities) - Waste-to-resource plants
Treatment	Biological/thermal treatment	- Composting (organic loop) - Anaerobic digestion - Waste-to-energy	- Biogas plants - Controlled incineration
Reuse & remanufacture	Extending product/component lifecycle	- Refurbishment - Repurposing - Remanufacturing	- Second-hand markets - Industrial reuse networks
Landfilling (last resort)	Residual waste disposal	- Only for non-recoverable materials	- Sanitary landfills with methane capture
Enablers	Cross-cutting mechanisms	- Policies (EPR, bans) - Digitalization - New business models	- PPP (public–private partnerships) - Awareness programs

replacements of basic components (e.g., structure). To assess the compliance with these principles, a circularity index has been proposed as a quantification instrument. The circularity index quantifies the degree to which the studied implementation conforms to the circularity principles. The result is presented as a dimensionless quotient between 0 and 1, where 1 indicates complete compliance and 0 indicates no compliance [10].

Applications in Manufacturing

The results of the interviews and workshop show that specifications for energy, water, chemicals, and waste are already being implemented and further development will continue along these lines. Bespoke machine designs for resource efficiency are still rare. The subsequent quantification of the resource consumption of relevant textile processes by the participants indicates the need for additional actions to reduce resource consumption [8].

Implementation issues for plant efficiency and device performance would be very helpful, as would shareable reliable information on efficiency for common devices. Interesting pilot programs would be the development of device performance measures based on clear specifications and the establishment of a benchmarking platform for industrial devices on resource consumption. The existing European Company Awards for the ecodesign of the production process and product could be updated to include material recovery and recycling criteria [2].

WASTE REDUCTION STRATEGIES IN MANUFACTURING

Lean Manufacturing Techniques

Lean manufacturing, or lean production, denotes a manufacturing strategy to reduce wastes. Originated from the mass manufacturing practices of the Toyota production system (TPS), it derives its name from the ideal of succint resource usage and a fully value-adding process. Lean typically describes improvements in five aspects: product and service features, process ownership, staff involvement, and drawing on partnership arrangements and forecasting system [11].

Lean considers any activity that does not add value, or waste, to a product is non-lean. Thus, waste reduction is considered a strategy for improvement. Waste is not only defined as excess or scrap but also in terms of time, workflow, arrangement, employees, etc. Similarly, value is considered in an enlarged sense, related to the employee satisfaction together with the customer. The aim of lean, therefore, involves multiple facets of efficiency and optimization related to the resource usage in a manufacturing process [12].

Recycling and Upcycling Practices

Recycling and upcycling practices have gained increasing attention for fresh approaches to waste reduction and circularity in manufacture. These techniques represent added-value strategies compatible with the circular economy approach, which involves limiting the waste generation and resource consumption from manufacture processes [13]. Sustainable waste management implies minimizing waste before it is generated. Waste reduction techniques can be classified into several groups, such as product or input redesign, manufacturing process redesign, management and control mechanisms, recycling and upcycling practices, and product or process reuse [2].

Recycling is the transformation of waste into a new product, often altering its physical or chemical properties to make it reusable. Recycling manufacturing often results in a change in the material structure, which prevents reusing the product in the same manufacturing process due to the loss of its initial shape, performance, or qualities. Upcycling is a recycling practice gaining increased attention, referring to the transformation of waste into a new product of equal or higher value. This approach is often applied in premature technologies when the removal of contaminants or the technical limitations of the mechanical recycling process prevents the return of the end-of-life products back to the same manufacturing process and quality.

Case Studies and Best Practices

The research findings have been validated using published case studies and exemplary practices to describe how manufacturers have successfully adopted circular economy principles at different levels. It describes practical insights and approaches that can be replicated by others. Circular economy principles are a relatively new development in manufacturing and, therefore, it would be appropriate to use published examples to demonstrate the successful implementation of these principles.

These case studies have been reported in international journals with an established reputation for scholarly rigor and integrity, as well as through presentations at conferences organized by established organizations. The cases have been chosen to be representative and show a diversity of client industries, methods of implementation, and locations. Their presentation reflects ongoing progression concerning early movers and introduces the reader to a wider array of circular economy principles within manufacturing contexts [10].

Successful Implementations of Circular Economy in Manufacturing

As circular economy (CE) moves to the forefront of international agendas, potential avenues for its adoption are being investigated with haste. This research concentrates on significant instances of CE's implementing in a manufacturing context. Manufacturing has been chosen as the main focus of the study since it delivers a considerable opportunity for resource consumption reduction, justifying the need for a paradigm shift of this nature. Accordingly, large firms worldwide already practicing some form of CE and its principles are sought out through a combination of a detailed literature review and examination of sought industry examples [10].

1. The Pratt & Whitney [11] case shows how a product-based solution in combination with end-of-pipe treatment effectively reduces the volume of waste. The company estimates that the solution saves it as much as $2 million per year in disposal costs and presents a lower volume of waste to increasingly environmentally conscious customers.
2. The case study on mini-mills highlights that it is good business to invest in manufacturing processes that reduce environmental impact. There was no compulsion to clean up bottom and fly ash, depositing it typically in tailing ponds [12]. The process was standard industry practice. Faced with problems in obtaining new water resources, Chapleau used the locally available river and drew its supplies upstream, giving rise to significant differences from inlet to outlet for river and mill discharges. This acute sensitivity to effluent, in turn, gave rise to the new system for removing redundant materials to reduce contamination.
3. Cummins Engine Co. set a 5-year target to reduce all air pollutants by 40%. By 1998, it had managed 63%. This move has not only made business sense, but it has also been profitable in looking to the long-term $45 million in environmental and safety costs per annum. In the engine-manufacturing business, the company rolls out three new products per day [13]. Six months before production of a new engine model begins, a cross-functional team starts work. Cummins is the best engine maker and has won awards mainly for waste-reduction work. Such a market focus makes it exceedingly sensitive to environmental costs.
4. Interface pioneered the radical concept of selling carpet as a service or lease and only guaranteeing that it was sufficiently clean and free from defects [14]. The payback times were four and six months, respectively. The company now sells its eco-efficiency carpet to 8% of the market. It is the market leader and has been so for many years. Overall, the company claims that it has made $124 million of efficiency profit.
5. Nike [15] found that by installing a wholly integrated waste treatment system, it was able to safeguard both the product and the environment and, if necessary, guarantee to withdraw waste. This solution recovers and recycles 98% of the water used in production, eliminating waste from the production process. Here, production waste is reused with all of the recycling economic, environmental, and operational benefits. This system is compact enough to require only ten workers to operate it. Furthermore, with this design, the company stores waste materials that are reused throughout the production process.

Manufacturing places enormous demands on a limited supply of global resources, creating significant environmental burdens and CO2 emissions. CE is defined as a regenerative economic model wherein resource input, waste, emissions, and energy leakage are minimized by closing resource loops. CE aims to erect a strong manufacturing base while stopping net material use expansion. Implementation examples with supporting factors from CE principles are additionally highlighted to distinguish best practices from CE functions. This addresses how the CE could be tailored specifically for the manufacturing context, in turn prompting the uptake of CE through significant illustrations and managed expectations from its adoption. Exploring CE's principles in a manufacturing context is found to be timely, relevant, and important [16]. Of the 212 companies adopting in some form a CE and its principles, all but two operate at a manufacturing level. CE principles include closing material loops, keeping resources in use, and promoting systems thinking and cooperation (up to 12 illustrations thereof).

Challenges and Barriers to Implementing Circular Economy in Manufacturing

Although significant advances have been made in addressing waste management in manufacturing, many difficulties and challenges remain. Therefore, this study investigates the CE principles that reduce waste generation as well as their implementation challenges in manufacturing. In general, circular economy principles can reduce waste generation in manufacturing by accommodating several approaches, such as sustainable supply chain management, cleaner production, industrial ecology, and life cycle assessment [17]. However, in practice, implementing man-factors initiatives, other than technology initiatives, is mostly neglected.

The principles of CE and green manufacturing are very important, however difficult to implement and very challenging in developing countries. It is because from the nation perspective, even though there are policies that promote CE or green manufacturing that a lot of small and medium enterprises (SMEs) cannot comply with these policies. The principles of the CE have concerned with the reduction, reuse and recycling (3R) of waste [18]. Various efforts such as development of strategies and methodologies, improvement of machines and equipment, and recycling innovations have been taken, however a significant reduction in current waste generation has not been achieved.

Technological Limitations

Focus is placed on technological constraints which hinder a seamless adoption of circular economy practices. Industry stakeholders may encounter technology challenges, such as lack of advance technology and equipment, inadequate technical capabilities as constraints to CE implementations. Scientific artifacts are presented as a novel model to streamline boundary conditions of CE adoption to these technological challenges and barriers

[18]. In this model, CE visions can only be attained generally by realizing technological transitions, value chain reconfigurations, and market expansion efforts when available scientific artifacts conform to boundary conditions specified by these realizations. Systematic searches are needed to identify and onboard scientific artifacts conform to boundary conditions whereby a certain technology challenge or barrier is circumvented. It is also conceptually examined how and how much scientific artifacts used within CE implementations should be processed to account for boundary conditions (i.e. upper and/or lower limits thereof). Realizing relational implementation procedures formats have to be investigated in future research to assess CE visions attainment likelihoods and derivable boundary conditions. Extensions to broader longer time horizon frames CE visions that might change with a retrofitting procedure based on learning effect, better understanding of devices or knowledge about them would be potential future researches. Since CE intends using energy and materials at manufacturing upmost beneficially, providing scientific artifacts enhancing energy and materials better utilization with a CE concept such as Design of Active Manufacturing Systems (as having methodologies from macro strategic ones to enhance energy and material usage) could yield interesting research results [19].

This section describes the approach of the literature review adopted in this paper, which began with identifying articles related to "circular economy" and "manufacturing," followed by refining the set of documents to include those contained in databases and sorting them on a time basis up to January 2022. The aim of this comprehensive review is to ensure that academic and practical evidence can be seen from more than one perspective, with the view that the sources chosen provide alternatives for many different research and development profiles. The electronic databases used in this literature review include various academic sources. By not excluding or including specific databases, the search strategy encompasses a wide range to overcompensate for missing information across just one or two search engines, thus ensuring more inclusivity in terms of results. The multi-database strategy seeks to improve the exploration process within research and avoid any possibility of underlying errors or misinformation. Moreover, it is to be noted that, at this point, this review is based neither on a meta-analysis of a specific topic nor on a decisive aggregation of themes according to quantitative criteria. Furthermore, it is pivotal to emphasize and draw attention to the fact that both databases and engines are indispensable tools, since no specific academic engine can be considered a standalone site for comprehensive research. The exhaustive search herein includes searching for the keywords, with the engine sorted by "relevance."

The approach was extracted from the literature of "study-level design," and its work state stemmed from the five definitions developed for the "epistemic context." In summary, epistemic studies focus on research communities, work, and products. Also, this review has focused on addressing the frequently cited scholarly literature published in top-tier journals, as well as commonly referenced trade press/media. Excluded were surveys, secondary literature, and purely theoretical research outputs. The approach outlined above supports criteria and research questions to facilitate the review process and collate information dealing with factors driving implementation agendas and activities related to the circular economy and opportunities for manufacturing. The emphasis is driven by the potential to use tried and tested technologies, processes, tools, models, and practices that are adaptable across supported activities, given the alignments.

Economic Considerations

The exploration of the Circular Economy (CE) as an emerging alternative business model is a direct response to the multitude of socio-economic and ecological sustainability concerns facing today's society and the planet. Considered to be part of the trend away from the traditional linear "take-make-dispose" business model, CE principles provide a more holistic conceptual framework and way of thinking concerning sustainability and sustainable resource management [20]. However observable in society over the previous couple of decades, the increased attention and prominence afforded to CE principles has predominantly emerged over the past 5-10 years, leading to the term being variously coined as a new movement, trend, paradigm shift, the next industrial revolution, and so on.

There is a distinct feeling of excitement, hype, utopian vision, and optimism about embracing CE principles. Nevertheless, there are on-going and fundamental economic considerations, factors, and drawback / hurdles standing in the way of the broader acceptance and adoption of CE principles within the relevant decision making / policy influence circle. Hence, this analysis will explore some economic factors and considerations, standing as challenges to the broader acceptance and adoption of CE principles. It is appreciated that whilst an amplification of CE principles may result in net economic benefits, improved economic growth, reduced socio-economic inequalities and some other economic benefits, there are nevertheless economic concerns, factors, and considerations that do stand in the way of wider societal acceptance and adoption.

Policy and Regulatory Frameworks

Several EU Member States have adopted comprehensive policy frameworks to support the transition to a Circular Economy (CE), with a focus on eco-innovation and the support of CE business models in India by specific financing instruments. The European Commission regards the CE policy initiative as a priority, motivated by economic considerations and resource dependency, as well as the aspiration to re-establish Europe as a leader in sustainable loss-prevention technologies [20].

The EU's CE policy initiatives comprise a package of proposals related to the waste framework directive, packaging waste directive, land-filling directive, and the integrated policy state-of-play on the CE. The European Strategy for Plastics in a Circular Economy was updated in January 2018, followed by the Circular Economy Action Plan. Considerable efforts have been made to formulate complete regulatory frameworks within broader CE initiatives in a number of EU Member States. The policy mix concerning the CE is, by most definitions, multi-faceted, comprising, among others, regulatory standards to Smith to foster eco-innovation, with a set of measures directed at the whole production-distribution-consumption chain. Given the complexity and multi-facetedness of the CE concept, it is essential to focus on major systemic components, and these components should be included in the CE policy frameworks. Firstly, recent waste management targets concerning separate collection, recycling, and recovery of wastes are barely sufficient standards on their own [21].

Government Initiatives and Incentives

In recent years, a variety of initiatives and incentives have been adopted by governments at national and regional levels to promote the more sustainable manufacturing and consumption of products. Regulatory agencies and trade promotion organizations have provided guidelines on sustainable manufacturing practices, and broad incentives have been provided in the form of tax credits and more targeted initiatives to foster new technologies for more sustainable manufacturing [21]. Regarding the latter, improved interactions of policymakers with different stakeholders have fostered competitive advantages in Europe for higher sustainability standards in the manufacturing sector. The role of government is seen as key for the transition towards a circular economy, with an active involvement in the establishment of required infrastructures for reused or recycled products, strict legislation for resource consumption reduction with transparent indicators, and facilitation towards research and development on new technologies [22].

In European countries, current government initiatives and incentives for sustainable manufacturing were reviewed. The majority of countries have established broad guidelines on sustainable manufacturing and consumption. A more product-centered approach was adopted by regarding sector-specific guidelines on eco-design and eco-labeling. In conjunction with these guidelines, broad incentives are provided in the form of tax credits and voluntary agreements with industries. Currently, many countries are implementing new sector-specific taxes for certain goods and materials, environmental disclosure and reporting, and environmental standards for products. Broad business models have been proposed for increased sustainable practices in manufacturing. Some initiatives propose the establishment of a directory of available technologies (processes, materials, equipment, etc.) with well-documented evaluations of their life cycle environmental impacts, costs, and effects on work environments. By making such information widely available and easy to understand, companies can compare different options for improved sustainability.

Measuring and Assessing the Impact of Circular Economy in Manufacturing

Assessing and Evaluating the Impact of Circular Economy in the Manufacturing Sector is one of the important tasks to consider Industrial Revolution 4.0, covering Industry trends, Green Manufacturing and Sustainable Manufacturing. It is a dilemma to evaluate this opportunity adequately by finding Key Performance Indicators and Methods of Assessment to evaluate this CE application properly and give a handy tool for further research. As the transition to Sustainable, Green and CE manufacturing seems unavoidable, current and future manufacturing companies must meet new challenges and opportunities in order to stay competitive and on a safe side [23]. There is a problem that current CE definitions in manufacturing are vague. A business model based on shifting to CE would require comprehensible and unambiguous definitions of how this principle should change current manufacturing strategies by covering environmental aspects and flexibility in term of disposable resources [24]. If CE practices in manufacturing are properly defined, new Key Performance Indicators would be needed, as a reflect of CE principals, but also a reflect of sectors within the manufacturing itself. In this manner, it is hard to talk on universally adopted KPIs for the CE manufacturing approach without having clearly defined CE principals themselves.

Assessment and evaluation of Sustainable Manufacturing has not received attention from researchers at this time. Most of the methodologies are mainly focused on very vague and subjective a Sustainable index, which in reality has no base in strict and numeric terms. Likewise, Option 3 could serve as a good framework for various discussions and works; but, practical calculations are impossible as this Option is vague and has not been developed to a level of applicability, where it could provide numeric coverage and performance assessment of sustainability to almost any system. This dilemma simply calls for further research [25].

Future Trends and Innovations in Sustainable Manufacturing

A new generation of savvy, sustainable products and production systems is emerging as environmental, economic, and social pressures shape the future of industrial practice. The focus on sustainability will gain momentum as eco-efficiency and greener products and processes become vital facets of the competitive strategies of industry leaders [1]. Market demands for sustainable products are connected to manufacturers being more environmentally friendly in their production processes. Market pressures exist on organization producers to demonstrate that their processes and practices are more sustainable—using less harmful materials, minimizing energy use, and extricating the creation of waste. Investigations into applying particular resource-efficient technologies to process systems are expected. Greater engagement by organizations in the economic, social, and environmental sustainability of their supply chain is anticipated.

Radical changes in manufacturing products, processes, and systems are anticipated. The evolution of new sustainable or greener products and production processes will likely maintain ultimate product performance and function while enhancing sustainability [25]. Many manufacturers have adopted sustainable practices in product design, sourcing, production, distribution, and marketing, and environmental compliance programs. Advances in sustainable manufacturing processes based on renewable energy, particularly solar, hydropower, and bioenergy, will trace a 30-year innovation and investment trajectory. New materials and composites for manufacturing will emerge, adapted to rationalized and flexible production technologies, with improved performance and lower environmental impacts.

Emerging Technologies

This section delves into the latest technological innovations and advancements that hold promise for further enhancing sustainable manufacturing practices. It sheds light on future trends and developments.

Emerging Technologies in the Manufacturing Plastic Value Chain. A total of 15 emerging technologies related to the transition towards circularity in the plastic materials value chain were identified [27]. The largest group addresses the early stages of the value chain, feedstock and polymer producers, while the second largest group addresses the end-of-life stages of waste management and recycling. Very few specifically address the mid stages of plastic value chains. The literature highlights the complementarities between the technologies:

(1) Enabling a shift in the production-consumption system (distributed economies),
(2) Facilitating the development of high-added value products from biological materials (bio-based systems), and
(3) Reducing the need for raw materials to produce high-quality recycled plastic (chemical recycling).

These technologies exhibit great potential for increased circularity in the manufacturing stages of the plastic value chain. Favourable forces behind this group include a promise of efficiency and productivity increase, the generation of positive marketing messages towards consumers, enabling materials' re-utilisation, a potential seizing of mixed waste sources, and enabling transparency and collaboration among actors [27]. The concept of distributed economies refers to shifting the economic paradigm into more local sourcing, manufacturing, consumption, and recycling systems. The combination of emerging technologies that enable this concept are 3D printing, IoT, blockchain, AI, and cloud computing as well as small-scale chemical transformation processes [28].

Machine Learning and Artificial Intelligence in Circular Economy: A Bibliometric Analysis and Systematic Literature Review. Their study found that large global enterprises are not concerned about their packaging waste; however, the problem can be solved by using the right technology and providing the appropriate motivations to the involved actors. Vlachokostas et al. proposed a generic model using a decision support system that can concurrently examine environmental, economic, and social criteria to generate three different units of alternative biowaste treatment to enhance the production of bioenergy and bioproducts. Bio energy is clean and renewable which completely satisfies the idea of CE. Their experiments showed notable results [29].

CONCLUSION

Sustainable manufacturing practices are essential for industries looking to gain competitive advantage while contributing positively to the environment. This study evaluated these practices and their effect on waste reduction in manufacturing industries based on the principles of Circular Economy. To meet its objectives, the study conducted qualitative interviews with manufacturing industry professionals. The findings indicate that sustainable manufacturing practices are effective in waste reduction. However, the extent of reduction varies based on the application of different Circular Economy strategies. Further, the study presents an evaluation model that provides reference to industry professionals looking to adopt these practices. The model details a sustainable manufacturing practices framework that categorizes the practices based on effective Circular Economy strategies into resource efficiency, recovery, remanufacturing, green technologies, and recycling. The study assesses the level of adoption and implementation of these practices to provide an estimate for waste reduction potential. Further, the study details waste reduction estimation calculations based on the assessment of sustainable manufacturing practices. To assist with calculations, the study presents a cost equation that allows industry stakeholders to evaluate monetary gains from adopting these practices.

Based on the findings, the study highlights two recommendations that can be beneficial for industry stakeholders pursuing sustainable manufacturing efforts. First, an immediate priority for companies is to focus on improving resource efficiency practices such as resource recovery, reuse of natural resources, and the development of energy-efficient technologies. Engaging in these practices will catalyze the adoption of other practices while reducing waste by preserving natural resources [30]. Second, there is an urgent need for academic researchers to shift focus toward investigating sustainable manufacturing practices centered on Circular Economy principles. Research in this area will create awareness in the manufacturing industry about the significance of adopting sustainable manufacturing and Circular Economy practices for waste reduction.

Further, it can guide industry professionals in appropriately adopting practices for maximum waste reduction potential.

Summary of Findings

Sustainable manufacturing practices are developing rapidly worldwide, and major companies are undergoing industrial transitions to more sustainable processes and resources. Waste is a major global problem, and concerning manufacturing processes, wastes have been produced since the beginning of the industrial revolution. The need for sustainable manufacturing practices has arisen, and such practices are under a generalized acceptance stage globally. A circular economy of sustainable manufacturing practices has been envisioned to close waste loops. Such circular economy principles enhance the manufacturer's efficiency by utilizing the major waste sources as resources and closer to the zero-waste scenario. This research endeavors to clarify the link between sustainable manufacturing practices and circular economy principles while providing insights into indicators. It has been demonstrated that there are noticeable links between sustainable manufacturing practices and circular economy principles. There are numerous circular economy indicators concerning manufacturing processes; however, not all questions of the desired practice are inferred in these indicators. A complementary and non-overlapping indicator list has been proposed to assess the role of circular economy principles in these desired sustainability circumstances. Additionally, it has been validated whether these indicators are reasonable concerning the manufacturing processes. In light of the increasing industrial awareness, more stringent petitions, and industrial competition, sustainable manufacturing and circular economy assessment will be hourly anticipated in the completing decade. It is hoped that the indicator list can engender awareness and inspire more disclosures and works on sustainability in academia and industry.

Recommendations for Industry Stakeholders

The interest in implementing circular economy principles in manufacturing processes has been growing, as evidenced by the rising number of publications discussing the topic and the increasing popularity of the phrase. Manufacturers interested in capitalising on the advantages offered by circularity may find it daunting to know where or how to start embracing these principles in practice. They may also be unsure what difficulties and challenges may arise along the way. To this end, a set of recommendations was formulated for industry stakeholders, taking the academic knowledge found in scientific literature and sector-specific documentation on circular manufacturing, sustainability, and industry 4.0, and connecting it to the practical requirements to make small first steps or larger transformational efforts to drive this change towards circularity [31].

To ensure that the changes undertaken by pilot projects can be replicated in other projects across industrial contexts, this research effort must be backed up with full stakeholder engagement and provide detailed and hands-on direction for circularity implementation. In other words, the recommendations should be undertaken as a set of guiding principles that can serve as building blocks in different industrial settings. Hence, the recommendations aim at showcasing and collectively explaining approaches and tools that can readily be used as the foundation for circularity implementation. It must be clearly stated that, in general, these recommendations should not only be considered techno-centric solutions, but rather considers the strategy, stakeholders, technological aspects, product characteristics, and closures as integrated and interdependent aspects that must be addressed simultaneously. Circularity cannot be achieved unless a thorough understanding of the system as a whole has been gained, which can be accomplished through these sets of investigations and chain of events as a first step in a change process for circularity [32].

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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