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Advancing manufacturing sustainability with industry 4.0 technologies

Md Bahar Uddin [1, 3, *], Md. Hossain [2] and Suman Das [3]

[1] *Pran RFL Group, Dhaka-1212, Bangladesh.*

[2] *Bangladesh University of Textiles (Former Name: College of Textile Technology), Dhaka - 1208, Bangladesh.*

[3] *Department of Mechanical Engineering, Khulna University of Engineering and Technology, Khulna, Bangladesh.*

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Abstract

This study reviews the role of Industry 4.0 technologies—such as IoT, AI, big data analytics, cyber-physical systems, and digital twins—in achieving manufacturing sustainability. These technologies enhance efficiency, optimize resources, and reduce environmental impact, aligning with the UN's Sustainable Development Goals (SDGs) for 2030. Despite their significance, limited research comprehensively examines their sustainability implications. The review identifies current research trends, explores key technological contributions, and highlights future research opportunities. The role and impact of different Industry 4.0 technologies for manufacturing sustainability is discussed in detail. The findings of this study provide new research scopes and future research directions in different research areas of Industry 4.0 which will be valuable for industry and academia to achieve manufacturing sustainability with Industry 4.0 technologies.

Keywords: Industry 4.0; Sustainability; Manufacturing; Smart manufacturing; Artificial intelligence; Sustainable manufacturing.

1. Introduction

Sustainable manufacturing integrates environmentally responsible practices across all levels of production—product, process, and system. This concept has expanded to encompass additional sustainability principles, such as reducing, reusing, recovering, recycling, redesigning, repurposing, remanufacturing, and refurbishing. To maximize effectiveness, reduction efforts should begin at the source, emphasizing sustainability from the initial product design phase to account for environmental impacts throughout the product's life cycle [1-3].

To drive growth and global competitiveness, an increasing number of companies are embedding sustainability as a core objective within their strategic and operational frameworks. Sustainability 4.0 leverages advanced technologies to achieve specific sustainability goals. The fundamental aim of sustainability is to enhance the development of both manufacturing processes and products. While technological advancements facilitate process and product innovation, integrating digital technologies with sustainability is crucial for achieving long-term sustainable development [4-5].

Manufacturers are actively working to harness the full potential of Sustainability 4.0 for sustainable production. Industry professionals and researchers are utilizing Sustainability 4.0 technologies to address the challenges of sustainable manufacturing. These technologies play a crucial role in mitigating environmental issues such as climate change and resource depletion while promoting environmental conservation. This approach expands the scope of Industry 4.0 beyond mere digitalization, positioning it as a key driver of sustainability. Green design and product development emphasize the use of recyclable and recycled materials, component recovery, chemical reduction, and energy-efficient production. Green manufacturing focuses on minimizing the consumption of natural resources and

* Corresponding author: Md Bahar Uddin

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reducing environmental pollution. Sustainable facilities strive to generate less waste, lower carbon emissions, and minimize overall environmental impact [6-8].

As sustainability gains traction in manufacturing, companies that adopt eco-friendly and green practices are enhancing efficiency, reducing costs, differentiating themselves from competitors, and proactively adapting to evolving regulations. The increasing scrutiny from consumers, employees, and business partners further underscores the importance of sustainability initiatives. Improved productivity typically leads to lower production costs, higher profitability, and enhanced market competitiveness, ultimately contributing to sustainable growth and long-term success [9-12].

A total of three research questions have been formulated in the present study as follows:

- What is the role of different Industry 4.0 technologies in achieving manufacturing sustainability?
- How can Industry 4.0 technologies contribute to sustainability in manufacturing?
- What are the main research gaps in Industry 4.0 technologies for manufacturing sustainability and what are the research issues that need to be addressed in future?

2. Sustainable Manufacturing

Sustainable manufacturing encompasses three fundamental aspects—processes, products, and systems—that collectively drive economic growth and sustainable value creation within industries [14]. To achieve sustainability in manufacturing, each of these elements must independently deliver benefits across social, economic, and environmental dimensions [15]. Sustainable manufacturing can be defined as the integration of various systems and processes to produce high-quality products while minimizing resource consumption, utilizing sustainable resources, and ensuring safety for consumers, employees, and communities [16].

The concept of sustainability was first introduced in the United Nations (UN) Brundtland Commission report published in 1987, which defined it as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [17]. This definition has been widely used in sustainability initiatives, including the 2015 UN Sustainable Development Goals (SDGs). However, this broad definition is often considered insufficient for addressing the operational aspects of manufacturing [18].

Numerous studies have sought to define sustainable manufacturing more precisely [14], [16]. Jayal et al. [16] described sustainable manufacturing as the design of industrial systems that preserve natural resources to ensure a high quality of life while minimizing environmental and human health impacts. Similarly, the U.S. Department of Commerce defines sustainable manufacturing as "the creation of products through processes that minimize negative environmental impacts, reduce energy and resource consumption, ensure safety for employees, communities, and consumers, and remain economically viable" [19].

3. Industry 4.0

Industry 4.0, also referred to as the "Fourth Industrial Revolution," was introduced at the 2011 Hanover Fair in Germany [20]. The German Federal Government formally launched Industry 4.0 in 2014 as a high-tech strategy to modernize German industries [13]. This revolution focuses on automation and data exchange in manufacturing, facilitating the development of "smart factories" that adapt to dynamic production environments, evolving management objectives, and emerging business models.

Industry 4.0 integrates key enabling technologies such as cyber-physical systems (CPS), augmented and virtual reality, blockchain, additive manufacturing, flexible manufacturing systems, reconfigurability, the Internet of Things (IoT), machine learning, deep learning, artificial intelligence (AI), big data analytics, and cloud computing [21], [22]. Previous industrial revolutions—Industry 1.0 (mechanization), Industry 2.0 (electrification), and Industry 3.0 (information technology)—significantly enhanced productivity and resource utilization [23].

A core component of Industry 4.0 is cyber-physical systems (CPS), which enable mass customization through modularity and adaptability in manufacturing. CPS connects physical entities, enabling seamless interaction between humans, machines, infrastructure, and industrial processes. When integrated with IoT, CPS facilitates real-time connectivity and coordination between the physical and digital realms [24]. The interaction between IoT and CPS enables data exchange between physical components and virtual environments, utilizing sensor data and real-time analytics from manufacturing processes [25]. Additionally, other Industry 4.0 technologies serve as key enablers, driving digital transformation and innovation in modern business practices.

4. Main Technologies of Industry 4.0 for Achieving Sustainability

4.1. Additive Manufacturing

Traditional manufacturing methods rely on subtractive processes such as drilling, cutting, and grinding to shape raw materials into final products. These processes generate significant waste in the form of chips and scraps, negatively impacting both economic and environmental sustainability. In contrast, Industry 4.0 promotes the adoption of additive manufacturing (AM), which minimizes material waste and reduces environmental impact compared to conventional manufacturing techniques [26]. Furthermore, AM enables the production of customized products using a layer-by-layer approach based on computer-aided design (CAD) models, aligning with Industry 4.0 practices [27].

Several studies have explored the role of AM in Industry 4.0. Korner et al., and Haleem & Javid [28], [29] examined how additive manufacturing contributes to sustainability and Industry 4.0. Godina et al. [27] assessed the impact of AM on sustainable business models, while Ford & Despeisse [30] highlighted its role in resource efficiency, sustainability, and closed-loop material flow. Research in [31, 32] emphasized AM as a crucial enabler for sustainability within Industry 4.0. Mittal et al. [33] underscored its significance in developing the Industry 4.0 roadmap.

4.2. Big Data Analytics and Digital Twins

Big data analytics refers to the application of advanced computing technologies to analyze large datasets, identify trends, and facilitate informed decision-making in industrial settings [34]. Within Industry 4.0, big data analytics plays a crucial role in smart manufacturing, where sensor data collected from production activities is processed for real-time monitoring and predictive maintenance. The key benefits of BDA include process optimization, automation, improved production efficiency, and enhanced decision-making, all of which contribute to the transformation of industries in the Fourth Industrial Revolution [35].

Wang & Wang [34] explored the role of big data analytics in Industry 4.0 and cyber-physical systems (CPS), demonstrating that its implementation in manufacturing can reduce machine breakdowns and unscheduled downtime by 25%. Studies by Branco et al., Frank et al., and Papadopoulos et al. [36-38] emphasized the benefits of automating production processes through big data, reducing reliance on human intervention. Li et al. [39] proposed a big data-enabled smart factory framework, demonstrating improvements in efficiency and load balancing through cloud-based communication between shop floor operations and smart products.

A digital twin is a virtual representation that mirrors a physical entity in real time. This technology enables continuous improvements in product design, manufacturing, and operational efficiency. Digital twins serve as software representations of physical assets, processes, or systems, leveraging real-time data analytics for optimization, prediction, and fault detection.

Ke et al. (2019) [41] introduced an interaction framework integrating digital twins, augmented reality (AR), and virtual reality (VR) to enhance Industry 4.0-based manufacturing practices. The role of digital twins in electronic waste recovery was examined in [42] highlighting how computer graphics contribute to their development.

4.3. Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are considered as fundamental bases for Industry 4.0 which helps to make industries more productive and autonomous [43]. AI is the combination of several technologies that allow machines and software to understand, sense, act and learn based on self-learning or augmented human activities [44]. Research on AI in industry can be categorized into four major areas: (1) predictive quality and maintenance; (2) generative design; (3) supply chain activities; (4) human–robot collaboration [43]. The benefits of using ML are discussed in the three aspects of sustainability with some new research scopes for Industry 4.0 practices. The major benefits of using ML and AI approaches result in error reduction, cost reduction and revenue growth in manufacturing industries. In the initial efforts, Lee et al. [43] discussed the roadmap for AI-enabled manufacturing systems for Industry 4.0 practices. Yao et al. [45] discussed the evolution of smart manufacturing from intelligent manufacturing with AI technologies.

5. Sustainability 4.0 applications in manufacturing

5.1. Pollution Control

Digital technologies have been assisting organizations with their sustainability performance for decades, mainly focusing on energy efficiency, pollution control, and value chain optimization. Today's industrial businesses are putting emphasis on enhancing their sustainability performance. Many businesses are increasingly critically focused on the precarious balance of sustainability goals, taking people, the planet, and profit into account. Sustainability 4.0 technology is altering the game, upending the long-standing status quo by giving knowledge and assistance to improve sustainability performance, particularly at the manufacturing level. Many businesses currently utilize several digital solutions to decrease energy usage or potential waste from production. Advanced emission tracking equipment is used to analyze output directly, tracking and linking emissions to specific processes, allowing businesses to change operational activities or process design [46-48].

5.2. Digitization

Sustainability 4.0 is closely linked to the digitization and empowers the co-creation of prosumers to reshape the economy and society towards social inclusion and ecological soundness, as co-creation is a basic premise of the digital economy. It begins with goods and processes such as smart cities, zero waste, and smart garbage. Cocreation, production, and usage of sharing services, such as carsharing, tool sharing, co-working etc., are mainly commercially driven. Under a market governance framework, the sharing economy remains focused on competitive economic action based on the acquisition and utilization of capital. [49-51]

5.3. Transformational potential

Sustainability 4.0 has enormous, disruptive, and transformational potential. The combined forces of sustainability and digitalization are creating a digitally empowered existence as co-creators in a digital economy, with a larger purpose of constructing a more sustainable society with others. Many firms recognize the significant financial and environmental benefits of sustainable business practices. Industries must better understand how to respond to environmental, economic, and social concerns and modify industrial behavior to create more sustainable societies. Co-creation is primarily cooperatively oriented, like repairing caffes, market spaces, urban farming, local exchange trade systems, etc. The commons economy is centered on cooperative economic activity based on reciprocity and redistribution of value, power, and decision-making; democratic governance in a collaborative culture; and partially autonomous from markets and more self-sustaining [52-55].

5.4. Employee safety

Sustainable manufacturing refers to developing items with a complete perspective of the environmental effect and helping in the safety of employees and consumers. It incorporates both lean and green production processes and adds new aspects to them. Sustainable manufacturing focuses on the entire product life-cycle, from manufacture through 'end-of-life,' after which remanufacturing and recycling occur. Modern technologies have quick thinking, efficient engineer or operator capabilities, providing the holistic perspective required to know how to change operations to guarantee productive operations. Technology provides the managers, engineers, and the operator with a consistent lens to make better judgments throughout the production process. [56-59]

5.5. Waste reduction

Sustainability 4.0 aids in waste reduction through its simplified production process and successful recycling and remanufacturing activities in terms of the environmental aspect of sustainable manufacturing. Various sensors and smart technologies significantly improve transparency in any industrial activity or process. Throughout the product's life cycle, such sensors give vital information such as behavior, consumption, failure models, performance indicators, emissions, performance under stress, etc. This information is utilized to design better goods and processes via the use of various simulation systems to limit harmful impacts on the environment. This also aids in the monitoring and management of losses suffered over the product's life cycle, both during manufacturing and us [60, 61].

6. Future Research Directions

6.1. Lean Production Systems for Environmental Management in Industry 4.0

Existing research on lean manufacturing highlights its benefits in improving efficiency and customer satisfaction, particularly in mass production environments. Ghobakhloo & Fathi [62] examined the integration of lean principles with Industry 4.0, identifying practical implications and research opportunities for both small- and large-scale industries. Varela et al. [63] explored the relationship between lean practices and Industry 4.0, finding that sustainability pillars are strongly linked to Industry 4.0 technologies.

However, studies focusing on the integration of lean manufacturing with Industry 4.0 remain limited. Future research could explore the impact of lean Industry 4.0-driven manufacturing, particularly in waste reduction and efficiency improvements. Additionally, developing an integrated lean-Industry 4.0 framework could enhance manufacturing performance while minimizing environmental waste.

6.2. Establishing the Relationship Between Sustainability and Industry 4.0 Factors

Most Industry 4.0 research originates from developed countries, where adoption and technological advancements are more prevalent. However, Industry 4.0 adoption remains low in developing nations, primarily due to resource limitations and infrastructure challenges. Studies in [64] research opportunities in exploring how Industry 4.0 technologies contribute to sustainability.

Despite this, few studies have examined the direct relationship between Industry 4.0 factors and sustainability in business practices. Additionally, political and risk-related factors have not been sufficiently incorporated into existing models, despite their significant impact on sustainability efforts [65]. Future studies could integrate Industry 4.0 theories with sustainability models, addressing both technological and socio-political challenges to provide guidelines for emerging industries.

Furthermore, advanced decision-making techniques such as hybrid multi-criteria decision-making (MCDM), uncertainty-based decision models, and statistical tools could be applied to analyze the interconnections between sustainability and Industry 4.0 adoption.

6.3. Impact of Sustainable Supply Chains in Industry 4.0

Industry 4.0 technologies have disrupted traditional supply chain models, forcing manufacturers to rethink supply chain design and logistics. Over the past few years, several emerging technologies—including big data analytics, AI, machine learning, automation, blockchain, and IoT—have accelerated the transition from traditional to digital supply chains [66].

Studies indicate that digitalization in supply chains can lead to:

- 30% reduction in operational costs
- 70% decrease in inventory requirements
- 60% decrease in lost sales opportunities [67-69]

Despite these advantages, transitioning to a fully digital supply chain requires long-term investments and significant efforts. Future research should explore strategies for optimizing digital supply chains, reducing transition costs, and enhancing operational effectiveness. Additionally, investigating sustainability-oriented supply chain models—such as closed-loop supply chains, circular economy models, and green logistics—could offer practical solutions for achieving Industry 4.0-driven sustainability [13].

7. Conclusion

Manufacturing systems integrate Sustainability 4.0 at every level, ensuring energy efficiency while maintaining product quality. The concept of zero-emission manufacturing views production as an industrial ecosystem, promoting waste reuse, material substitution, and adaptive material flows to improve sustainability without compromising competitiveness. Sustainability 4.0 plays a vital role in enhancing the environmental performance of existing processes while developing new green manufacturing methods.

As a service-oriented and network-based paradigm, manufacturing sustainability has rapidly evolved with Industry 4.0 technologies such as blockchain, big data analytics (BDA), AI, machine learning, and IoT. These technologies enable data-driven decision-making across the product life cycle. Despite its transformative impact, research on Industry 4.0's role in sustainability remains limited. Addressing this gap, future studies should explore how Industry 4.0 technologies can further enhance manufacturing sustainability at different stages of the production process.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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