

Review

The Application of Industry 4.0 Technological Constituents for Sustainable Manufacturing: A Content-Centric Review

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Abstract: Industry 4.0 has been associated with the rise of disruptive intelligence and information technologies. These cutting-edge technologies have the potential to increase productivity while simultaneously having a significant impact on social and environmental sustainability. As a result, manufacturers must evaluate the role of these innovative technologies in sustainable development, as these technologies have the potential to address prevalent sustainability issues. A content-centric study of the implementation of these Industry 4.0 cutting-edge technologies in sustainable manufacturing is currently absent. A systematic literature study was conducted to explain the potential contribution of these novel technologies to the economic, social, and environmental dimensions of manufacturing industries. This study describes how these cutting-edge technologies are used in sustainable manufacturing. The findings of this study are particularly beneficial to practitioners who seek to apply one or more digital technologies to sustainable development.

Keywords: Industry 4.0; manufacturing systems; digital technologies



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1. Introduction

According to Simmert et al. [1], “traditional” enterprises confront new business issues as a result of progressive globalization, large-scale customization, and a competitive economic climate. Demands for shorter delivery times, more efficient and automated processes, greater quality, and customized goods are propelling the firm into the so-called Fourth Industrial Revolution or Industry 4.0.

The Industry 4.0 phenomenon originates in Germany’s manufacturing industry [2]. Denoting the Fourth Industrial Revolution, Industry 4.0 builds on its predecessors, ushered in by mechanization, electricity, telecommunication, and information technology. Moreover, Industry 4.0 represents a connected business ecosystem where value chain partners create global networks to connect their assets, resources, machines, insights, and infrastructure as cyber-physical systems that communicate and control one another in a decentralized manner and through information sharing that trigger decisions and actions. Thus, the idea of hyperconnected digital business systems known as Industry 4.0 has been widely accepted by numerous sociopolitical associations such as the European Union or countries such as Australia, China, South Korea, and India, to name a few [3].

According to Ooi et al. [4], many Southeast Asian countries, such as Vietnam, are already transitioning to Industry 4.0 because these network platforms help in controlling

plant operations to form smart manufacturing or smart factories. Peruzzini et al. [5] defined this new concept as the development of real-time synchronous flow and data exchange via the Internet of Things (IoT), cloud services, and cyber-physical systems to execute smart factories. With the digital developments, the firm is expected to increase its digital level and be able to work with clients and vendors in the digital ecosystem [6].

Traditional manufacturing processes are renowned for causing environmental problems. For example, traditional manufacturing systems and technology may be linked to a cascade of increased resource use, global warming, broad environmental damage, and increased pollution [7]. Thus, sustainability has emerged as one of the most pressing challenges on the global market. Ignorance of sustainability has resulted in massive financial losses for many manufacturing businesses [8].

Many studies have examined Industry 4.0 enabling technologies and their application [9,10]. However, all processes must be included when analyzing the influence of Industry 4.0 [11]. The systematic review approach is used in this work to address the following research question:

- How are Industry 4.0 enabling technologies used in sustainable manufacturing?
- How do Industry 4.0 enabling technologies help manufacturers' sustainable performance?

This study contributes to the literature on sustainable manufacturing by outlining how these innovative technologies influence the economic, social, and environmental performance of contemporary manufacturers. Then, the study might serve as a starting point for further discussion and research by both scholars and practitioners. This study also recommends future research paths on these innovative technologies in sustainable manufacturing.

2. Background of the Industry 4.0 Concept

2.1. Overview of Industry 4.0

The 20th and 21st centuries are significant industrial epochs in manufacturing. In reality, the industry has gone through and is now going through three industrial revolutions. The shift from agricultural to industrial civilization (Industry 1.0), and then from 2.0 to 3.0, has been generally acknowledged and accepted by society. Similarly, understanding irreversible changes in the shift from Industry 3.0 to Industry 4.0 necessitates considerable investigation. According to Lukać [12], the first industrial revolution occurred at the end of the 18th century, and was represented by a mechanical factory driven by water and steam. The second industrial revolution began at the turn of the 20th century, and was represented by large-scale labor production powered by electricity. The third industrial revolution, which began in the 1970s, was defined by automated production based on electronic and Internet technologies; the fourth industrial revolution, namely, Industry 4.0, is currently underway and is defined by the production of cyber-physical systems (CPS) based on heterogeneous data and knowledge integration. Figure 1 depicts the progression of the various stages of the industrial revolution.

Industry 4.0 provides new possibilities that have the potential to challenge industrial organizations' traditional procedures. As the number of new digital technologies increases, Industry 4.0 has a wide range of implications and applications in all main operations. At the same time, technology might have varying effects on different processes; certain technologies may have a horizontal impact on all processes, while others may focus primarily on specific processes.

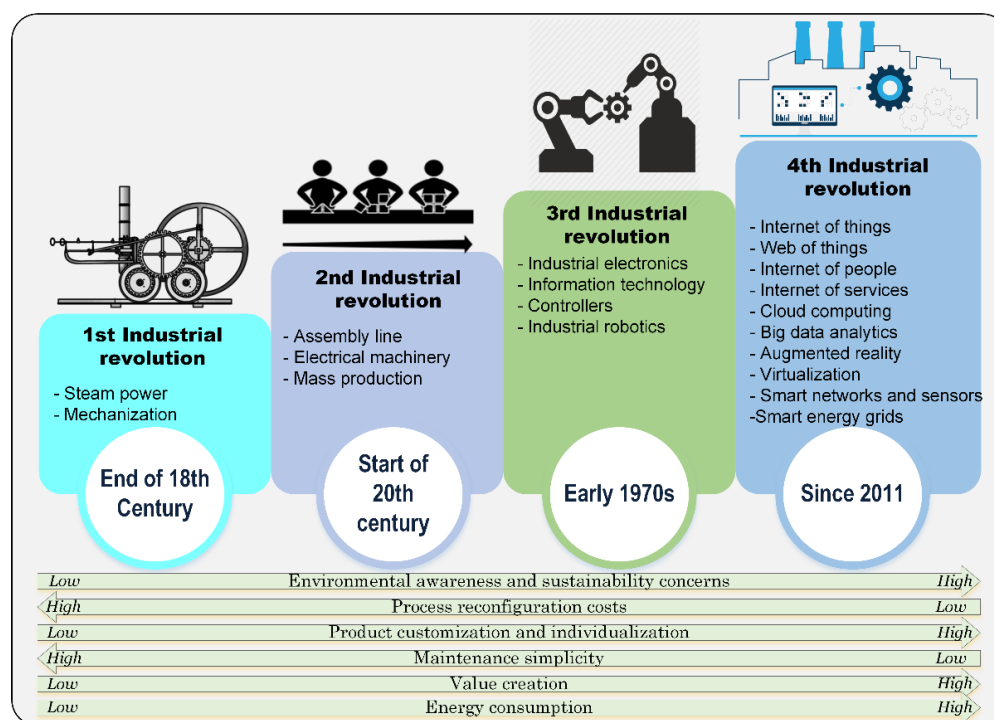


Figure 1. Four industrial revolutions.

2.2. Industry 4.0 Technological Trends

Industry 4.0 is known for a variety of disturbing and cutting-edge technological innovations that enable effective and precise engineering choices in real time by combining a number of information and communication technology (ICT) technologies with existing manufacturing systems. Technology flows are a crucial component of Industry 4.0, and the coupling of digital technologies and operations and manufacturing technologies can allow vertical integration of intraorganizational systems and horizontal integration of interorganizational systems via IoT, cloud data and computing services, and end-to-end solutions across the value networks.

There are several technologies involved in this global trend: cyber-physical systems (CPSs), blockchain, artificial intelligence (AI), digital twinning, the Internet of Things (IoT), big data and analytics, cloud computing, technology, and additive manufacturing. A cyber-physical system (CPS) is a computer-assisted system that integrates real-world physical processes to computers and communication infrastructure [13]. The Internet of Things (IoT) is defined as the concept of gathering information from physical objects by using a computer network or accelerating wireless connectivity [14]. Big data and analytics is concerned with the analysis of data generated by IoT networks in order to capitalize on raw insights and optimization opportunities [14]. Cloud computing is a large-scale, scalable computing paradigm that provides software, infrastructure, and platform-as-a-service, allowing for real-time data sharing across the supply chain. In contrast, blockchain technology refers to clean transaction digital ledgers programmed to record the value of any type of transaction and provide low assets for secure and transparent forms of shared transaction data [15]. Artificial intelligence (AI) is a general term for technologies that enable continuous learning and adaptive decision making based on massive, sometimes unstructured data sets [16]. Additive manufacturing, often known as 3D printing, refers to the method of creating a three-dimensional item by forming a layer of material under computer control [17].

2.3. Application Areas

Industry 4.0 will have the greatest impact on machinery and equipment engineering, particularly in logistics, agricultural, and automotive engineering [18].

Logistics 4.0 makes active use of ICT and contemporary logistics technology to actively decrease delays in the management and execution of logistical business operations, hence boosting organizational responsiveness, logistics capabilities, and competitiveness [19]. For example, logistics must respond to enterprise resource planning (ERP), warehouse management system (WMS), transport management system (TMS), and intelligent transportation system (ITS) to be successful [20]. According to a simple logistics-oriented Industry 4.0 application model, inventory is managed by self-driving robots and vehicles, as well as tracking and decision-making systems; smart products and cloud-enabled networks keep data flowing; and real-time big data analysis of vehicle, product, and facility locations finds the optimal route for material and product delivery [21].

Today, the agrifood industry is heavily influenced by the implementation of manufacturing technology known as “Industry 4.0”. As a result, the focus of these strategies is to provide processes and services that benefit from the rapid growth of the IoT, primarily through the use of ICT methods, modern machinery and tools, and the digitization of processes and services [22]. The agrifood value chain provides consumers with sustainable, cheap, safe, and sufficient food, feed, fiber, and fuel, while also ensuring the seamless and effective functioning of these value chains through the use of sophisticated Internet technologies [23]. For example, blockchain technology can be combined with other technologies, such as radio-frequency identification (RFID), in the agrifood business to track food supply in real time, streamlining food operations, enhancing food safety and quality, and eliminating unethical behavior and social risks [24].

As the demand for industrial automation grows, the automobile sector is being pushed by the projected shift in operator skills and organization on the route to Industry 4.0 [25]. Today, typical mass-produced cars will receive minor design updates every year or every 6 months, and new models will be introduced every few years, so simple electronic devices have given way to ubiquitous systems throughout the car to manage comfort, control, and safety, all of which must be carefully integrated into manufactured vehicles [26]. For example, blockchain can be used in smart vehicle maintenance programs to digitize toll station activities in collaboration with original equipment manufacturers (OEMs), generate digital twins of automobiles based on blockchain technology, build shared mobile ecosystems, and monitor life-cycle events throughout a car’s life cycle [27]. Manufacturers will confront challenges reacting to product changes in their operations and supply chains in the absence of innovation to increase supply chain flexibility [26].

3. Sustainable Manufacturing

Today, the evolution of sustainable manufacturing is driving the entire product life cycle, not just internal operations. This is because sustainability should be viewed not only from the within but also from the perspective of external acceptance and support, which implies that all relevant activities impacting individuals both inside and outside the organization must be assessed [28]. Therefore, contemporary manufacturers must concentrate on all aspects of the supply chain, from product creation through disposal or post-use management as eco-friendly products, and processes cannot be manufactured unless sustainable manufacturing standards are in place [28]. Inspections and interaction with suppliers are also necessary to verify the safety of green materials and supporting infrastructure. Moreover, a business model based on breakthrough technology is required in order to fulfil the objective of sustainable development [29].

A supply chain is a collection of interconnected operations that include the coordination, planning, and management of products and services between suppliers and customers [30]. Supply chain processes are designed to guarantee supply chain operations are dependable, timely, flexible, and adaptive to changing conditions in order to efficiently manage operations-related expenses, such as labor, materials, and transportation costs, as

well as effective asset utilization [31]. As measured by the timeliness and dependability of product delivery to end customers, delivery performance is regarded as a vital indication to support supply chain operations in the supply chain network [32]. The new digital age's impact on the Fourth Industrial Revolution, ICTs, and IoT-based CPS architecture for supply chain application has resulted in the innovations required to implement and accelerate the industry digitalization [29,33].

The supply chain operations reference (SCOR) model examines supply chain operations in five corporate processes: sourcing, planning, making, delivering, and returning [34]. Automating supplier selection is part of the sourcing process; the planning process balances aggregate demand and supply in order to determine the optimal course of action for meeting sourcing, production, and delivery needs; the making process incorporates the plan into the production; the delivery process encompasses all processes associated with the execution and administration of orders; the activities related to removing products and services from the client are referred to as the returning process [34]. As mentioned in this review, Industry 4.0 enabling technologies can help manufacturers stay competitive in a range of business processes.

4. Methodology

4.1. Literature Selection Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard was used to conduct this systematic literature review [35]. To address the research's questions concerning the contribution of Industry 4.0 technology trends to manufacturing firms, the data were assessed utilizing a content-centric approach to the study [36]. The next three sections explain search keywords, inclusions and exclusions, and search results. Articles were collected from the Scopus and Web of Science databases at the end of December 2021 using search phrases related to Industry 4.0 to assess the published article on the contribution of Industry 4.0 technology trends to manufacturing firms. While terms such as smart manufacturing, manufacturing digitization, and future factories are used as synonyms for Industry 4.0, we decided to limit our search to the term "Industry 4.0" [37]. Scopus was chosen because it has the most peer-reviewed journal data [38]. The four inclusion and exclusion criteria are established as follows in order to filter the article and identify related works: (1) the paper must be written in English, (2) it must be published in a journal, (3) the article must discuss the application of digital technology in manufacturing systems, and (4) the complete text of the identified article must be available for additional study. The results are 19454 works in the title, abstract, and keywords of Scopus-indexed publications (Figure 2). Searches were limited to journal articles and English based on the first and second inclusion criteria, yielding 1477 items. Using the study's third inclusion criterion, the authors evaluated the titles and abstracts of 186 identified papers. The first screen, which was based on titles and abstracts, yielded 40 articles. Nine articles were eliminated owing to a lack of full-text availability, and 25 articles were excluded because they did not fulfil the inclusion criterion based on the full-text screen. Finally, 10 articles were added by verifying the references of included articles, and 122 publications connected to Industry 4.0 technology trends' benefits to manufacturing firms were discovered. The publications were evaluated by the authors, and Industry 4.0 technology trends' applications to manufacturing firms detailed in the articles were recognized.

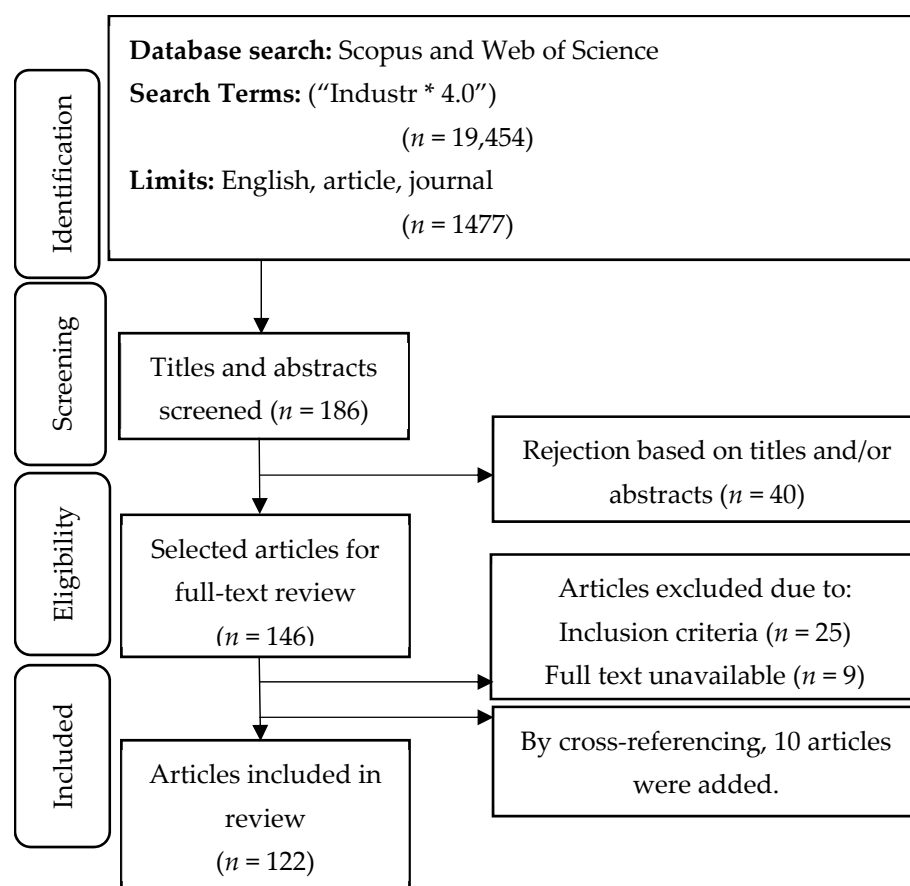


Figure 2. Flow diagram of the article search and selection process.

4.2. Sample Description

4.2.1. Yearwise Publication Analysis

A preliminary mapping based on a yearwise publication analysis is conducted in order to offer a comprehensive view of the literature analyzed. Figure 3 shows an increasing trend in the number of papers published on Industry 4.0 in manufacturing each year, indicating that Industry 4.0 issues are gaining traction in academia. From 2017, contributions began to increase rapidly. Since this literature review excludes conference proceedings, it is reasonable to conclude that, due to the topic's novelty, the papers published in peer-reviewed journals emerged predominantly in 2017 and after.

4.2.2. Journal Contributions

Figure 4 shows the journals sorted by the number of articles published in this journal. The top 5 listed journals for Industry 4.0-related publications are *Journal of Cleaner Production*, *Journal of Manufacturing Technology Management*, *International Journal of Production Economics*, *Computer and Industrial Engineering*, and *IEEE Access*. Most of the articles are published in technology-oriented and manufacturing-focused journals as Industry 4.0 is enabled by advanced manufacturing technologies, including operations technology and information technology. In addition, we highlight the coverage of many journal types related to business and sustainability, indicating the broad impact of Industry 4.0.

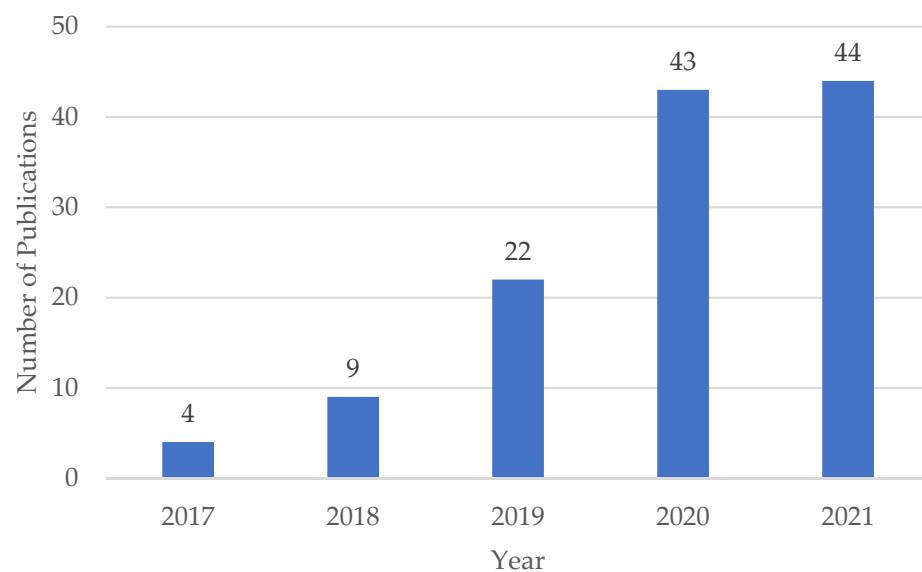


Figure 3. Yearwise publication.

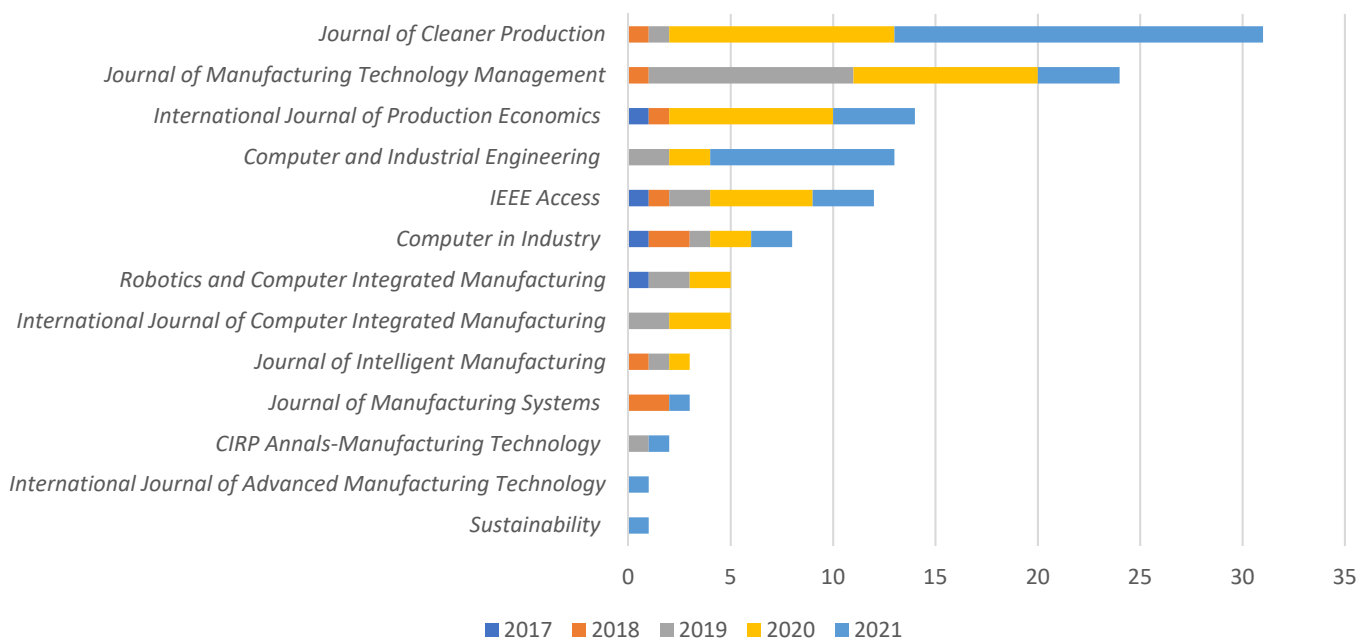


Figure 4. Journal contribution on the topic of Industry 4.0.

5. Uses of Industry 4.0 Enabling Technology in Sustainable Manufacturing

Globally, manufacturers are suffering a scarcity of resources as a result of unsustainable production and resource consumption methods [39,40]. Energy sustainability is undoubtedly the most important socioenvironmental challenge in contemporary times, with roughly 80% of global energy production relying on fossil fuels, leaving a dreadful environmental legacy [41]. Under demand from a range of stakeholders, including customers and investors, sustainability has emerged as a critical business problem, and organizations are implementing more sustainable practices at the organizational level as well as across their supply chains [42]. Thus, sustainable manufacturing is a priority for future global growth because it enables the production of higher-quality products by using sustainable manufacturing technology and the capacity to manage the whole supply chain [43]. It is defined as satisfying the requirements of the present without jeopardizing future generations' ability to satisfy their own needs [44]. Besides that, it helps manufacturers effectively adapt to difficulties and is critical in attaining their economic and social benefit goals while

maintaining environmentally friendly practices [45–48]. Industry 4.0 technologies have the potential to deliver enormous innovation and competitive growth, as well as to enhance the sustainability of existing industrial systems [7,49].

5.1. Economic Performance

Nowadays, manufacturing firms encounter issues such as high manpower costs, complexity in high-risk business contexts, and quick changes in consumer and demand. Thus, manufacturers must manage their operations and supply chains effectively and efficiently in order to meet these difficulties and achieve economic sustainability. Product pricing, financial capabilities, quality, and efficient production processes should be used to assess the economic performance of the manufacturing supply chain [50].

5.1.1. Product Pricing

Product pricing is a powerful instrument used by businesses to obtain a competitive edge, and they are typically decided by the overall cost involved in making a certain product [50]. A strategic approach should be used to select more important investment elements since companies frequently have limited resources to adopt Industry 4.0 enabling technologies. Thus, manufacturers will pay attention to economic indicators, such as cost, delivery time, damage and loss, and inventory turnover, in order to ensure the sustainability of the supply chain [51]. Three-dimensional printing technology offers the benefit of removing the requirement for mold and workshop occupation while also allowing for the production of objects with complicated structural designs. It can cut transportation and storage logistics expenses for a manufacturing firm, and by allowing manufacture at any time and location, as long as the manufacturing firm has the proper equipment, it may prevent losses caused by unpredictability in the logistics process [52]. Thus, the final price of a standard product increases with its own quality and decreases with the quality of the customized product [52]. The development of new inventive technologies has decreased the cost of product manufacture since these trend customers have begun to demand more personalized production [53]. Besides that, savings in material consumption can occur due to the extension of product life cycle resulting from product design, waste upgrading, and re-engineering [28]. Thus, companies profit economically when resource consumption falls [54].

5.1.2. Financial Capabilities

The most significant economic challenges to adopting Industry 4.0-enabled technologies are unknown economic rewards and the substantial investment required. The rising digitalization of manufacturing processes provides a variety of financial advantages, including considerable savings in human resources, inventory management, and operational expenses [55]. The huge financial resources necessary to transition to Industry 4.0 may raise concerns about profitability and return on investment [56]. However, fixed and variable costs may be reduced by increasing quality and productivity [57]. Among Industry 4.0 enabling technologies, 3D printing technology is the most cost-effective. Even though the process costs of this technology are greater than traditional manufacturing techniques, the technological process can minimize other types of expenses, such as inventory and warehousing costs [58]. Besides that, labor expenditures are unimportant in comparison with the entire product cost since this technology requires minimal labor [58]. Industry 4.0 may not guarantee great profitability every year, but it will ensure long-term success [59].

5.1.3. Quality

Compliance with essential standards, specifications, and requirements for supply chain sustainability is referred to as quality [50]. Quality concerns occur practically every day in almost all production processes. They have the potential to result in undesirable outcomes such as product recalls, consumer turnover, and production interruptions. Quality issues that arise during the manufacturing process must be corrected as soon as possible to minimize losses and hazards. From the standpoint of product design and quality manage-

ment, 3D printing technology allows for incremental revision with new ones (whether due to product feature upgrades or fixing design quality issues) without scrapping obsolete inventory [58]. Besides that, quality is a main component of sales as profitability because aspects of quality, such as after-sales service or technical assistance, can influence the number of products sold [60]. In reality, research has shown that quality has a favorable influence on an organization's financial success as well as customer satisfaction [60].

5.1.4. Efficient Production Processes

Efficient production processes need the employment of sustainable production methods by manufacturers in order to prevent negative environmental impacts and increase the whole supply chain's sustainability [50]. Industry 4.0 enabling technologies facilitate production planning and control decision making through effective information processing, enhancing operational efficiency, lowering costs, and raising profitability [29]. Manufacturers configure IoT, cloud computing, big data, and analytics in smart manufacturing systems to gather and analyze information relevant to production and operations more efficiently. IoT and cloud computing can achieve full sharing, free circulation, on-demand use, and optimal configuration of the information required by the manufacturing industry, resulting in high operational efficiency, whereas big data and analytics can help to identify and extract valuable information for making the effective and correct decision for manufacturing enterprises by generating, collecting, and integrating large amounts of data in manufacturing systems [61]. Besides that, customers may earn value by working with manufacturers to create customized goods that match unique customer requirements and demands by utilizing Industry 4.0 enabling technologies [62]. For example, a direct customer's engagement in design will help enterprises to develop tailored products in less time and at a cheaper cost [63,64]. To be economically feasible, sustainable manufacturing must first have a core supply and demand connection for sustainable goods, and the initial step of a sustainable system is the purchase of waste products [65]. Besides that, data transparency has the potential to reduce waste and enhance environmental performance by minimizing erroneous deliveries and unnecessary material flows, as well as preventing damages along the value chain [66]. Table 1 shows the contribution of Industry 4.0 technological constituents to economic performance.

Table 1. Contributions of Industry 4.0 technological constituents to economic performance.

Economic	Description	Source
Profit	Industry 4.0 does not guarantee to make high profits every year but ensures overall profit making, which provides long-term profitability.	Sharma et al. [59]
Productivity	Industry 4.0 helps businesses to function more efficiently and effectively by utilizing smart and efficient tools.	Sun et al. [52], Müller [57], Chan et al. [58], Li et al. [61]
Minimized logistics cost	Transport expenses are reduced because of Industry 4.0 technology and sophisticated coordination between transport vehicles, material handling, and storage equipment.	Sun et al. [52]
Minimized cycle time	Industry 4.0 encourages cost-effective integrated production and logistics operations that minimize cycle time due to optimal utilization of each workstation.	Sun et al. [52], Chauhan et al. [67]
Minimized inventory costs	Smart warehouse management improves inventory levels by reducing product life cycles and responding intelligently to variable demand.	Chan et al. [58]
Minimized labor expenses	Labor expenses are reduced when labor-intensive activities are automated using Industry 4.0 technology.	Chan et al. [58]
Revenue sharing	Revenue-sharing contracts, an alternative profit-based model that emphasizes collaboration among stakeholders, particularly consumers, are enabled by Industry 4.0	Nosalska et al. [62], Ortt et al. [63], Chauhan and Singh [64]

5.2. Social Performance

Social sustainability is an increasing concern for supply chain management. However, harmful practices persist due to insufficient stakeholder pressure on market leaders [44]. Thus, a sustainable supply chain innovation is the implementation of techniques that enhance one or more of the following areas: human rights, labor practices, product stewardship, and corporate social interactions [44].

5.2.1. Human Rights

Manufacturers should respect human rights in their internal operations and verify that their supply chain partners' actions are human rights compliant. The automated supply chain can be formed by applying Industry 4.0 enabling technology. For example, blockchain technology provides the infrastructure to monitor manufacturing businesses' activity, decreasing workplace abuse [27]. Supply chain visibility assists in tracking supply chain operations and identifying unethical activity by corrupt individuals or organizations [27]. Visibility encourages efficiency, gives insights into data obtained from trustworthy settings, and makes it available to all stakeholders [27]. As a result, manufacturers are able to monitor their suppliers' actions to ensure that human rights and justice are respected [27]. When stakeholders have minimal clout, supply chains may be unwilling to accept their requests for more sustainable production methods, such as tackling child labor in mines [44].

5.2.2. Labor Practices and Decent Work

Labor practices and decent work refer to employee health and safety issues associated with the workplace. Their goal is to forecast how production processes will lose operational continuity as a result of events such as unexpected failures and to assess the cost implications for safety, the environment, operations, and production [68]. The future assembly work system will have unparalleled social technology integration and reconfigurability—bringing people and technology together to take benefit of each other, not just with technical requirements, but also with operator needs in mind [69]. Thus, manufacturers must adopt practices that decrease health and safety concerns while still ensuring worker safety. Autonomous and intelligent (smart) manufacturing systems improve employee health and safety by addressing the issue of repetitive and ergonomically undesirable tasks, leading to higher employee satisfaction and motivation [7]. Failures and injuries can be decreased, while overall quality is improved [70]. CPS has the potential to revolutionize production system performance by enabling a broader range of functions that outperform the current paradigm in terms of speed, delivery accuracy, quality, versatility, and responsiveness to demand. However, it may also change the industrial workforce and work environment to make it more human-centered at the same time [68]. Green training helps to adopt green supply chain practices; therefore, green employee training must be coordinated with green supplier training to satisfy the criteria of sustainable production [71].

5.2.3. Product Stewardship

Among the widely acknowledged design principles of Industry 4.0, horizontal and vertical integration of production and manufacturing management systems are arguably the more important ones, which are enabled by real-time data interchange and information sharing. These principles, in turn, enable flexible manufacturing and customized production [61]. As a result, manufacturers must redesign their strategies and procedure, as well as restructure their production processes, in order to create tailored goods and services that have the potential to boost consumer satisfaction [33]. To achieve consumer satisfaction, manufacturers should closely follow the various phases of the product according to the life-cycle analysis [8]. Furthermore, the use of decentralized systems and continuous inventory as well as work-in-progress inventory tracking help the seamless functioning of the complete production system [8]. Blockchain technology's smart contracts, decentralized nature, and information-sharing capabilities allow direct partnerships between customers, manufacturers, suppliers, and merchants [27]. Thus, customers can contact

the manufacturer directly to request customized items, whereas merchants, suppliers, and manufacturers may connect directly, pooling resources and skills to satisfy their customers' demands better. This enables contemporary manufacturers to establish production personalization plans, the most recent kind of differentiation strategy, and remain competitive in the digital era [72].

5.2.4. Business–Social Interaction

The breadth of the manufacturer's community efforts or welfare activities connected to the value generation of stakeholders and shareholders in order to achieve sustainable development advantages is referred to as business-social interaction [50]. Manufacturers should adopt regulations, policies, and strategies that positively influence society and communities to satisfy societal commitments. Under the shared blockchain systems, each participant can access the same transaction data, which results in complete transparency [30,73]. This makes it impossible for participants to cheat the system. Ripple consortium is a worldwide network of over 300 financial institutions in over 40 countries that provides society with an automated, dependable, less expensive, and near-real-time remittance platform [55]. Another example is that blockchain technology can assist in the creation of end-to-end value chains, hence reducing the risk of counterfeiting and fraud in the food sector supply chain [55]. Table 2 shows the contribution of Industry 4.0 technological constituents to social performance.

Table 2. Contributions of Industry 4.0 technological constituents to social performance.

Social	Description	Source
Improved ergonomics and safety	Improved ergonomics can benefit from assessing and identifying potential changes, as well as offering a safer working environment.	Bai et al. [7]
Noninvasive interactions	Provide employees with a digital environment in which they may engage with machines with minimum involvement.	Bai et al. [7]
Collaboration	The Industry 4.0 initiative promotes cross-disciplinary collaboration in process/product development and with customers.	Reddy et al. [27]
Community development	Industry 4.0 aids in the development of a collaborative community because factories and equipment are synced and connected as a whole unit	Reddy et al. [27]
Human rights	Manufacturers are able to monitor their supplier's actions to ensure that human rights and justice are respected.	Reddy et al. [27]

5.3. Environmental Performance

Manufacturers have traditionally concentrated solely on the economic components of sustainability, but external forces are now compelling them to implement environmental sustainability initiatives [74]. These forces include environmental capabilities needed for competitiveness, green product design and innovation, regular environmental audits, and training facilities [50]. As a result of these flaws, manufacturers may violate sustainability standards, exposing them to financial, social, and environmental hazards.

5.3.1. Environmental Competence

By enhancing manufacturing processes, Industry 4.0 technology can help with better planning, eliminate overproduction, and reduce material consumption [28,75]. For example, the agrifood industry is currently inefficient since it wastes a lot of food and uses a lot of water and energy. As a result, introducing lean and green manufacturing practices, as well as resource-saving procedures, can aid in the resolution of these issues [76]. The effective utilization of water resources is critical to agricultural growth. Water shortage, which is strongly tied to agrifood development, must be addressed in order to support sustainable water development. For example, a blockchain-enabled peer-to-peer trading platform (Water Ledger) was created to allow more irrigators to engage in the platform, which safely and transparently permits and distributes water, boosting overall water resource efficiency [23]. Industry 4.0 technologies have the potential to assist in reducing waste management challenges across the country [66,77,78]. They may also improve

production quality through smart and sustainable design coordination as well as intelligent planning and execution [59]. Besides that, the manufacturing digitalization provides various opportunities for carbon reduction because new business models, such as the shift from mass production to mass customization and even product personalization, can optimize the end user market, contribute to the realization of a low-carbon future, and promote environmental sustainability [72].

5.3.2. Green Product Design

Designing sustainable manufacturing is indispensable nowadays as environmental concerns grow and legislation becomes more stringent. New product development methodologies are constantly proposed to meet the changing needs of consumer markets, manufacturing industries, and environmental regulations. As a result, an adaptable and modular green product design is preferred during the development phase [79,80]. An appropriate product design, service, and transportation can reduce global warming while also making manufacturing companies more competitive in international markets [40]. Manufacturers can increase competitiveness by applying advanced manufacturing capabilities by applying 10R-based manufacturing methods, such as refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover options [40]. For example, designers focus on the three stages of a product's life-cycle: manufacture, usage, and end to life in the agrifood industry. When the data presented reveal important information, this technology considers sustainability, which pertains to its manufacturing process, usage, and end-to-life care in comparison with previous technologies [22]. This not only reduces production waste, but also helps businesses interact with consumers and shorten response times, all while projecting a green image [59].

5.3.3. Regular Environmental Audits

Manufacturing firms are a major cause of pollution due to the release of hazardous gases, so they must focus on preventative steps to limit emissions that contribute to environmental damage [8]. Manufacturing firms can introduce environmentally conscious manufacturing, also known as green development techniques, to create eco-friendly goods by concentrating on conceptual design till they are discarded [81]. Manufacturing businesses may utilize sustainable technology to restrict their usage of hazardous materials in order to reduce their emissions [59]. For example, BS ISO 8887-1:2017 is used to specify the content and structural requirements of technical documentation at the design stage as mandatory output deliverables to include information about the manufacturing and end-to-life processing of products during potentially multiple life cycles, with a focus on minimizing environmental impact [82]. Besides that, it also keeps track of the assembly process and batch size, test certifications and results, previous life cycles, and end-of-life options [82]. These standards benefit the remanufacturing business as well as customer perceptions of remanufactured components. Three-dimensional printing technology is a superior way of cost savings because 3D CAD models are encouraged to assist in recycling, and manufacturers are required to dispose of hazardous parts/materials [81]. Then, regular environmental audits must be taken in order to assess the environmental effect of a manufacturing firm's current practices [50].

5.3.4. Presence of Training Facilities

Training activities are intertwined with other industrial processes. Thus, they have an impact on all workers, particularly operators and technicians. Training effectiveness denotes that one of the primary benefits of technology is connected to worker training, and includes benefits such as effective knowledge transfer and retention, freeing up specialists to educate new operators, and minimizing unnecessary production pauses for training [83]. Training facilities are related to manufacturers actively organizing sustainability training and development programs for their workers who may not have the knowledge and resources to practice sustainability [50]. Thus, practicing knowledge management must

be required in the supply chain in order to improve the supply chain's sustainability and logistics performance [84]. Industry 4.0 comprises sustainable and environment-focused operations that reduce the likelihood and frequency of ecological disasters as it supports environmental management and decreases energy and material consumption [59]. Thus, safety can be improved, and penalty payments can be minimized by implementing Industry 4.0 and sustainable practices. Table 3 shows the contribution of Industry 4.0 technological constituents to environmental performance.

Table 3. Contributions of Industry 4.0 technological constituents to environmental performance.

Environment	Description	Source
Possibility for implementing green initiatives	Through the execution of green initiatives, the use of Industry 4.0 technology may help to build competitive advantages and decrease competitive pressures.	Bag et al. [40]
Minimized production waste	It entails manufacturing processes that reuse products/materials.	Bag et al. [40], Kinoshita et al. [81]
Minimized emissions	Industry 4.0 contributes to the development of a collaborative community by reducing the consumption of hazardous chemicals and consequently their emissions.	Ghobakhloo [72], Sharma et al. [59]
Smart product design	Smart and sustainable design coordination and smart planning and execution all contribute to higher production quality.	Kinoshita et al. [81]
Minimized environmental accidents and effects	Industry 4.0 entails eco-friendly activities that reduce the likelihood and frequency of natural disasters.	Sharma et al. [59]

6. Sustainable Manufacturing Challenges

Technological advancement and commercial globalization have drastically altered the globe in recent years [85,86]. Product demand has become more dynamic, and market-places have become more competitive; therefore, enterprises must remain competitive by growing revenue and decreasing expenses in the face of these massive changes [87,88]. The competitive market forces several sectors to create products with shorter lead times [89]. However, production system owners are currently faced with the problem of implementing sustainable manufacturing. There is no doubt that this will be a lengthy process involving major adjustments in practically every aspect of the organization [90].

New business models will arise as a result of the implementation of sustainable manufacturing [91–93]. The key objective is to transition from the existing linear economic paradigm of “extract, create, consume, and trash” to one that maximizes the use of all available resources [94,95]. Its design concepts, including as interoperability, decentralization, and real-time capabilities, have drastically altered how organizations design and deliver new products and services [72,96]. Thus, new modes of working may be necessary in the future, which may have both beneficial and bad consequences for employees. For example, blockchain-based applications need a high degree of specialized technical knowledge, and human resources are limited and expensive [97]. Thus, professional education must be turned into a new paradigm that focuses on the development of interdisciplinary skills, as well as problem-solving abilities and the capacity to handle the difficulties given by Industry 4.0 technology [98,99]. The changes in working circumstances might cause disagreements in business organizations [100]. Furthermore, as conventional firms are phased out, a large number of employees would be laid off [101].

A lack of financial resources is also a key impediment to adoption [102,103]. Perceptions of industrial entrepreneurs toward creative, integrated, and sustainable energy-saving solutions can be a big impediment if these choices are seen to be too risky and these solutions are not widely recognized and understood [104]. For example, food processing enterprises can benefit from energy efficiency in the long run, but in the short term, they must invest in new equipment to achieve the recommended approach [104]. Sustainable manufacturing has resulted in major investment in technological infrastructure, technical training, and information technology support; thus inadequate infrastructure will be

unable to adapt to the idea of sustainable manufacturing [105]. Thus, green initiatives that need additional expenditure are difficult to execute in emerging nations with poor manufacturing margins [59].

The usage of many smart applications, such as smart agriculture, has risen enormously owing to the growth of ICTs over the last several decades, yet security and privacy are key problems given the use of open channels (i.e., the Internet for data transmission) [106]. Thus, mechanisms for protecting data security and privacy must be given to prevent unauthorized attackers from obtaining information from production operations [107]. For example, data and shared information must be safeguarded by cybersecurity solutions with unauthorized usage, which can result in repercussions, such as loss of reputation and consumer confidence, production problems, and intellectual property loss [2,108,109]. However, transmitting data over a wireless network or uploading data to a web or cloud service might result in unintentional or purposeful data breaches [110].

Industry 4.0 transformative change is quick and necessitates proper skill development and training, which might be difficult without strong management backing [111]. Top management has been identified as the most important role in achieving sustainability through the integrated usage of Industry 4.0 [82,112]. If companies decide to use new technologies and collaborative human-machine work, they must prepare workers to better comprehend the dangers and potential, as well as provide the projected advantages in terms of integration and workplace enrichment [105]. To enhance sustainability, top management should allocate enough resources and funds to spend in research and development initiatives [46]. However, it is vital to foster an open and enthusiastic attitude toward future technical challenges for ensuring the success of the innovation process [113]. Furthermore, engineers and managers should collaborate to build a shared vision and knowledge of sustainable manufacturing in order to allow cross-functional interaction [114].

Suppliers play a critical role in the sustainable manufacturing process and can be considered as the primary input parameters for efficient sustainable manufacturing execution [115]. For example, a supplier has a considerable impact not only on the buyer's manufacturing cost, but also on the product's quality and ultimate supply capacity [116]. Uncertainty regarding the availability of sustainable products might hinder demand development, causing the market to be delayed for potential customers [116]. Thus, suppliers must closely monitor the sustainability criteria and assist in their seamless implementation. However, a shortage of competent suppliers is a major barrier for businesses looking for diverse technological solutions [103]. Today, many suppliers are restrictive and do not provide valuable counsel and creative ideas, which might stymie Industry 4.0 deployment [59].

Contemporary manufacturers are also confronted with the difficulty of a lack of world-wide standards and guidelines for the deployment of sustainable technology [117,118]. Changes in the business climate and technological innovation have an impact on the short-term success and long-term sustainability of businesses. Thus, companies must construct suitable technology strategies to support their plans to engage with anticipated future technology breakthroughs such as Industry 4.0 when future technology paths and options are confusing and unpredictable [119,120]. Unfortunately, manufacturing enterprises, particularly small and medium-sized enterprises (SMEs), frequently lack the requisite knowledge and awareness of Industry 4.0's strategic relevance in order to effectively plan for possible digital transformation [121–123]. As a result, SMEs may become victims rather than beneficiaries of this transformation, as the pre-existing digitization-related gap between large and small enterprises is likely to widen [124,125]. Besides that, contemporary manufacturers may be unwilling to adapt and adjust their practices if the stakeholders do not see the benefits of Industry 4.0 [59]. Table 4 depicts the challenges that contemporary manufacturers confront.

Table 4. Challenges that contemporary manufacturers confront.

Economic	Description	Source
High implementation cost	Industry 4.0 is projected to raise overall implementation costs due to extra expenditures in technological equipment and employee training.	Ma et al. [46], Cimini et al. [102], Da Silva et al. [103]
Social	Description	Source
Manage employee anxiety	The deployment of Industry 4.0 will require the contemporary manufacturers to manage their workers' worries and insecurities.	Raj et al. [100]
Disruptions in employment	Employees are concerned that the transition to Industry 4.0 may result in loss of their jobs.	Wan et al. [101]
Development of social infrastructure	To prepare for Industry 4.0, the organization needs to invest in and build an infrastructure for staff training and skills development.	Garcia-Ortega et al. [105]
Compliance of regulatory standards with social requirements	Significant data are gathered from both internal and external clients. While processing this information, firms will be expected to respect social norms.	Mullet et al. [2], Sanchez et al. [107], ElMaraghy et al. [108], Cui et al. [109]
Environment	Description	Source
Lack of supplier's flexibility to make the transition to sustainability	If suppliers become too stiff, the introduction of Industry 4.0 may be hampered.	Da Silva et al. [103], Sharma et al. [59]
Lack of awareness among supply chain stakeholders	Manufacturers may be unwilling to adapt and adjust their practices if stakeholders do not see the benefits of Industry 4.0.	Sharma et al. [59]
Market uncertainty about the availability of green suppliers	Uncertainty regarding the availability of sustainable products might hinder demand development, causing the market to be delayed for potential customers	Veile et al. [116]

7. Conclusions and Future Research

The main objective of this systematic review is to systematize the literature on the use of Industry 4.0 enabling technologies in sustainable manufacturing. This study's goal is to provide answers to two research questions: (1) "How are Industry 4.0 enabling technologies used in sustainable manufacturing?" (2) "How do Industry 4.0 enabling technologies help manufacturers' sustainable performance?" Industry 4.0 and sustainability are developing technology and organizational developments impacted by higher productivity and sustainable manufacturing [126]. Sustainable manufacturing necessitates the engagement of all stakeholders in the cocreation of sustainable value, but Industry 4.0's fully connected nature allows value chain partners and even customers to integrate with sustainability. Industry 4.0 is a complex and diverse phenomenon involving several technologies and application in a highly networked industrial environment. Each Industry 4.0 technological trend has a distinct influence on sustainability. Industry 4.0 technologies strive to address current difficulties, such as global competitiveness, volatile markets and needs, enhanced customization via communications, information and intelligence, and decreased innovation and product life cycles [7,127]. As a result, it was vital to investigate the drivers of sustainability adoption.

Adopting Industry 4.0 efforts to supply chain operations as one of the current trends may boost a company's overall sustainability performance [128]. In terms of economic performance, implementing these innovative technologies in the supply chain may save money by boosting productivity and providing a greater return on investment. These innovative technologies have the potential to have a substantial influence on the social sustainability of supply chains by encouraging transparency and strengthening the commitment to sustainability in order to foster ethical collaboration at the supply chain level. Furthermore, these technologies can aid in the early decision-making process for technology, processes, resource consumption, and downstream and upstream flows, all of which

are related to environmental performance. However, the socioenvironmental effect of Industry 4.0 should be measured in terms of manufacturing-economic prospects brought forth by digital transformation. When corporate survival becomes the main strategic objective, manufacturers do not have the freedom to prioritize environmental protection and social development in the absence of economic sustainability.

Today's manufacturing business must adapt to an increasingly dynamic environment and various developments in order to fulfill market expectations. Product life cycles are becoming shorter, production batches are becoming smaller, and dynamic product variations are coupled with growing complexity, all of which pose difficulties to traditional manufacturing processes [129,130]. Thus, traditional manufacturing plants have been compelled to evolve into smart factories equipped with Industry 4.0 enabling technologies [131]. Manufacturing companies' business models are then shifting as a result of Industry 4.0. This transition of Industry 4.0 is accomplished not only by allowing smart robots in factories, but also by increasing human skills. Improved workflows and the implementation of new training techniques are thus required to enable successful human skills development [132,133]. When the future direction and alternatives to technology are uncertain, it is widely accepted that businesses must develop appropriate business models to support their plans to interact with future technological developments, such as the digitalization of manufacturing in the era of Industry 4.0 [134]. Thus, organizational culture and top management commitment are critical to the success of sustainable projects. Furthermore, the utilization of ICT systems and digital interconnects must be safeguarded against external influence and other data security risks [135]. Sustainable supplier selection is regarded as an effective method for manufacturing firms to achieve supply chain sustainability and realize the advantages of projected performance [136].

This study synthesizes the literature on the use of Industry 4.0 enabling technologies in sustainable manufacturing and adds to it in three ways. The research begins by providing an overview of existing academic knowledge on the use of these innovative technologies in sustainable manufacturing. Then, the article classifies the role of these innovative technologies to the sustainable performance of the manufacturing supply chain. Finally, the gaps in the literature are identified, and recommendations for further study are made. The following future studies are needed:

1. The contribution of these innovative technologies to sustainability is intertwined. Future study will necessitate the development of the interpretive structural model to identify the inter-relationships of sustainable uses of Industry 4.0-related technology.
2. The social performance of sustainability is less studied in this innovative technology literature. Thus, future studies should look into the role of these innovative technologies in the social performance of manufacturing firms.
3. The challenges and determinants of using these innovative technologies to promote sustainable development have received less attention in the literature, and further study is required to address the gap.

Even though the study met both of the research objectives, several limitations should be acknowledged. They are:

1. Future evaluations may incorporate conference papers and book chapters.
2. Authors may screen the articles separately, and issues were addressed by consensus among all the authors since the article inclusion and exclusion for this review were dependent on subjective judgment.
3. Publications were chosen from two databases (Scopus and Web of Science), and we may have overlooked some literature due to their enormous populations.

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