Industry 4.0 Technology Communication Models for Achieving Sustainable Supply Chain: A Roadmap and Impact Dimensions

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ABSTRACT

Industry 4.0 technologies are rapidly transforming production processes and value creation in the global economy. In recent years, significant attention has been directed toward linking these technologies with sustainable development goals, particularly sustainable production. This study addresses the existing gaps in understanding the role of digital processes in achieving sustainable production, and presents a roadmap for leveraging Industry 4.0 technologies to support sustainable supply chains. Through a systematic literature review, we identified 15 sustainability functions that can benefit from Industry 4.0 technologies. This study outlines pathways for implementing these technologies to enhance the economic, social, and environmental dimensions of sustainable supply chains and highlights their importance in achieving sustainability goals.

KEYWORDS

Economic Sustainability, Environmental Sustainability, Industry 4.0, Social Sustainability, Supply Chain, Sustainable Production.

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Introduction

Compliance with energy and material costs, along with exceeding stakeholder sustainability expectations, is a growing challenge that manufacturers worldwide are increasingly facing (Jena, 2020). Sustainable production and operating in a more responsible and sustainable manner are becoming essential business imperatives for maintaining competitiveness in manufacturing (Margherita & Braccini, 2020). Globally, manufacturers are already taking the necessary steps to better contribute to economic, social, and environmental development. Industry reports indicate that leaders in sustainable manufacturing benefit from more profitable opportunities and improved competitiveness. On the other hand, smaller-scale manufacturers are often unable to seize sustainable production opportunities, as they typically struggle with market turmoil and a lack of knowledge, strategy, and resources necessary for sustainable development.

It is difficult to provide a unified definition of sustainable production, but various definitions can be offered depending on its dimensions and applications (Moldavska & welo, 2020). The economic, environmental, and social dimensions, often referred to as the triple bottom line (TBL), are the most widely accepted dimensions of sustainable production among both industrial and academic communities (Junior et al., 2018). Sustainable production encompasses the entire product life cycle, from concept development and the production process to the end-of-life phase (Kamble et al., 2020). This requires a specific degree of integration and collaboration, scenario planning, and process innovation across the value chain (Bhatt et al., 2020). In such circumstances, Industry 4.0 technologies may offer promising opportunities to address the TBL challenges of sustainable production at both the factory and value chain levels.

From economic development perspective, Industry 4.0 and underlying digital technologies, such as cyber-physical systems and the Internet of Things (IoT), are expected to reduce operational costs associated with manufacturing activities (Gouda & Saranga, 2020; Ngu et al., 2020). Additionally, Industry 4.0 is expected to contribute to the environmental dimension of sustainable production by reducing waste during production activities, creating value, and promoting clean energy (Machado, 2020). Regarding the social sustainability dimension, it is believed that implementing Industry 4.0 will improve working conditions, enhance customer experience, and create new job opportunities (Sartal et al., 2020).

This research seeks to answer the question: "How can Industry 4.0 and its underlying industrial and digital transformation contribute to sustainable production?" For example, Ghabakhloo and Fathi (2020) demonstrated that Industry 4.0 technologies, such as industrial automation and IoT, by improving product quality and reducing errors, contribute to economic sustainability. Strandhagen et al. (2020) empirically demonstrated how certain Industry 4.0 technologies can overcome design barriers for sustainable production. A review of the literature reveals that only a few studies have empirically explained the applications of Industry 4.0 for sustainable production. However, the scope of Industry 4.0 extends far beyond the industrial application of isolated standalone digital technologies, such as value-added production (Beier, 2020).

This research aims to address the existing knowledge gaps regarding the applications of Industry 4.0 in sustainable production by providing a strategic roadmap that synthesizes and analyzes previous findings to clarify the pathway toward sustainable production within the framework of industrial digital transformation.

Literature Review

Sustainable Production

Sustainable production refers to the process of creating products through economically viable practices that minimize negative impacts on the environment. This approach represents the intersection of production management, sustainability, and sustainable development. Thus, the three key objectives—economic, social, and environmental—are central to sustainable production activities. In this context, manufacturing companies strive to reduce energy consumption, environmental pollutions, and industrial waste while utilizing processes that also maintain profitability and economic viability. Ultimately, society reaps the rewards of this production method (Le Bourhis, 2013).

The adoption of sustainable production is not merely an attractive slogan; it is a practical approach being implemented by various manufacturing firms. Given the significant importance of corporate social responsibility for these companies, the emphasis on sustainability in production has become a critical issue. Sustainable production has emerged as a focal point for both academic researchers and industry managers. By applying appropriate strategies in this field, organizations can achieve profitability alongside their social and environmental objectives (Le Bourhis, 2013).

Recognizing the substantial scientific and practical relevance of this concept, the literature reveals that sustainable production is increasingly being conceptualized through the lens of Industry 4.0 transformations (Beier, 2020)

Environmental Sustainability in Production

The environmental sustainability pillar of production focuses primarily on reducing the overall negative impact of manufacturing operations on the environment, which is evident chiefly in the reduction of carbon footprints, harmful gas emissions, energy consumption, and waste (Le Bourhis, 2013). In contrast, the social sustainability pillar is often considered the most underdeveloped aspect of sustainable production, as it is less clearly defined. The most recognized dimensions of social sustainability include improving customer shopping experiences, creating better working environments, and establishing fair job opportunities. However, this aspect of sustainability can also address a wide range of social concerns, such as child labor practicies or issues related to fair wages for workers (Sutherland et al., 2016; Mani et al., 2018). Furthermore, the social dimension of production sustainability deals with the welfare of stakeholders and the communities where production takes place (Ghobakhloo & Fathi, 2020).

Generally, implementing sustainability initiatives incur higher short-term costs for companies. However, when sustainability is strategically planned and successfully executed, sustainable production initiatives can yield numerous dvantages for manufacturers (Sartal et al., 2020). Cost savings due to improved material, energy, and resource efficiency are the most apparent advantages of sustainability. Additionally, brand reputation, public trust, and greater competitiveness are among the other benefits associated with sustainability (Ngu, 2020).

Social Sustainability in Production

The Social Life Cycle Assessment (S-LCA) guidelines, developed under the United Nations Environment Programme, provide a valuable methodology to address the ambiguities in the concept of social sustainability. S-LCA offers a detailed framework for both internal and external stakeholders to effectively evaluate and map the social and socio-economic impacts throughout the product life cycle. Experts believe that sustainable production represents the next evolutionary step following green production, drawing from the philosophy of lean manufacturing (Kishawy, 2018). Unlike lean production, which aims to eliminate any non-value-adding activities solely for economic efficiency, green production advocates for environmental preservation even if it means reduced productivity (Inman & Green, 2018).

Sustainable production advances green production by considering the long-term perspective and prioritizing the sustainability of current production activities for future generations (Moldavska & Welo, 2017). Today, sustainable production is seen as a dynamic transition process, as the underlying elements, values, tools, and methods are continually evolving (Yong et al., 2020). Recent studies consistently strive to develop roadmaps that facilitate the implementation of innovative sustainable production practices, with a growing understanding of how production value addition or blockchain technology can contribute to sustainable thinking (Longo et al., 2017).

Sustainable production is defined as a set of techniques, strategies, and activities aimed at producing manufactured goods through processes that generate appropriate economic value, minimize adverse environmental impacts, conserve energy and natural resources, and enhance the well-being of stakeholder (employees, consumers, and communities). This approach to sustainable production encompasses both construction and manufacturing processes (Olfat et al., 2014).

Economic Sustainability in Production

Sustainable processes and the development of more sustainable products aim to deliver essential economic, environmental, and social benefits (Yong et al., 2020). Sustainable production adopts a holistic view of the entire product life cycle, supporting value creation and delivery channels that contribute to the Triple Bottom Line (TBL) of sustainability (Kamble et al., 2020). The economic sustainability aspect of production emphasizes that manufacturers must seek profitability to effectively pursue other sustainability objectives. However, the economic dimension of Industry 4.0 is marked by ambiguities (Ardito et al., 2019; Dev et al., 2020). Given the uncertainties surrounding Industry 4.0, researchers tend to define it in terms of digital transformation, focusing on two main areas: design principles and technology trends (Garetti & Taisch, 2012; Sharma, 2020; Machado et al., 2020).

The design principles of Industry 4.0 establish the necessary conditions for industrial digital transformation and its unique advantages. While perspectives on these principles vary, real-time capability, virtualization, interoperability, decentralization, and extensive virtual/horizontal integration are among the most widely recognized (Zheng et al., 2021).

The Fourth Industrial Revolution or Industry 4.0

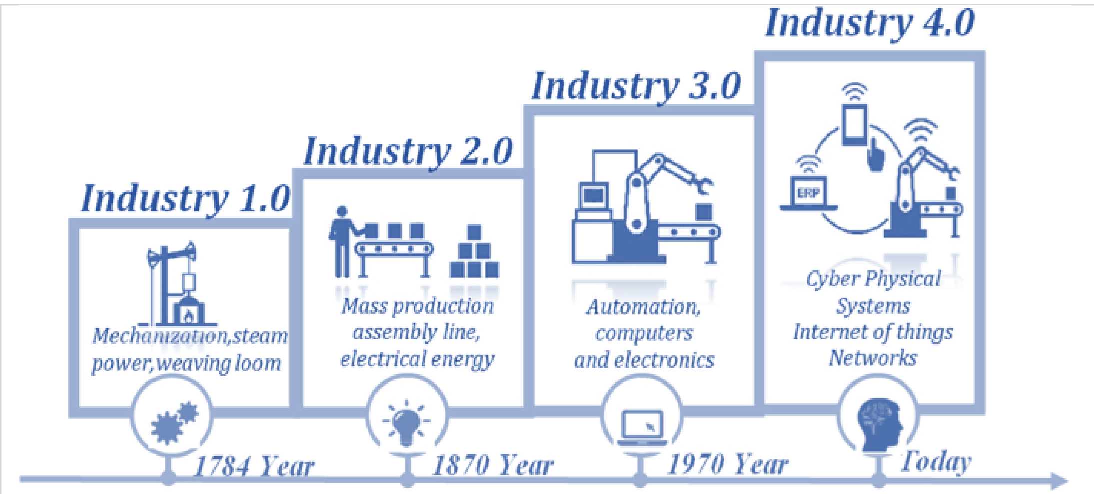
The Fourth Industrial Revolution, commonly referred to as Industry 4.0, has emerged over recent decades, emphasizing the application of digital technologies to elevate various industries. Industry 4.0 leverages the Internet of Things (IoT), real-time access, and cyber-physical systems to create a more integrated and comprehensive approach to production. By bridging the physical and digital worlds, it enables improved collaboration and access among sectors, partners, suppliers, products, and individuals.

Industry 4.0

Industry 4.0 empowers business owners to better control and understand various aspects of their operations, allowing them to leverage their data to enhance productivity, improve processes, and drive growth. From the 18th century to the present, four industrial revolutions have brought significant transformative changes, particularly in manufacturing (Mozafari, 2014).

This fourth industrial revolution integrates advanced technologies, such as artificial intelligence (AI), big data analytics, and automation, reshaping how businesses operate and compete in the global market. Real-time data collection and analysis enable organizations to make informed decisions, optimize resource allocation, and quickly respond to market changes. As a result, Industry 4.0 not only enhances operational efficiency but also fosters innovation and sustainability in production practices.

Figure 1.
Evolution of the Industrial Revolution 4.0



(Source: Khorasanchi, 2021)

What is the Fourth Industrial Revolution (Industry 4.0)?

The Fourth Industrial Revolution can be seen as an extension of the Third Industrial Revolution. While Industry 3.0 introduced computers into the manufacturing process, Industry 4.0 focuses on interconnecting these systems. However, it extends far beyond systems that can communicate within a single factory; when fully implemented, it enables the creation of smart factories and digital manufacturing. The Fourth Industrial Revolution facilitates connectivity across various production components through diverse technologies (Khorasanchi, 2021).

The notion of Industry 4.0 was first presented in 2011 and was defined by GTAI (Germany Trade & Invest) in a paper titled "Industry 4.0: Smart Manufacturing for the Future" It stated:

> "Smart industry, or 'INDUSTRIE 4.0,' refers to the evolution of technology and the shift towards intelligent systems. INDUSTRIE 4.0 represents the fourth industrial revolution and the accessibility of the Internet of Things, data, and services. Decentralized intelligence contributes to the creation of smart object networks and independent process management, showcasing a new aspect of the manufacturing process through the interaction between the real and virtual worlds."

It is clear that definitions of Industry 4.0 vary widely. In practice, Industry 4.0 holds different meaning to different stakeholders, each interpreting it differently. Generally, Industry 4.0 is defined as "a term for the current trend of automation and data exchange in manufacturing technologies, including smart systems, the Internet of Things, cloud computing, cognitive computing, and the establishment of smart factories" (Neshathi, 2017).

Technologies of the Fourth Industrial Revolution

Industry 4.0 is founded on nine key technology pillars, which create a bridge between the physical and digital worlds, enabling the establishment of intelligent and autonomous systems. While businesses and supply chains are currently utilizing some of these advanced technologies, the full potential of Industry 4.0 will be realized only when all these technologies work in synergy. By facilitating communication between the physical and digital realms, the technologies of the Fourth Industrial Revolution drive the development of smart processes and businesses (Almalki et al, 2022).

Figure 2.
Technologies of the Fourth Industrial Revolution

(Source: Almalki et al., 2022)

Big Data and Artificial Intelligence Analytics

In Industry 4.0, big data is collected from a wide range of sources, including factory equipment, Internet of Things (IoT) devices, Enterprise Resource Planning (ERP) systems, Customer Relationship Management (CRM) systems, as well as weather and traffic applications. Furthermore, AI and machine learning analytics are applied to this data in real-time, providing insights that can be utilized to enhance decision-making and automation across various areas of supply chain management, such as supply chain planning, logistics management, production, research and development, engineering, enterprise asset management (EAM), and procurement (Neshathi, 2017).

Horizontal and Vertical Integration

The backbone of Industry 4.0 is its horizontal and vertical integration. Horizontal integration involves the complete unification of processes at the "domain level," including manufacturing, production facilities, and the entire supply chain. Vertical integration, in contrast, connects all organizational layers, enabling free data flow across different levels. In other words, production is closely integrated with business processes such as research and development, quality assurance, sales and marketing, and other departments (Shafiei Nikabadi et al., 2023).

Cloud Computing

Cloud computing is a major "enabler" for Industry 4.0 and digital transformation. Recently, its impact on businesses extends far beyond speed, scalability, storage, and cost efficiency. In fact, cloud computing serves as the foundation for many advanced technologies like AI, machine learning, and the Internet of Things, equipping businesses with tools for innovation. Moreover, much of the data supporting Industry 4.0 technologies resides in the cloud, where physical systems leverage cloud infrastructure to communicate and coordination (Shafiei Nikabadi et al., 2023).

Augmented Reality (AR)

Augmented reality, which overlays digital content onto real-world environments, is a key concept in Industry 4.0. With augmented reality systems, employees can use smart glasses or mobile devices to visualize IoT data, digital components, repair or assembly instructions, training content, and more. While AR technology is still evolving, it has already made significant strides in areas such as maintenance, service, quality assurance, and technician training and safety (Sarasht & Afsar, 2009).

Industrial Internet of Things (IIoT)

The Internet of Things (IoT) and, specifically, the Industrial Internet of Things (IIoT) are so crucial to Industry 4.0 that the terms are often used interchangeably. In Industry 4.0, most physical objects, such as devices, robots, machinery, equipment, and products, utilize sensors and RFID tags to provide real-time data about their status, performance, or location. This technology allows organizations to execute their supply chains more effectively, design and refine products rapidly, prevent equipment failures, maintain consumer preferences, and track products and inventory erffectively (Neshathi, 2017).

Additive Manufacturing / 3D Printing

Additive manufacturing, or 3D printing, is another technology driving Industry 4.0. originally developed as a tool for rapid prototyping, 3D printing now offers a broader range of applications, including mass customization and distributed manufacturing (Almalki et al, 2022).

Autonomous Robots

Alongside Industry 4.0, a new generation of autonomous robots is emerging. These self-driving robots, designed to perform tasks with minimal human intervention, vary significantly in size and function, ranging from inventory scanning drones to autonomous mobile robots for operations. Equipped with advanced AI software, sensors, and machine vision, these robots can perform complex and delicate tasks, analyzing and acting on the information they gather from their surrounding environment (Shafiei Nikabadi et al., 2023).

Simulation /Digital Twins

A digital twin refers to the virtual simulation of a real machine, product, process, or system based on data from IoT sensors. This core component of Industry 4.0 enables businesses to better understand, analyze, and improve the performance and maintenance of industrial systems and products. For example, an operator can use a digital twin to identify a specific faulty part, predict potential issues, and enhance uptime (Shafiei Nikabadi et al., 2023).

Cybersecurity

With the increasing connections and utilization of big data in Industry 4.0, cybersecurity has become critically important. By implementing a Zero Trust architecture and technologies such as machine learning and blockchain, organizations can automate the processes of threat detection, prevention, and response, minimizing the risk of data breaches and production delays within their networks (Almalki et al., 2022).

Impact of the Fourth Industrial Revolution on Business and its Applications

Industry 4.0 can be applied at all levels of the production process, from product development to end-of-life management. Additionally, some manufacturers utilize Industry 4.0 for concepts such as supply chain management. This way, these businesses can better predict supply disruptions and facilitate product manufacturing through optimal resource utilization.

Another application of Industry 4.0 is the acquisition of real-time data during the production process. Analyzing this data leads to optimizing operations, ultimately resulting in improved efficiency, reduced time to market, and increased organizational productivity. One of the best ways to better understand the concept of intelligent manufacturing is to think about its efficiency and how it can be applied within a business. Here are three examples of Industry 4.0 applications in business that can help illustrate the value of Industry 4.0 in a manufacturing environment (Shafiei Nikabadi et al., 2023).

Supply Chain Management and Optimization

The components of the Fourth Industrial Revolution provide businesses with more significant insights, control, and visibility over data throughout the supply chain. By leveraging supply chain management capabilities, companies can bring their products and services to market faster, at a lower cost, and with better quality, thereby gaining an advantage over traditional competitors (Sarasht & Afsar, 2009).

Maintenance, Repair, and Predictive Analytics

Fourth Industrial Revolution solutions empower manufacturers to anticipate potential problems before they occur. Without IoT systems in a factory, preventive maintenance is performed based on routines or scheduled timelines; in other words, it is manual. With IoT systems, preventive maintenance becomes much more automated and simplified. These systems can detect when issues arise or machinery needs repairs, thus enabling businesses to address potential problems before they escalate into more significant issues (Almalki et al., 2022).

Additionally, predictive analytics allows companies to not only ask reactive questions such as “What happened?” or “Why did this happen?” but also answer proactive questions like “What will happen?” and “What can we do to prevent it from happening?” This type of analysis enables manufacturers to shift from preventive to predictive maintenance.

Asset Tracking and Optimization

The components of the Fourth Industrial Revolution assist manufacturers in operating more efficiently at every stage of the supply chain, providing better control over inventory, quality, and optimization opportunities related to logistics. By utilizing IoT in a factory, employees gain better visibility into business assets anywhere worldwide. Standard asset management tasks, such as transferring assets, reclassification, and adjustments, can also be managed in a centralized and real-time manner (Culot et al., 2020).

Technology Trends of Industry 4.0

The technology trends of Industry 4.0 refer to a wide range of information, digital, operational, and advanced manufacturing technologies that collectively create the digital industrial revolution. Based on their functionality, these trends can be classified into two categories: facilitating technologies and core technologies. Facilitating technologies include mature and accessible technologies that enable core technologies' implementation, integration, and proper functioning. Examples of facilitating technologies are legacy networking infrastructures, software, computer-aided design and manufacturing tools, and sensors (Muscio & Ciffolilli, 2020).

On the other hand, core technologies are digital technologies that have recently been commercialized, allowing for maximum flexibility, integration, and automation. Core technology trends in Industry 4.0 include cyber-physical systems, IoT, big data, 3D printers, AI (automation robots), and cloud computing. Although this concept is new and emerging, the literature on Industry 4.0 is rich, and the number of academic contributions to this field is growing exponentially (Oztemel and Gursev, 2020). Previous studies have made valuable contributions to understanding the fundamental concept of Industry 4.0, its scope, constituent components, implications, and trends.

The concept of sustainability in the digital industrial transformation is becoming one of the most popular research streams in the Industry 4.0 community. The contribution of Industry 4.0 to new economies and sustainable supply chains and logistics has been, respectively, the most popular research streams in Industry 4.0 and sustainability (Ding, 2018). Surprisingly, empirical assessments of Industry 4.0's sustainability implications for manufacturing still need to be improved in the literature to understand how manufacturers implement the digital technologies of Industry 4.0 and navigate the underlying digital transformation (Sharma et al., 2020). This means that there more studies need to examine how the implementation of Industry 4.0 relates to the scalability of various technologies and, subsequently, sustainability development (Machado et al., 2020). Industry 4.0 represents the current industrial revolution encompassing the digital transformation of value-creation processes across various industries, including manufacturing.

The integration of Industry 4.0 (I4.0) Technologies into Supply Chain

Integrating Industry 4.0 (I4.0) technologies into supply chain communication models significantly enhances the achievement of sustainable supply chains. These technologies, including IoT, big data, and cloud computing, facilitate improved operational efficiency and transparency, which are crucial for sustainability goals. The following sections elaborate on the key aspects of this relationship.

Role of I4.0 Technologies:

- *Efficiency Improvement*: I4.0 technologies streamline logistics and manufacturing processes, reducing waste and resource consumption (Qureshi et al., 2024).
- *Enhanced Visibility*: Technologies like IoT enable real-time tracking of materials, fostering supply chain visibility (SCV) and supporting circular economy practices (Junaid et al., 2024).
- *Data-Driven Decision Making*: Big data analytics allows firms to make informed decisions that align with sustainability objectives (Stroumpoulis et al., 2024).

Impact on Sustainability:

- *Transparency and Trust*: Blockchain technology ensures the traceability of sustainable materials, promoting ethical practices and consumer trust (Laturkar & Laturkar, 2024).
- *Holistic Approach*: Integrating digital transformation with sustainability practices enhances overall business performance and societal impact (Stroumpoulis et al., 2024).

While the benefits of I4.0 technologies in promoting sustainability are evident, challenges such as the initial investment costs and the need for skilled personnel may hinder widespread adoption. Addressing these barriers is essential for maximizing the potential of I4.0 in sustainable supply chain management.

Introduction to Sustainable Production Function Patterns

To date, numerous models for sustainable production have been proposed. Below, we identify 15 unique sustainable production functions for Industry 4.0. It is essential to note that the functions of Industry 4.0 for sustainable production, as explained below, provide pathways to a more sustainable production ecosystem with varying qualities. While the literature offers the necessary support to link Industry 4.0 functions to different aspects of sustainable production, the sustainability benefits of these functions should be taken seriously, as they depend on the context and conditions under which producers operate. More importantly, these functions may be common to production systems utilizing Industry 4.0 technologies. Industry 4.0 primarily provides these functionalities by promoting and facilitating other tools, methods, and techniques for improving production and processes, including lean production or concurrent design and manufacturing. Below is a brief description of each of sustainable production functions, including: (Li et al., 2020).

- *Business Model Innovation (BUMI)*: Industry 4.0 and its components, such as real-time capabilities, decentralization, or modularity, complemented by modern technologies like value-added manufacturing and IoT, enable producers to transform their operational models and value creation capabilities (García-Muina et al., 2020; Li et al., 2020). Business model innovation enhances the value proposition of producers to customers by offering safer, cleaner, and more functional products and services (Leng et al., 2020).

- *Customer-Centric Production (CUOM)*: Under Industry 4.0, technologies such as value-added manufacturing, service-oriented Internet, and the Internet of People, combined with the principle of modularity, empower producers to develop a more agile and flexible production system that facilitates the customization of products based on customer demands economically, thereby creating higher value for all stakeholders (Wang et al., 2017).

- *Employee Productivity (EMPP)*: Industry 4.0, through real-time information sharing, improved communication clarity, task automation, interdepartmental connectivity, enhanced human-machine interaction, and simplified production operations, can increase the relative performance of employees (Strandhagen et al., 2020; Beier, 2017). Higher employee productivity typically leads to healthier profit margins, improved working conditions, and a healthier business network (Jacobs et al., 2016).

- *Reduction of Harmful Emissions (HAER)*: Industry 4.0 technologies and principles, such as the Industrial IoT, cyber-physical systems, intelligent robots, real-time capabilities, interoperability, and horizontal and vertical integration, along with emerging concepts like smart factories and digital supply networks, offer significant opportunities for industrial productivity and subsequently for controlling and reducing emissions while preserving the environment (Bag, 2020).

- *Improvement of Production Profit Margins (IMPM)*: Smart factories under Industry 4.0 are more agile, flexible, and responsive (Yli-Ojanpera, 2019). In a smart production environment, efficient and automatic decision-making, higher product quality, satisfied customers, and reduced business risks, among many other benefits, provide higher profit margins for producers. Economically productive manufacturers are better equipped to enhance social and environmental sustainability (Vrchota et al., 2020).

- *Intelligent Production Planning and Control (IPPC)*: Digital technologies in Industry 4.0, such as the Industrial IoT, AI, big data analytics, and features like data transparency, real-time information sharing, context awareness, and resulting process clarity, facilitate the development of intelligent capabilities for production planning and control. This includes automated data collection and adaptive scheduling at the shop floor level. Optimized and intelligent production is widely accepted as a facilitator for sustainable production (Tsai et al., 2020).

- *Manufacturing Agility (MANA)*: The integrated, decentralized, and interactive production ecosystem under Industry 4.0 provides the necessary agility for manufacturers to effectively address environmental uncertainties (Braccini & Margherita, 2019; Müller et al., 2018). Industry 4.0 also enables supply chain partners to quickly and cost-effectively adjust the product processes and necessary adjustments while optimizing social and environmental impacts.

- *Productivity and Efficiency of Manufacturing (MAPE)*: Industry 4.0 enhances the productivity and efficiency of manufacturing systems through technological development and improved connectivity (Jena et al., 2020). Automation of production, process monitoring, and supply chain oversight lead to higher equipment reliability, reduced machine downtime, optimized inventory, and improved employee engagement (Ivascu, 2020). These conditions promote manufacturing profitability and environmental sustainability (Kiel et al., 2017; Jacobs, 2020).

- *Serious Employment Opportunities (NEEP)*: Digital transformation under Industry 4.0 significantly increases the complexity of manufacturing systems (Bag et al., 2020). Despite the undeniable job losses due to automation, Industry 4.0 creates new types of jobs that previously did not exist. Manufacturers investing in digital transformation have no choice but to add new professional job positions, such as software engineers, IT specialists, and operators of new machinery, to their workforce (Gualtieri et al., 2020). If adequately managed, new job opportunities under Industry 4.0, can reduce employment and income inequality (Sung, 2018).

- *Resource and Energy Efficiency (REEE)*: Resource and energy efficiency are at the core of Industry 4.0, as innovative technologies underpin real-time monitoring of energy and resource consumption across the supply chain (Bonilla et al., 2018). At the smart factory level, machines equipped with sensors, machine controllers, smart production execution systems, and cloud-based energy management systems enable continuous and real-time resource and energy consumption monitoring, reinforcing long-term sustainability (Nascimento et al., 2019; Ren et al., 2019).

- *Reduction of Manufacturing Costs in Industry 4.0 (REMC)*: Opportunities for savings in manufacturing costs include 24/7 automated production, increased production volume, improved product quality, greater precision in manufacturing, reduced production errors, and enhanced equipment effectiveness (Braccini & Margherita, 2019). Reducing manufacturing costs and increasing economic performance allows producers to prioritize and commit better to social and environmental development (Kamble et al., 2020).

- *Safe and Smart Work Environment (SSWE)*: Technologies of Industry 4.0 lead to more intelligent and connected employees (Dalenogare et al., 2018). Smart covers enable employees to acquire the necessary skills to maintain safety and productivity in the industrial environment (van Lopik et al., 2020). Automation and collaborative robots also free workers from non-ergonomic and hazardous tasks (Taylor et al., 2020).

- *Integration of Supply Chain Processes (SCPI)*: Horizontal integration and transforming traditional supply networks into a digital and integrated entity are among the fundamental principles of Industry 4.0 design (Ismailian et al., 2020). Integrated technologies such as the Industrial IoT, service internet, data internet, blockchain, and cloud analytics facilitate the integration of activities, real-time information sharing, integration of physical flows, and financial flow capabilities among resource members (Strandhagen et al., 2020). The integrated supply chain process and its features, such as collaborative knowledge management, product development, product planning, demand planning, and decision-making initiatives, provide significant economic and environmental development opportunities (Ding, 2018).

- *Sustainable Product Development (SUPD)*: Sustainable product development (SUPD) heavily relies on resources, information, and technologies from Industry 4.0. SUPD supports facilitating life cycle assessment approaches for new product development

(Leng et al., 2020). Digital twin technology and simulation of the entire life cycle of a product transform the ideation phase of SUPD (Tao et al., 2018). Furthermore, computer-aided design and high-efficiency computational methodologies enhance the effectiveness of SUPD (Dev, 2020). The development phase, which is crucial, is further promoted by smart manufacturing features, as Industry 4.0 enhances the commercialization phase of SUPD due to its efficiency and productivity capabilities (Lin, 2018).

- *Sustainable Value-Creation Networking (SVCN)*: Creating shared sustainability across value chains requires all value chain members, from the lowest-level suppliers to end consumers, to embrace the concept of sustainability to generate shared value (Kiel et al., 2017). Fortunately, Industry 4.0 and its underlying technologies enable the integration of value chains, allowing all value chain members to collaborate in the joint creation of more sustainable products and services (Ardito et al., 2019). Additionally, Industry 4.0 facilitates the incorporation of environmentally friendly technologies, raw materials, and renewable energy sources into production chains, ensuring that sustainable features are identified throughout the value chains. This way, sustainability benefits are distributed fairly among all value chain members (Ivascu, 2020; Sartal et al., 2020).

Methodology

In this research, we employed a bibliometric approach to review existing studies on the impact of Industry 4.0 technologies on sustainable supply chains. Bibliometric analysis is a quantitative method that helps researchers identify key concepts and trends within a specific field by mapping the intellectual structure and development of the domain. For this purpose, we searched the Scopus database using the following keywords:

- "Industry 4.0"
- "Industry 4.0 technologies"
- "Sustainable supply chain Industry 4.0"
- "Industry 4.0 revolution"

After data extraction, we conducted output analysis similar to previous studies, such as those by Zarei et al. (2023) and Nourahmadi et al. (2021), to uncover trends, patterns, and influential areas. This research follows a three-stage data analysis protocol: (1) dataset setup, including identification, screening, eligibility, and inclusion of relevant studies; (2) dataset refinement; and (3) data analysis from functional perspectives, scientific mapping, and network analysis.

The search was conducted in the Scopus database on October 19, 2024. In the subsequent step, the results of the articles were analyzed using the Bibliometrix package in R. The analysis revealed 3,684 documents related to this topic, of which only 1,746 were articles authored by 8,713 authors.

Table 1.
Descriptive Statistics of the Studies Conducted from 2013 to 2024

Results	Description
	Main Information About Data
2013:2024	Timespan
1141	Sources (Journals, Books, etc)
3684	Documents
51.83	Annual Growth Rate %
2.72	Document Average Age
28.87	Average citations per doc
0	References
	DOCUMENT CONTENTS
8151	Keywords Plus (ID)
6804	Author's Keywords (DE)
	Authors
8713	Authors
391	Authors of single-authored docs
	AUTHORS COLLABORATION
442	Single-authored docs
3.31	Co-Authors per Doc
29.13	International co-authorships %
	Document Types
1746	article
8	article article
3	article book chapter
6	article conference paper
1	article review
61	book
559	book chapter
3	book chapter article
2	book chapter book chapter
2	book chapter conference paper
1	book chapter review
1049	conference paper
6	conference paper article
1	conference paper book
1	conference paper book chapter
3	conference paper conference paper
39	editorial
5	erratum
23	note
4	retracted
156	review
5	short survey

(Source: Researcher's Findings)

The data spans from 2013 to 2024, encompassing 3,684 documents sourced from 1,141 publications, including journals and books. The annual growth rate of publications in this field is notably high at 51.83%, indicating increasing interest in the intersection of Industry 4.0 technologies and sustainable supply chains. The average age of the documents is approximately 2.72 years, with an impressive average citation count of 28.87 citations per document.

Regarding keyword usage, there are 8,151 Keywords Plus and 6,804 Author's

Keywords, reflecting a diverse range of topics within the research area. The research involved 8,713 authors, with 391 of them contributing to single-authored documents. Collaboration among authors is also significant, as evidenced by the 3.31 co-authors per document and an international co-authorship rate of 29.13%.

Regarding document types, the majority of the publications are articles (1,746), supplemented by various formats, including conference papers (1,049), book chapters (559), and reviews (156). The results indicate a robust and collaborative research environment in exploring the implications of Industry 4.0 technologies on sustainable supply chains.

Figure 3.
Important Keywords Used in the Studies

(Source: Researcher's Findings)

Table 3 highlights the most significant keywords frequently used in studies related to Industry 4.0. The term "Industry 4.0" dominates the list with 1,479 occurrences, reflecting its central role in the discourse around modern industrial advancements. Other prominent terms such as "Internet of Things" (250 occurrences) and "Sustainable Development" (210 occurrences) emphasize the importance of integrating emerging technologies with sustainability efforts.

Interestingly, terms like "Supply Chain" and "Supply Chain Management" appear frequently (171 and 91 occurrences, respectively), signifying the increasing focus on how Industry 4.0 technologies are transforming supply chain operations. The keyword "Cloud Computing" (178 occurrences) also indicates the growing reliance on cloud-based solutions to support digitalization.

Additionally, "Decision-Making" (168 occurrences) and "Electronic Transfer" (146 occurrences) suggest a strong interest in how these technologies are enhancing decision processes and data handling in modern industries. This table provides valuable insight into the key focus areas within Industry 4.0 research, highlighting the intersection of technology, management, and sustainability.

Table 2.
The Most Important Keywords Used in the Studies

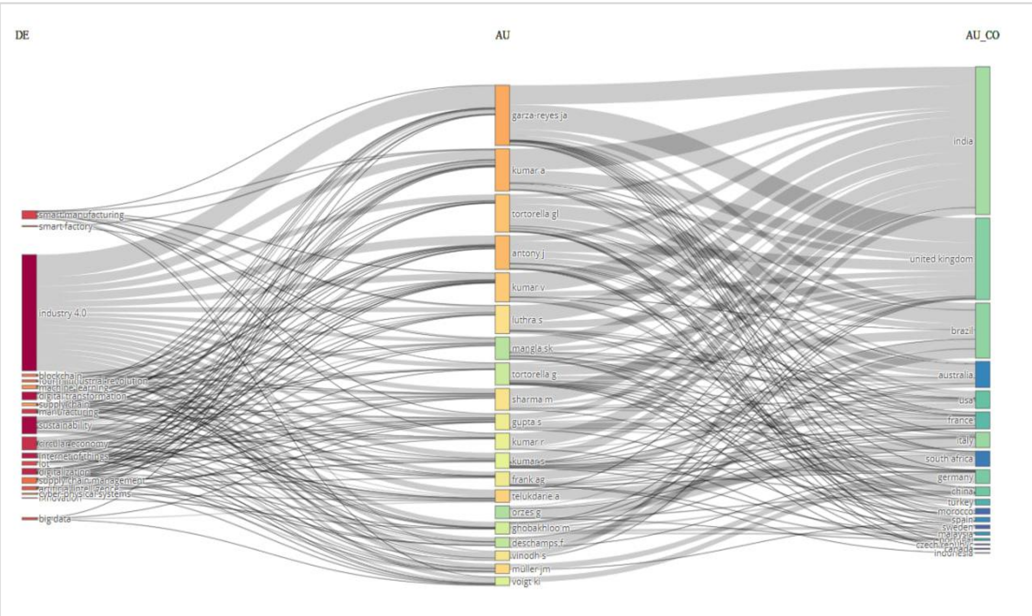
Keywords	Frequency
Industry 4.0	1479
Industrial Revolution 4.0	234
Internet of Things	250
Supply Chain	171
Sustainable Development	210
Cloud Computing	178
Decision-Making	168
Electronic Transfer	146
Supply Chain Management	91

(Source: Researcher's Findings)

Findings

Figure 4 illustrates the relationships between keywords, countries, and authors of the articles. This visualization highlights the interconnection of various keywords, the geographical distribution of research output, and the collaborative efforts among authors from different regions. Such insights can help identify trends and patterns in the research landscape concerning Industry 4.0 technologies and their impact on sustainable supply chains.

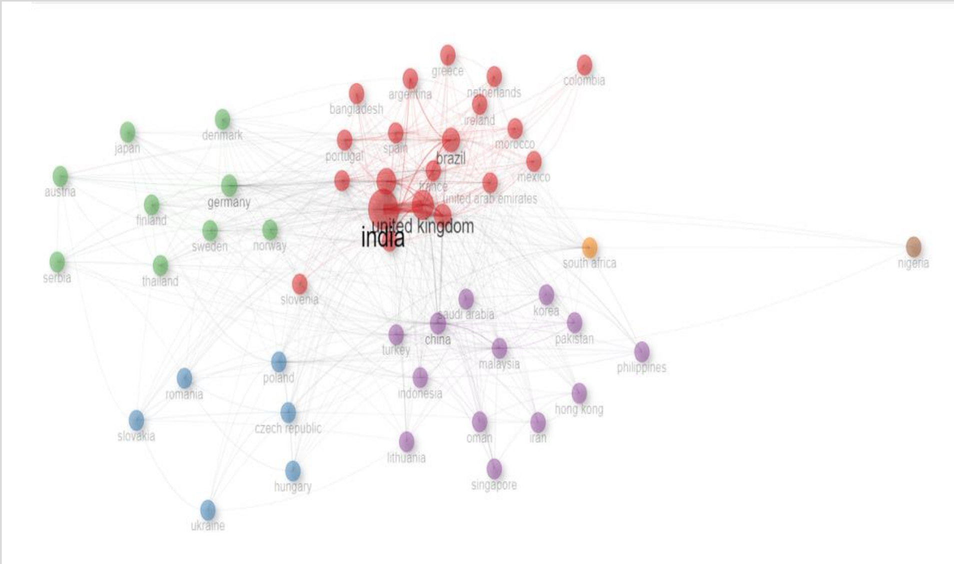
Figure 4.
Network of Communication between Authors, Keywords and Countries Producing Research



(Source: Researcher's Findings)

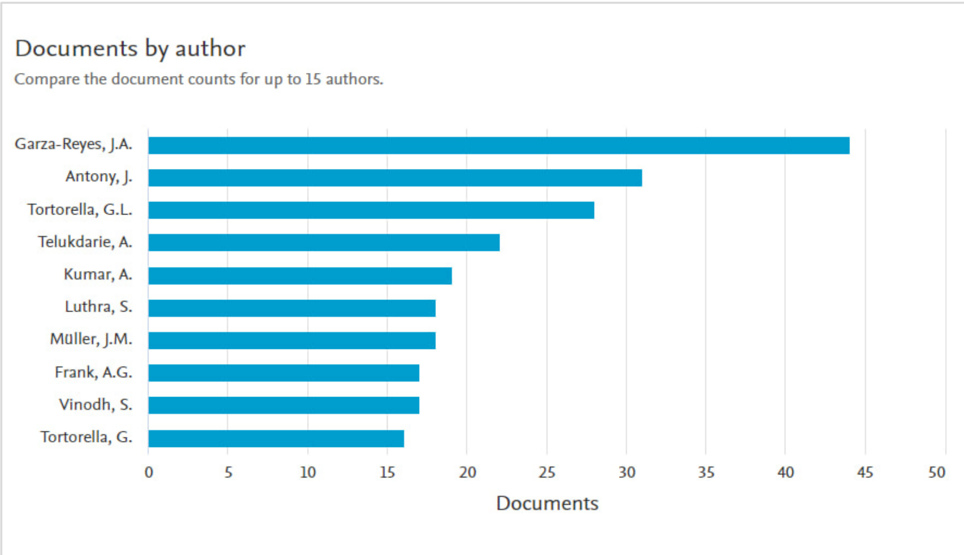
Figure 5 depicts the network of connections between countries with the highest number of published articles. This network visualization reveals the collaborative relationships and research outputs among these countries, illustrating how they contribute to the body of knowledge on Industry 4.0 technologies and sustainable supply chains. It provides insights into global research trends and the extent of international cooperation in this field.

Figure 5.
The Network of Connections between Countries with the Most Studies



(Source: Researcher's Findings)

Figure 6.
Authors with the Most Research

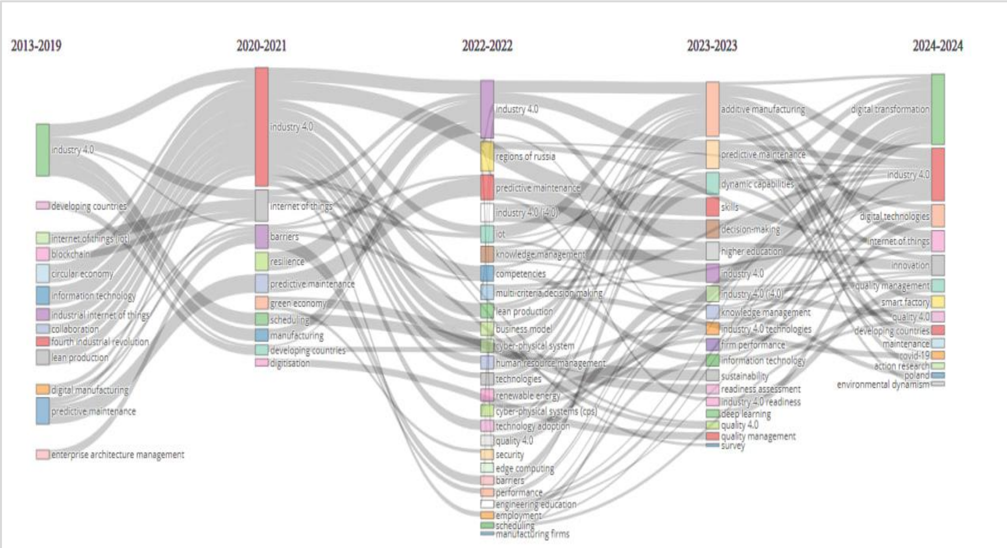


(Source: Researcher's Findings)

As shown in Figure 6, the authors Garza-Reyes, J.A., Antony, J., and Tortorella, G.L. are identified as the leading researchers in the field of Industry 4.0 technologies.

Figure 7 illustrates the evolution of the topic and research over five distinct periods, highlighting the significance of relevant keywords during each period. Notably, in 2022, there is an increased emphasis on Industry 4.0 technologies in conjunction with sustainable supply chains.

Figure 7.
Subject Evolution Over Time



(Source: Researcher's Findings)

Figure 7 illustrates the evolution of keywords in Industry 4.0, leading to several key conclusions:

1. Shifts in Focus over Time:

- *Phase One*: At the beginning of the timeline, keywords such as "knowledge development" and "innovation" were predominant. This indicates that initial attention was directed towards foundational concepts and establishing necessary infrastructures for transitioning into the Industry 4.0 era.
- *Phase Two*: Over time, keywords like "Industry 4.0," "artificial intelligence," and "Internet of Things" have gained prominence. This shift demonstrates a transition in research focus towards key technologies that underpin Industry 4.0.
- *Phase Three*: In later stages, keywords such as "smart manufacturing," "smart supply chain," and "data analytics" emerged as critical concepts. This indicates an increased emphasis on the practical application of Industry 4.0 technologies within production processes and supply chain management.

2. Interconnections between Concepts: The diagram reveals a strong correlation between many keywords. For instance, "artificial intelligence" is closely associated with terms like "machine learning," "neural networks," and "data analytics." This suggests that these technologies are utilized as primary tools to achieve the objectives of Industry 4.0.

3. Emergence of New Concepts: With technological advancements and shifting industry needs, new concepts have also entered the discourse of Industry 4.0. Keywords such as "digital twin," "collaborative robotics," and "cybersecurity" have gained increased importance in recent years.

Table 3.
The Background of the Research Done on Integrating Industry 4.0 (I4.0) Technologies into Supply Chain

Papers	Insights	Conclusions
Investigating industry 4.0 technologies in logistics 4.0 usage towards sustainable manufacturing supply chain (Karishma et al., 2024)	This study shows that I4.0 technologies enhance communication models in Logistics 4.0, influencing subjective norms and attitudes, which drive sustainable practices in the manufacturing supply chain.	I4.0 tech in L4.0 influences subjective norms, attitudes, and behavior control. It also enhances word-of-mouth and purchase intention for sustainability in SC.
Enhancing Sustainable Supply Chain Management through Digital Transformation: A Comparative Case Study (Stroumpoulis et al., 2024)	The study emphasizes that Industry 4.0 technologies enhance communication models, facilitating the integration of digital transformation and sustainability practices, thereby improving supply chain performance and operational excellence.	Digital transformation enhances sustainable supply chain management effectiveness. A holistic sustainability approach improves business performance and market share.
Creating a sustainable future through Industry 4.0 technologies: Untying the role of circular economy practices and supply chain visibility (Junaid et al., 2024)	The study emphasizes that I4.0-Tech enhances sustainable supply chains by improving supply chain visibility, enabling circular economy practices, facilitating real-time tracking, and optimizing resource utilization for sustainability goals.	I4.0-Tech impacts sustainability through SCV and CEP. SCV, CEP, and SUS have a positive relationship.
Harmonizing Innovation - Bridging Industry 4.0 with Supply Chain Sustainability. (Laturkar & Laturkar, 2024)	The study emphasizes that Industry 4.0 technologies enhance supply chain sustainability by improving transparency and traceability. This enables organizations to ensure sustainable materials and fair labor practices, thus fostering consumer trust and loyalty.	Integrating Industry 4.0 and supply chain sustainability benefits businesses. Industry 4.0 enhances transparency, traceability, and brand trust.
Investigating the Role of I4.0 Technology Using Extended Theory of Planned Behavior (ETPB) (Qureshi et al., 2024)	The study highlights that I4.0 technologies enhance communication models in Logistics 4.0, facilitate improved subjective norms and attitudes, and ultimately contribute to sustainable supply chain achievements.	I4.0 technology influences subjective norms and attitudes. It also promotes sustainability in manufacturing supply chain through L4.0 adoption.
Industry 4.0 Technologies: Opportunities in the Sustainable Supply Chain Management (nimal& reddy, 2023)	The study emphasizes that Industry 4.0 technologies enhance communication models, facilitate real-time data sharing and collaboration, which are crucial for optimizing sustainable supply chain management, and improve overall sustainability performance	Industry 4.0 tech aids sustainable supply chain management. SWOT analysis, limitations, and potential are discussed for technologies
The impact of emerging technologies of industry 4.0 on sustainability dimensions (Alnahhal et al., 2024)	The study highlights that I4.0 technologies enhance communication and collaboration in supply chains, contribute to sustainability by reducing waste, and improve efficiency through advanced systems like IoT and NFC.	It demonstrates that emerging technologies enhance sustainability and customer satisfaction. It also argues that challenges might be encountered during sustainability goals' Implementation.
Industry 4.0 Technology-Supported Framework for Sustainable Supply Chain Management in the Textile Industry (Chen et al., 2023)	The study emphasizes that Industry 4.0 technologies enhance communication models in supply chains, enable data-driven decision-making, and facilitate sustainability through improved tracking, traceability, and efficient information transmission in the textile industry.	This study proposes a sustainable closed-loop supply chain for textiles. It also recommends using Industry 4.0 technologies for sustainability.
Challenges for the Adoption of Industry 4.0 in the Sustainable Manufacturing Supply Chain (Hakeem et al., 2023)	The chapter emphasizes the need for effective communication models in Industry 4.0 to address data management complexities, ensuring sustainable supply chain practices through collaboration and technology integration.	It addresses challenges for successful Industry 4.0 adoption. It also prioritizes sustainability, energy efficiency, data ethics, and collaboration.
Nexus of Industry 4.0 and circular economy in solid waste management supply chains: a literature review (Afshari & Gurtu, 2024)	The study emphasizes that Digital technologies enhance communication models in supply chains, improve waste management efficiency and sustainability by enabling better segregation, and reduce environmental impacts of municipal solid waste.	It addresses efficient waste management through digital technologies It also focuses on the reduction of environmental impact and operational costs of waste management

(Source: Researcher's Findings)

The findings of this study further reveal that the successful integration of Industry 4.0 into sustainable manufacturing requires a clear strategy for overcoming technological and organizational challenges. Moreover, the study indicates that while larger manufacturers with greater resources are more capable of implementing Industry 4.0 technologies comprehensively, smaller manufacturers often face obstacles due to limited resources, insufficient expertise, and market instability. Therefore, customized approaches that support smaller firms in adopting key Industry 4.0 technologies, like energy-efficient systems or resource optimization tools, can help bridge this gap. Additionally, the study underscores the importance of cross-industry collaboration, policy support, and knowledge sharing to maximize the potential of Industry 4.0 in fostering sustainable production practices across the manufacturing sector.

Discussion and Conclusion

This study aims to address the knowledge gap regarding the opportunities that Industry 4.0 and the digital industrial revolution may offer for sustainable manufacturing. The findings indicate that Industry 4.0 supports sustainable manufacturing through 15 highly relevant functions, including business model innovation, customer-oriented production, employee productivity, reduction of harmful emissions (air pollution reduction), improvement of production profit margins, smart production planning and control, manufacturing agility, increased productivity, job creation, resource consumption reduction, energy efficiency enhancement, lower production costs, safe and smart working environments, integration of supply chain processes, sustainable product development, and sustainable value-creation networks. The role of each sustainability function is thoroughly explained in the roadmap for the sustainable manufacturing developed in this study. Overall, the results suggest that Industry 4.0 can play a significant role in sustainable manufacturing.

The implications of this research can be summarized as follows: Industry 4.0 and sustainable manufacturing share many common grounds that emphasize efficiency, productivity, continuous improvement, and enhanced customer experience. The results show that Industry 4.0 promotes sustainable manufacturing through a complex, gradual, knowledge-based, and costly mechanism, requiring manufacturers to possess a certain level of technology and knowledge management. Not all manufacturers have the capacity for the digital transformation inherent in Industry 4.0. However, independent technologies within Industry 4.0, such as 3D printers or value-added manufacturing, can still contribute to specific aspects of sustainable manufacturing. Industry 4.0 is a complex and multifaceted phenomenon encompassing various technologies and their applications in an overly interconnected manufacturing ecosystem. Each technological trend in Industry 4.0 offers unique sustainability concepts. For example, 3D printing promotes sustainable manufacturing by providing customized products and facilitating environmentally friendly goods. Conversely, cyber-physical and smart manufacturing execution systems enhance sustainability through increased productivity, resource efficiency, and waste reduction across various industrial operations. Therefore, the outcomes of sustainable manufacturing from Industry 4.0 depend on how manufacturers understand this phenomenon, its underlying technologies, design principles, and sustainability functions. The significant synergy among Industry 4.0 technologies, design principles, and fundamental sustainability functions determines how chain-level digitalization contributes to sustainable development.

Industry 4.0 transforms the digitalization of industrial value creation processes, involving the implementation of modern digital technologies and the development of complex design principles. It is important to note that the digital transformation of Industry 4.0 is a gradual process that offers value partners new ways of value creation and transformation concerning the entire product and service life cycle. For this reason, Industry 4.0 presents significant opportunities for sustainable manufacturing, given that both are related to optimizing the entire product life cycle, value creation, and delivery channels. Sustainable manufacturing is multidimensional, encompassing sustainable development for the economy, environment, and society. It requires the participation of all stakeholders in the joint creation of sustainable value, and the integrated nature of Industry 4.0 enables value chain partners and even customers to converge towards sustainability. The findings suggest that integrating supply chain processes is a step towards sustainable manufacturing within the framework of Industry 4.0, emphasizing value chain thinking for sustainable development.

The social and environmental implications of Industry 4.0 should be viewed through the lens of productive-economic opportunities. Digital transformation suggests that without economic sustainability, manufacturers will lack the freedom to prioritize environmental conservation and social development since the survival of the company remains the only strategic priority. Not all the functions identified in this study are inherently sustainable. Each of the 15 functions has specific potential to empower or support particular aspects of sustainable manufacturing. For example, business model innovation is not inherently environmentally or socially compatible. Business model innovation can enhance environmental sustainability by enabling innovation in green products and processes, or it may contribute to social sustainability by facilitating product personalization and customer-centric strategies. A one-dimensional business model strategy may overemphasize production-economic efficiency and may also worsen the social and environmental sustainability impacts if poorly designed and managed. Therefore, the 15 functions of Industry 4.0 in sustainable manufacturing must be effectively managed based on the specific business environment of each manufacturer, thereby providing a balanced ecosystem of sustainable manufacturing among the triad (economic, social, and environmental).

The theoretical contributions to Industry 4.0 and sustainable manufacturing have been insignificant. Nevertheless, this field is in its embryonic stage, encouraging future research to address the impact of Industry 4.0 on sustainable development empirically. Furthermore, considering the complexity of Industry 4.0, future studies are invited to explore how the technologies of Industry 4.0, their integration quality, and synergy among them may impact sustainability outcomes.

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