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Review

Opportunities of the Technological Trends Linked to Industry 4.0 for Achieve Sustainable Manufacturing Objectives

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Abstract: In this work, we integrate the concepts of Industry 4.0, smart manufacturing, and sustainable manufacturing in a model that provides a conceptual framework for the study of long-term solutions with a high degree of specialization, according to the specific context of each investigation. This study offers a holistic analysis and evaluation of the main challenges facing the Industry 4.0 concept. We also diagnose the current methodological proposals aimed at solving the challenges of Industry 4.0 and sustainability using a systemic review of the literature from the past 5 years. Firstly, we identify 14 technological trends linked to Industry 4.0. Subsequently, the trends are integrated into the proposed model to identify opportunities, evaluating their relationship with three performance areas. This allows the identification of trends that present the greatest number of opportunities in the context of sustainability. The second stage complements the literature review with a descriptive analysis of the studies and discusses the findings. The study concludes that the identified technological trends positively impact Industry 4.0 challenges, helping to achieve sustainable manufacturing objectives.

Keywords: Industry 4.0; sustainable manufacturing; smart factory; circular economy; technological trends

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1. Introduction

Companies and consumers agree that the efficient use of economic resources, social welfare, and the responsible management of natural resources is a priority issue, requiring a profound evolution of supply chains. The current paradigm of the linear economic model (produce–use–throw away) is the main cause of today's challenges. The depletion of natural resources, the collapse of the waste system, or the increase in greenhouse gas emissions that cause climate change require urgent solutions [1]. Therefore, new approaches are required for production systems to become sustainable manufacturers. This model, based on circular economy and sustainability, converts waste into different resources, which are then returned back to the manufacturing process [2]. For sustainable manufacturing models to be profitable and competitive at the market level, they require Industry 4.0 technologies [3]. The central focus of this revolution is smart factories responsible for the circular design of the life of products.

The Industry 4.0 concept is being implemented by the governments of countries such as Germany with "Industry 4.0", China with "made in China 2025", the United Kingdom with "smart factory", and the USA with "advanced manufacturing partnership", among others [4]. Multiple research efforts are examining the Industry 4.0 effect on sustainability, generally focusing on specific issues such as sustainable manufacturing or supply chain management [5]. The sustainable manufacturing concept has evolved over time. According to Moldavska and Welo [6], different authors initially defined the concept as a creation or production of products and services. Currently, the sustainable manufacturing concept covers the entire useful life of the product, not only internal operations [7]. According to Stock and Seliger [8], the Industry 4.0 macro perspective is described by four phases: raw material acquisition, manufacturing, product use, and end-of-life (EOL). The manufacturing phase comprises product development, product engineering, process engineering, and value addition through manufacturing. During the EOL phase and with production waste, materials reuse, remanufacturing, and recycling are sought out [9]. Additionally, authors such as Kerin and Pham [2] consider that remanufacturing increases resource efficiency, reduces waste, and supports cleaner and more sustainable production.

Consumer preferences pressure different state agencies to regulate and control products and the environment. The political wills of different countries converge into measures that seek to balance the interests of producers and consumers and promote or protect their productive capacities. Regulatory frameworks can become entry barriers to developed industrial markets. The sustainable manufacturing enables industries to compete in these hyper-competitive markets.

The corporate governments of companies are obliged to develop lines of action that are perceived as corporate social responsibility. That is, incorporating the sustainability and other trends as elements of its competitive strategy, integrating them through new concepts such as open innovation and user/consumer experience [10]. As a result of redesign, sustainable manufacturing can reduce costs and increase the productive performance of industrial organizations [11]. The manufacturing sector already considers the importance of sustainable practices and promotes a wide range of approaches and tools to improve its performance. For example, recent research by Barletta et al. [12] emphasizes the importance of considering sustainable metrics as a novel framework to classical manufacturing metrics (time, flexibility, and quality); the objective is to investigate the impact of decisions in sustainability.

Within the sustainability framework, it is common to find the circular economy concept, which proposes a productive dynamic with Industry 4.0. The most widely used and accepted definition comes from MacArthur, who states that "circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the EOL concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims to eliminate waste through the superior design of materials, products, systems, and business models". The circular economy comprehensively considers the product life cycle and positively impacts production [13].

Technological trends could be defined as the potential level of a very specific technology based on market behavior, application, viability, and demand, with the potential of disruptive technologies. The accelerated development of new technological trends proposes the idea of a fourth industrial revolution, where the concepts of Industry 4.0, sustainable manufacturing, circular economy, and smart factory integrate a range of tools to support sustainable production processes, managing the information captured in the manufacturing processes of products or service cycles.

Industry 4.0 companies require technologies for monitoring and controlling productive tasks [14], forecasting, and performing automated execution tasks. These technologies expand the possibilities to achieve industry goals, including efficiency improvement and sustainable advancement. Taking advantage of productive resources in search of sustainability is an increasingly recurring goal of companies worldwide, assuming new challenges to comply with standards [15].

1.1. Relevance, Contribution, Limitations, and General Results

This document analyzes and evaluates the challenges identified for the adoption of Industry 4.0 technologies in the context of sustainability. The challenges identified in this study can be useful as a guide for decision makers, since we cover a large part of the potential barriers related to the adoption of Industry 4.0. Researchers have indicated that the implementation of Industry 4.0 is a complex process, and many companies in several countries face problems due to different barriers either in developing and developed economies. Developed economies are forced to continually create programs to promote the transition to Industry 4.0 technologies in order to help companies deal with barriers such as a lack of standards and government regulation. Performing a systemic literature review, we identified the main methodological contributions published between 2017 and 2022 that provide a solution to the nine challenges identified for Industry 4.0 implementation in the context of sustainable manufacturing. Additionally, 14 technological trends were identified and conceptualized. Our research question is what are the technology trends, challenges, and solution methodologies currently used to achieve sustainable manufacturing goals in Industry 4.0?

The main contributions of this study are summarized in the following four points: (1) presentation of the fundamental concepts of Industry 4.0, sustainable manufacturing, circular economy, and their relationship; (2) description of the core components of Industry 4.0, sustainability, and smart manufacturing; (3) identification and conceptualization of the main technological trends related to Industry 4.0, together with a conceptual framework summarized in a comprehensive model Industry 4.0/sustainable manufacturing/circular economy/smart factory onwards (I4.0/SM); and (4) discussion of the main technological trends identified together with the emerging research of Industry 4.0 and its impact based on industry type, research results, and current limitations/challenges of the reviewed methods.

The degree of specialization or technical depth can sometimes bias or dilute the information relevant to this review. Another point to consider when reviewing the articles is the organizational level at which the researchers interact or intervene in the study. For example, it is common to observe a more strategic point of view in higher hierarchies. In contrast, technological and methodological applications are observed in information management levels or operational areas. Furthermore, the scope and considerations of each study become relevant in the review. Some have an internal focus, such as processes or technological architecture, while others look at external factors, such as barriers to market entry, ecological impact, or legal frameworks. Due to space limitations, the review emphasizes the type of research, subgroup, domain that approaches the study, solution methodology, results, and industry type for each of the established nine groups. The systematic literature review is based on the evaluation of sustainable approaches in engineering, mainly methodological proposals focused on Industry 4.0 that analyze physical, chemical, mathematical, electrical, telecommunications, environmental, economic, and other problems framed in sustainable manufacturing.

The main components of the study are the following: (i) analysis of the different technological trends existing in Industry 4.0 with their respective conceptual definitions; (ii) an integrating graph of the I4.0/SM concept; (iii) bibliographic analysis of Industry 4.0 opportunities and challenges; and (iv) literature review of the main methodological approaches offered by sustainable Industry 4.0 technologies in response to the main challenges of the sector.

The review article is structured as follows. Section 1 presents a general introduction to the framework of sustainable production supported by sustainable manufacturing/circular economy/smart factory concepts and their importance for developing of Industry 4.0. Within the topic, different authors define technological trends and integrative concepts that impact Industry 4.0 and sustainability. Next, the study's main contributions, limitations, and general results are disclosed. Section 2 describes the methodology used. Section 3 details our literature review for the evaluation and analysis of the studies considering the proposed conceptual framework. This review focuses on the latest methodological proposals that contribute to developing the Industry 4.0 concept, responding to the sector's main challenges in the sustainability context. Next, a descriptive analysis of the studies is carried out. Section 4 presents the main discussions of the study topic. Finally, the conclusions are presented in Section 5.

1.2. Related Literature

1.2.1. Industry 4.0

The Industry 4.0 concept onwards (I4.0) was launched in 2011 at the Hanover Fair to promote computerization in manufacturing processes [16]. I4.0, also called smart factory, aims to increase factory productivity and efficient resource utilization in real time [17]. The authors [18–20] agree that three dimensions essentially outline the I4.0 paradigm: (1) horizontal integration through the value creation network based on intelligent interconnection between companies and the digitization of modules value creation throughout the life cycle of a product and its accessories, (2) engineering throughout the product life cycle through intelligent interconnection and digitalization in all phases, and (3) vertical integration through interconnected manufacturing and logistics systems [21]. For Szabó-Szentgróti et al. [22], I4.0 should have six fundamental principles: virtualization, interoperability, decentralization, real-time capability, service orientation, and modularity.

Smart interconnection and digitization enable a value-added solution using cloud-integrated information and communications technology (ICT) [23]. I4.0 is mainly represented by cyber-physical systems (CPS), cloud computing (CC), Internet of Things (IoT), additive manufacturing (AM), and other technologies through integrating technologies and seeking completely integrated solutions. In an I4.0 manufacturing system, intelligent interconnection occurs through the application of the so-called CPS that operate in a self-organized and decentralized manner [24,25]. CPS enable of physical/digital interface technologies. CPS exchange data in virtual networks, implement IoT and Internet of Services (IoS), and use human–machine interfaces to interact with human operators [26]. Authors such as [27,28] propose considering the human factor and go further by proposing a framework that emphasizes the increase in operator performance due to the use of I4.0 technologies.

The second part of the I4.0 system is CC, which provides competitiveness in terms of economic operation, speed of service, massive scale of operation, and accessibility, since information can be accessed anywhere in the world [29]. CC is an enabler of network technologies. The third part of the I4.0 system is IoT, which refers to machine–machine interaction without human intervention [30]. Electronic devices connected to the IoT system can be controlled remotely with high precision and efficiency. IoT aims to improve operational efficiency and production performance, reduce machine downtime, and improve product quality [31]. IoT is an enabler of physical/digital interface technologies. I4.0 uses a subset of IoT, called industrial IoT (IIoT), to achieve connectivity, interoperability, and decentralization [32]. IIoT collects big data with variety and complexity, requiring advanced cybersecurity frameworks, among other multiple challenges [33].

The fourth part corresponds to AM or 3D printing technology, a very active area of research and industrial transfer, mainly due to the growing need for sustainable production methods in the manufacturing industry. AM is an enabler of digital/physical process technologies combined with other modern technologies such as CAD, CNC, and simulation software [34]. By dominating conventional manufacturing processes, AM allows manufacturing complex geometries with minimal cost and less effort. AM devices are generally fed with raw materials such as powder, wire, and sheet materials such as metal, concrete, plastic, and human tissue [35]. However, AM still faces many challenges with processing metal-based physical components [36]. Otherwise, common heat sources are laser, electron beam, arc, and friction [37]. AM presents exponential advances in biomedical, medical, construction, energy, aerospace, and automotive areas, among others [38].

Products developed by AM featuring low material and energy waste improved quality by enhancing dimensional accuracy and material properties. This technology involves less human interaction and is environmentally friendly compared to conventional manufacturing [39]. Additionally, it reduces prototyping time and cost, promotes industrial digitalization, synthesizes assembly processes in a single part, etc. Although AM presents significant advances, there are still missing developments in material compatibility, availability of techniques for specific materials, insufficient desirable properties, and unstructured application [40].

In the new ICT I4.0 concept, CPS, CC, IoT, and AM systems dominate the generation of intelligent environments. In recent years, the development of these systems relates to interconnection, interdependence, collaboration, adaptability, and security of computing and communication processes, as well as monitoring and/or control of physical components/processes in different application domains.

Authors such as [41–51] propose technological clusters linked to I4.0 as vertical and horizontal integration systems throughout the value chain. In this study, based on a critical review of the previous authors and considering the fundamental I4.0 design principles, 14 technology trends were identified and conceptualized:

- IoT: Digital interconnection of electronic systems through an internet connection. In this dynamic network, physical and virtual entities have identities and attributes and use intelligent interfaces [52].
- IoS: Continued use of interconnected internet tools over time to create new forms of value for products, seeking to transform or add a service to a product [53].
- Internet of People (IoP): Technological infrastructure interconnected through the internet where people communicate with each other through their own profiles, edited by themselves, generating continuous intercommunication between users [54].
- Internet of Data (IoD): The process of organizing data that emerge from the IoT interconnection, compiling helpful information to manage, store, and process it for later analysis [55].
- CC: Interconnection through a cloud where users can upload, download, and manage relevant data. In the industrial field, it serves for the integration of the supply chain with online access to information [56].
- Big data analytics: Measurements of relevant information from large volumes of data for correct business decision making [57].
- Blockchain: Asymmetric cryptography technology to record and share data. This technology allows data and transactions to be recorded, shared, and synchronized through digital contracts via a distributed network to which its participants have access. Blockchain allows for eliminating intermediaries and storing transactions safely [58].
- Augmented reality (AR): Technology that projects virtual objects onto actual physical environments in the real world. It can provide people with a more realistic and intuitive sensory experience by overlaying virtual objects or blending them with the environment [59].
- Automation and industrial robotics: Use of robotic machines in production processes where humans are replaced by robots, which are more efficient in repetitive manufacturing processes [60].
- Cybersecurity: Procedures and tools that are implemented as a protection layer for electronic information files, generated and processed through computers, servers, mobile devices, networks, and electronic systems [61].
- AM: Manufacturing technologies with common characteristics to manufacture a specific component by adding materials, layer by layer, based on digital data and virtual 3D CAD models [62].
- Simulation and modeling: A set of computational tools that allow studying different systems. In the engineering field, these technologies will enable the generation of virtual models to analyze production systems [63].
- CPS: Evolution of the current ICT, which allows greater interconnection, collaboration, independence, adaptability, security, or usability of all types of objects, processes, or services [64]. CPS monitors physical processes, creates virtual copies of the physical world, and makes decentralized decisions.

- Semantic technologies: Technology capable of developing relationships between data with different formats and sources. This technology makes it easy to obtain data for business decision making quickly and economically [65].

1.2.2. Sustainability

In 1987, the Brundtland report introduced and defined the sustainability concept as a model of economic development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs [66]. Sustainability is a multidimensional concept that encompasses (i) environmental, (ii) social, and (iii) economic dimensions; they form the triple bottom line (TBL) view [51]. Authors such as Zhang and Zhu [67] define sustainability as the search for equitably distributed social welfare within the planet's ecological limits. Sustainability is based on (i) the trend of use, consumption reduction, renewal, and strengthening of ecological resources; (ii) capacity to preserve, develop, and distribute human and social well-being; and (iii) the creation of value and organizational policies of efficiency in the transformation of ecological consumption, balancing costs and revenues in the production and distribution of goods and services. Indicators based on human development and ecological footprint indices are established to meet the criteria.

Barletta et al. [12] proposed a model to determine the sustainable management capacity of businesses. The model variables represent a company's systems with the capacity to influence sustainability, such as manufacturing processes, physical assets, decision support systems, information systems, and organizational skills.

Finally, Rosa et al. [13] established the proximity of circular economy and AM concepts with sustainability. In addition, I4.0 enables the circular economy through its digitization and data analysis processes.

1.2.3. Smart Manufacturing

The concept of the fourth industrial revolution has the smart factory as its central element. The smart factory integrates production with sensors, actuators, computing platforms, communication technology, control, simulation, automation systems, data-intensive modeling, and predictive engineering [68,69]. These systems must guarantee a continuous production flow, improving yield and quality [70,71]. The main objective of the smart factory concept is to make factories highly flexible, intelligent, and dynamic. The emerging paradigms of Blockchain and edge computing as intelligent computing systems promise to address challenges in cybersecurity and scalability. Edge computing is a decentralized computing infrastructure that brings computing and storage capabilities closer to where they are needed [72].

Longo and Padovano [73] correlate the smart factory concept posing challenges to human interaction with automated systems. These authors propose implementing new technologies and discussing the social smart factory concept in a collaborative and interconnected framework of smart devices and operators.

Ravi [74] proposes smart factories for foundry processes. Since foundry processes consume a lot of energy, introducing technologies such as IoT in process monitoring can go a long way to reduce energy costs and improve efficiency.

2. Methodology

The methodology used for analyzing the studies is the systematic literature review (SLR) used by [5,75–81]. This document integrates and relates 14 technological trends linked to I4.0 with three thematic areas: financial (FI), operational (OP), and sustainable (SU).

Following the content analysis method proposed by di Stefano et al. [82], this document, accompanied by the concepts smart factory, sustainable manufacturing, and circular economy, discloses the latest methodological contributions to solve the problems presented by I4.0 technology in response to the main challenges of the sector.

Through SLR, authors such as Machado et al. [83] take sustainability into account. They evaluate the impact of I4.0 and smart manufacturing, identifying positive conceptual links between the technologies. Meindl et al. [84], through SLR, analyze how I4.0 literature in smart concepts has evolved over 10 years (manufacturing, working, supply chains, and product services). Similarly, Kamble et al. [85] used SLR to identify I4.0/sustainable research categories.

Search and Selection of Studies

The main databases used for the search and selection of articles were Springer Link, EmeraldInsight, Science Direct, Wiley Online Library, Taylor & Francis Group, Inderscience Publishers, IEEE Xplore Digital Library, and MDPI. The keyword search method was used to obtain information, using the terms "smart manufacturing technologies", "sustainable manufacturing", "smart factory", "digitalization", and "digital transformation". The terms were supplemented with "Industry 4.0" to broaden the search. Other keywords used were "Internet of Things", "intelligent factory", "cloud computing", and "cyber-physical systems" since some authors use them as synonyms for I40.

We carried out a scientific SLR of research published between 2017 and 2022, following the guidelines of the PRISMA declaration [86,87]. Figure 1 summarizes the proposed PRISMA methodology.

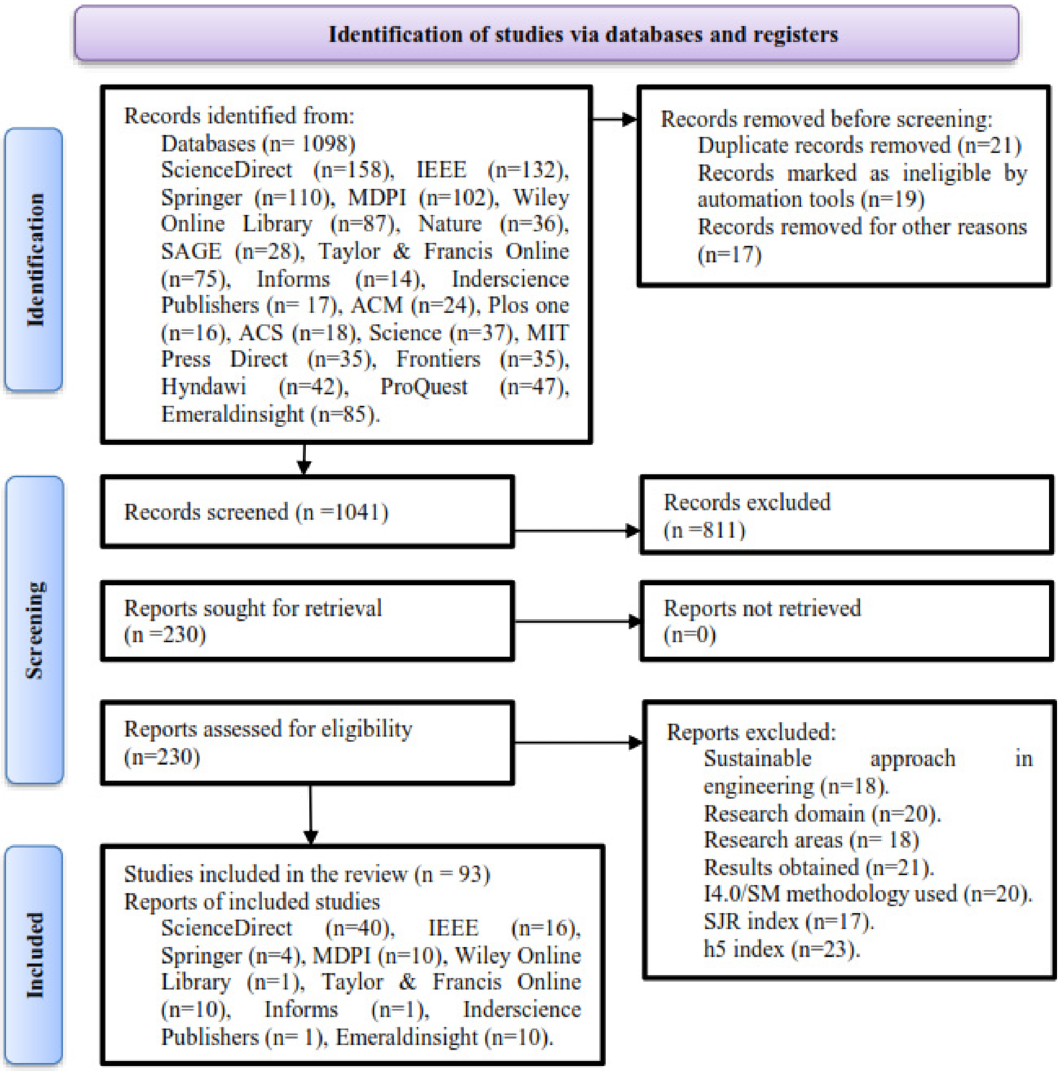

Figure 1. PRISMA flowchart at three levels.

The following exclusion criteria were considered when choosing articles: all articles must directly answer the research question. In addition to choosing an article, two types of quality measures were considered: SJR index $\geq$ 0.4 [88] and h5 index $\geq$ 40 [89]. For the selection, each of the articles belonging to SLR were reviewed and selected in WOS (www.webofknowledge.com), Scopus (www.scopus.com), and Google Scholar, preferably with a high impact factor. The authors of this article used the R-package for bibliometric analyses and the VOS viewer for keywords analysis. Only articles written in English were considered in this study. All selected articles must address the I4.0/SM domain of interest.

As a result, 1098 articles were identified in the first step. In the second step, the most relevant titles were selected. In the third step, the summaries were read. The fourth and last step consisted of a complete reading of the article (Figure S1). After this, the articles were reviewed according to the exclusion criteria. Finally, 93 articles formed part of the SLR.

3. Evaluation and Analysis of the Studies

Figure 2 represents the conceptual framework of this study. This conceptual map is based on previous studies published in Zamorano et al. [90]. The schematic representation integrates the technological trends linked to I4.0 and the smart factory, sustainable manufacturing, and circular economy concepts. I4.0 requires smart factories where the management of internal and external operations are framed in the sustainable and circular design of the life cycle of their products. This new production system is led by the concept of sustainable manufacturing, where all processes must have an interrelationship and positive impact between the dimensions that make up the TBL vision.

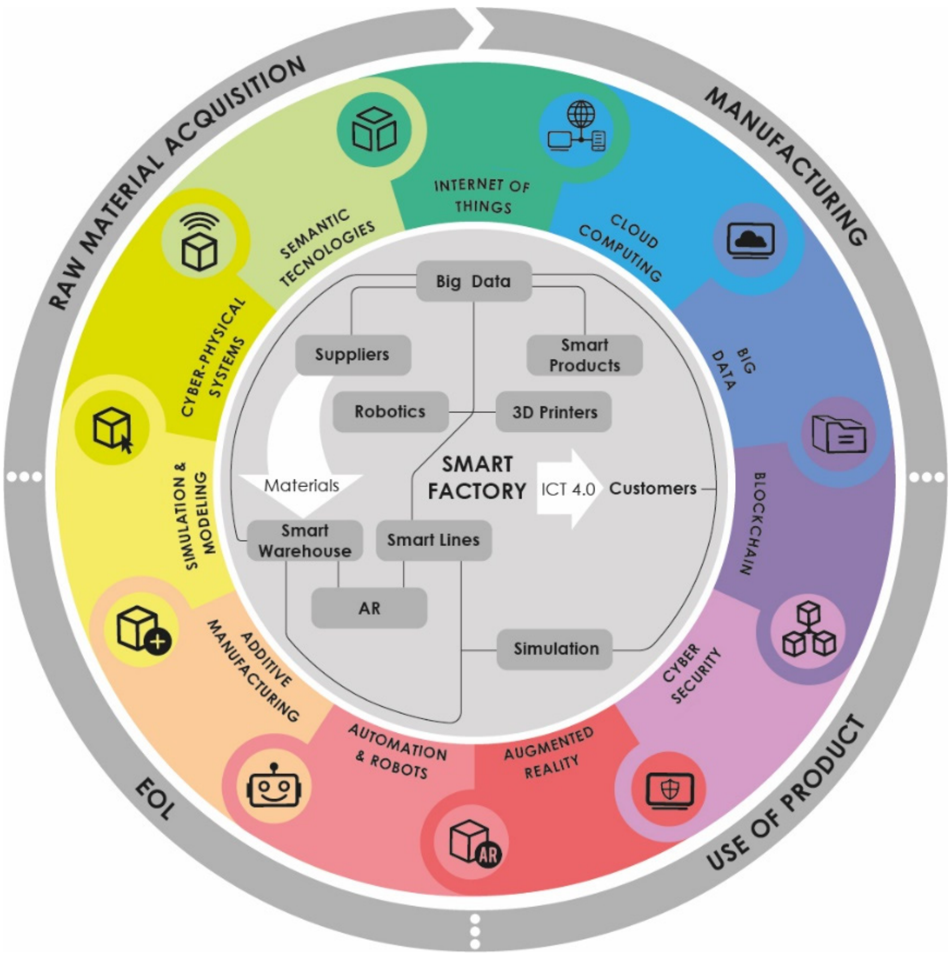

Figure 2. Conceptual framework—I4.0/SM integration model.

The outer ring represents the product life cycle. The arrow marks the direction of the continuous process, where the cycle's stages define some limits. A continuous cycle is featured to optimize ecological consumption. The concepts of I4.0 and circular economy have been growing in popularity in recent years, becoming essential topics of the current digital era. Most of the research is focused on studying the relationship between I4.0 and productivity, along with the challenges of implementing the circular economy. Recently, some studies have pointed to integrated methodologies such as circular I4.0 [91] and digital circular economy [92]. The research aims to assess the link between I4.0 and circular economy [64,93,94]. Implementing integrated I4.0/circular economy models still presents technological challenges in the smart factory. In this context, I4.0 can boost the circular economy through online monitoring of production processes; optimization of resources used in industrial systems; tracking, status, location, and composition of raw materials, products, and parts; scheduling of preventive and predictive maintenance; updating of digital products; product recovery strategies; and remanufacturing, among other characteristic areas of study [95,96].

Inscribed on the inner ring are the 14 new technological trends identified in this review, which make up the drive for the I4.0 model. The trends are transversal and can constitute different interconnected layers for any stage, type of product or service, or level of productive activity.

Inside, a general smart factory scheme is proposed, where technologies are integrated to automate and optimize the production process. Its interconnections graph the flows of information and data that are generated, interpreted, or transformed to produce smart manufacturing of products.

A critical node in big data where the largest number of information flows converge, business activities are supported in the cloud layers for data processing and analysis. This node generates demand forecasts in the different stages, product failure analysis, customer satisfaction estimation, or optimized logistics routes. Through different technologies, a smart factory seeks to exploit the interconnection and collaboration of all the links, managing the information obtained from intelligent entities and processes (suppliers, production lines, laboratories, logistics, products, and customers) to permanently improve energy efficiency, sustainability, and profitability.

In the past decade, I4.0 technological advances have become increasingly significant, developing new and promising technologies and applications. The conceptual and technological framework of the original I4.0 concept has undergone significant changes. To remain competitive, the transition to the new I4.0 generation will depend on the successful uptake of a new set of emerging enabling technologies. These technologies originate from different disciplines, including artificial intelligence, 5G/6G, and quantum computing [97].

3.1. Opportunities from Technological Trends Linked to I4.0 in the SM Context

Nineteen selected publications were reviewed and evaluated according to the specifications described in Section 2 to identify research and development opportunities. As an additional approach, the authors analyzed and discussed each of these publications in terms of their contribution to technology trends. To ensure the quality of the 19 studies, we considered the SJR index, with 89% of the articles belonging to quartile 1. Subsequently, the content of each publication was analyzed and classified, considering the three thematic areas: FI, OP, and SU proposals (Table 1). The aim of this article is not to evaluate sustainable performance criteria. However, all articles belonging to the SU subject area should discuss analytical implications considering the correlation between the three multidimensional perspectives: economic, social, and environmental, and their interrelation with I4.0 technological trends.

Table 1. Classification of opportunities.

		References																		
Technology Trends	**Areas**	[98]	[99]	[100]	[101]	[102]	[45]	[103]	[104]	[105]	[2]	[106]	[107]	[46]	[108]	[96]	[13]	[109]	[110]	[111]
	FI																			
AM	OP	√	√	√	√	√	√	√	√		√		√						√	
	SU		√		√	√		√	√		√		√				√		√	
	FI																			
AR	OP	√	√				√		√				√							
	SU		√						√				√							
	FI																			
Automation and industrial robotics	OP	√	√						√				√						√	
	SU		√						√				√						√	
	FI															√			√	
Big data analytics	OP	√	√	√					√				√			√		√	√	
	SU		√						√				√			√	√		√	
	FI													√						
Blockchain	OP		√				√		√					√						
	SU						√							√						
	FI												√						√	
CC	OP	√	√	√	√	√			√				√			√			√	√
	SU	√	√		√	√			√				√			√			√	
	FI																			
CPS	OP	√		√	√	√				√	√	√	√		√	√	√	√	√	√
	SU			√	√							√	√			√			√	
	FI																			
Cybersecurity	OP	√	√				√		√											
	SU		√						√											
	FI																			
IoD	OP																			
	SU																			
	FI																			
IoP	OP																			
	SU																			

Table 1. *Cont.*

		References																		
Technology Trends	**Areas**	[98]	[99]	[100]	[101]	[102]	[45]	[103]	[104]	[105]	[2]	[106]	[107]	[46]	[108]	[96]	[13]	[109]	[110]	[111]
IoS	FI																			
	OP	√		√																
	SU																			
IoT	FI						√					√							√	
	OP	√	√	√	√	√	√		√	√	√	√	√			√	√	√	√	√
	SU		√	√	√	√	√		√		√	√	√			√	√		√	
Semantic technologies	FI																			
	OP																			
	SU																			
Simulation and modeling	FI																			
	OP	√	√										√				√			
	SU		√										√				√			

The number of research opportunities found in the FI and OP thematic areas confirms the growing interest in developing I4.0 technologies. The importance given by researchers to digital transformation processes aimed at updating traditional supply chains is evident. These methodological developments are mainly framed in the thematic OP area. However, FI and OP are not discussed due to the thematic focus of this study. According to the study phenomenon, the SLR evaluation and analysis will focus on the SU area. Table 1 shows that I4.0 presents broad methodological approaches regarding SU, occupying the second position in research opportunities. The review of articles in the three areas showed that 83 mentions belong to OP, 55 to SU, and 8 to FI.

The technologies with the greatest number of mentions in the SU area correspond to IoT, AM, CC, and CPS technological trends. The IoT technology trend received 31 mentions, of which 12 belonged to SU. The technology trend AM received 20 mentions, of which nine belonged to SU. The CC technological trend presented a similar distribution with 20 mentions, of which eight belonged to SU. Finally, the CPS technology also obtained 20 mentions, of which six belonged to SU.

In the 19 selected works, there were no mentions for the SU area in the technological trends IoP, IoD, and semantic technologies. Only two SU mentions were obtained in IoS technology. The previous topics presented the greatest gaps and opportunities for SU investigative work. Additionally, automation and industrial robotics technology received ten mentions, of which four belonged to SU. AR received eight (with three SU), seven for simulation and modeling (with three SU), seven for Blockchain (with two SU), and seven for cybersecurity (with two SU).

3.2. Literature Review

In an increasingly globalized world, technological trends linked to I4.0 play a fundamental role in responding to the new sustainable challenges in manufacturing. Therefore, it is essential to investigate new opportunities to meet these challenges. Based on the analysis in Section 3.1, this literature review expands the information on the four main technological trends IoT, AM, CC, and CPS (subgroups). The subgroup technologies were selected considering the information in Table 1 (more research and development opportunities).

Authors [112,113] classify and discuss challenges identified for I4.0 implementation. These challenges were selected, analyzed, and discussed based on the experience and knowledge of each author of this study. After selection, they were classified into eight groups representing the technological, business, and political challenges identified for I4.0. The SLR objective is to know the methodological trends of each subgroup and solve the challenges identified in I4.0 (groups) in the sustainable context. The SJR and h5 index quality indices and the number of citations are automatically estimated and determined using the Scimago Journal Rank and Google Scholar Metrics software. Table S1 shows a detailed summary of the studies that are part of SLR.

3.2.1. Information Technology Security Issues

For Kumar et al. [114], the information technology security risk is the challenge with the greatest impact on implementing I4.0. I4.0 requires the construction of global network lines to connect machines, factories, and warehouses; this online integration will lead to security breaches and data leakage [112]. According to Laghari et al. [115], cyber theft is another dangerous threat. Big data cybersecurity in I4.0 is not an individual problem, becoming an enabler for I4.0 to continue to grow. Cybersecurity should be seen within I4.0 as a protection mechanism and a key differentiating element for competitiveness and business continuity [116]. Table 2 shows the methodological proposals to solve information technology challenges in the I4.0/SM context.

Table 2. SLR—information technology security challenges.

Study Domain	Solution Methodology	Result	Industry Type
Industrial monitoring and control [117].	Blockchain architecture.	Enhanced cybersecurity in IIoT sensors.	Manufacturing
Blockchain as an enabler of trust and security [118].	SLR.	Cybersecurity applications.	Manufacturing
Detection of botnet attacks and distributed denial of service [119].	N-BaIoT Method.	97% accuracy under a single attack, decreased false alarms and detection times.	-
Network architecture for interoperability and security issues [120].	Functional interoperability between IIRA and RAMI4.	Complementary coexistence in end-to-end IIoT solutions.	Manufacturing
Security and privacy in SF [121].	Blockchain architecture.	Improvements in privacy and security.	-
Security and privacy issues in autonomous vehicles [122].	SLR.	Blockchain/autonomous vehicles integration architectures.	Technology
Cyber-attack detection [123].	Kappa coefficient to detect and prevent distributed denial of service attacks.	97% accuracy under a single attack, 94% under multiple attacks.	-
Cyber-attacks on SCADA [124].	Random subspace and random tree.	Optimization and reliability in classification.	Manufacturing
Security and privacy risks in social networks [125].	Opinion mining, support vector machine, latent Dirichlet allocation, and textual analysis.	Data collection	Telecommunications
Cyber-attack detection [126].	Decision tree, random forest, and extreme gradient magnification.	High-precision attack recognition and fault diagnosis.	Manufacturing
Blockchain-based computer security framework [127].	Multi-signature and efficient storage technique.	Security guarantees without certificates.	Different industries
Critical IoT/IIoT infrastructure [72].	Secure and scalable Blockchain/edge computing convergence.	Layered architecture for critical IoT/IIoT infrastructures.	Different industries
Blockchain architectures for cybersecurity [128].	SLR.	Solutions, applications, advantages, and disadvantages.	Different industries

According to Table 2, the methodological solutions include nine research articles, three literature reviews, and one case study. The IEEE ACCESS journal makes the best contributions with four studies. Regarding the SJR quality index and h5 index, the highest correspond to the journal *IEEE Communications Magazine* with 2.82 and *IEEE Access* with 233. The most referenced article was Meidan et al. [119], with 586 citations. The industry with the greatest methodological advances was manufacturing, with five studies. Blockchain architectures and decision trees made the biggest contributions to the methodological proposals. The largest number of subgroup contributions is eight and corresponds to IoT.

3.2.2. Reliability and Stability for Machine-to-Machine (M2M) Communication

M2M refers to direct communication between devices using any channel, wired or wireless. Such communication is achieved by having a remote machine network that transmits information to a data center. M2M provides wireless communication between information centers and machines [129]. Table 3 shows the methodological proposals to solve the M2M challenges in the I4.0/SM context.

Table 3. SLR—M2M challenge.

Study Domain	Solution Methodology	Result	Industry Type
Blockchain technology in M2M electricity markets [130].	Test implementation.	Successful implementation of Blockchain technology to facilitate M2M interactions.	Chemistry
Communication protocol [131].	Secure and lightweight authentication protocol for M2M communication.	More secure protocol with less computation and communication overhead.	Manufacturing
Work-in-process alert system [132].	Historical data analysis, buffer control algorithm.	Real-time control system for work-in-process management.	Electronics
Communication protocol [133].	Hermes protocol for M2M communication.	Adjustment of the protocol and reduction of the percentage of error.	Electronics
Summary of existing M2M wireless technologies [134].	Content analysis.	Framework for organizing M2M approaches and technologies (trends, future directions, and open problems).	Different industries

According to Table 3, the methodological solutions include four research articles and a literature review. Regarding the quality index SJR and h5 index for both cases, the highest correspond to the journal *Applied Energy* with 3.04 and 203. The most referenced article is by Sikorski et al. [130], with 623 citations. The electronics industry presents the greatest methodological advances with two studies. The number of articles found was low, which indicates a lack of methodological proposals to overcome this challenge. The largest number of contributions to the subgroup is three and corresponds to IoT.

3.2.3. Integrity of Production Processes

I4.0/SM is considered a new industrial stage, where the integration of vertical and horizontal manufacturing processes and product connectivity helps companies achieve higher industrial performance [135]. Emerging and disruptive artificial intelligence technologies and information technology advances enable ever-higher production efficiency levels by managing vulnerabilities. They also have the potential to dramatically influence sustainable manufacturing development [99]. Table 4 shows the methodological proposals to solve integrity challenges in the I4.0/SM context.

Table 4. SLR—integrity challenge.

Study Domain	Solution Methodology	Result	Industry Type
Contribution in emerging countries of I4.0 technologies [135].	SLR.	Perception of I4.0 and its relationship with benefits.	Manufacturing
Relationship between sustainable manufacturing practices and sustainable performance [136].	Qualitative method.	The manufacturing process impacts the improvement of sustainable performance.	Manufacturing
Connection between circular economy and I4.0 [137].	Principal component analysis and DEMATEL.	Artificial intelligence as a main enabler of circular economy.	Different industries
Integration of emerging technologies I4.0 with circular economy [93].	Qualitative method.	Circular economy model for the reuse of waste.	Different industries
I4.0 technologies facilitating sustainable development [99].	Hesitant fuzzy set, cumulative prospect theory, and VIKOR.	Mobile technology and nanotechnology have greater impacts on sustainability.	Electronics, food, textiles

Table 4. *Cont.*

Study Domain	Solution Methodology	Result	Industry Type
Use of virtual reality and AR technologies in remanufacturing [2].	SLR.	Automation in remanufacturing processes.	Different industries
I4.0 technologies for waste collection [138].	Vehicle routing problem.	Optimum waste allocation and collection.	Collection services
I4.0 technologies for sustainable manufacturing [107].	Qualitative method and DEMATEL.	Hierarchy and identification of challenges.	Different industries
I4.0 technology disruptions in the supply chain [139].	Systematic synthesis of technologies.	Identification of technologies and lines of research.	Different industries
Relationship between lean tools and techniques and I4.0 technologies [140].	Content analysis	Identification of facilitated lean practices I4.0.	-
I4.0 key performance indicators related to sustainable development [1].	Multicriteria analysis.	IoT, CPS, and big data as sustainability facilitators.	-
Impact of I4.0 technologies on purchasing process [141].	Exploratory study of multiple cases.	Collaborative platforms in the purchase process.	Manufacturing
Impact of investments in advanced manufacturing technology on I4.0 [142].	Regression models	Positive impact on SMEs and advanced manufacturing.	Different industries
Identification of the latest achievements and industrial applications in AM [143].	SLR.	Identification of technological trends and new materials.	-
Smart factory model and analysis of key technologies [144].	Content analysis	Hierarchical smart factory architecture at each layer.	-
The role of smart factory in I4.0 [68].	SLR.	Conceptual framework for the categorization of studies.	Different industries
AR lens evaluation in smart factory [145].	SLR.	Model for classification and technological selection.	-
Smart factory implementation [146].	Exploratory model.	Smart factory model based on process innovation.	Manufacturing
Reconfigurable smart factory [147].	Smart factory architecture.	Data-driven reconfigurable manufacturing.	Manufacturing
Relationship between I4.0, sustainable manufacturing, and circular economy [148].	Qualitative method.	Conceptual framework for supply chain management.	-
I4.0 and sustainable manufacturing opportunities at the product and process level [149].	SLR.	Future research directions.	-
Process control with real-time data [150].	Discrete event simulation.	Reduction in delivery times.	Construction
I4.0 technologies for innovative manufacturing [151].	Content analysis.	Service architectures for 3D printing.	Construction
I4.0 technologies for sustainable manufacturing [152].	Vertical integration model.	Increase in performance indicators.	Construction
Reconfigurable manufacturing systems based on I4.0 [153].	Leading visualization method.	Integration framework for I4.0 technologies in reconfigurable manufacturing systems.	-

According to Table 4, the methodological solutions include ten research articles, nine literature reviews, and six case studies. The *International Journal of Production Economics* makes the best contributions, with three studies. Regarding the SJR quality index and h5 index, the highest correspond to the *International Journal of Information Management* with 2.82 and *Journal of Cleaner Production* with 245. The most referenced article is by Dalenogare et al. [135], with 960 citations. The industry with the greatest methodological advances is manufacturing, with five studies. Regarding methodological proposals, we found mainly quantitative and systematic studies that try to obtain integration frameworks between technologies and concepts of sustainable manufacturing, circular economy, and smart factory concerning vulnerabilities in production processes. The highest number of contributions in the subgroup is 12, corresponding to CPS.

3.2.4. ICT Problems—Costly Interruptions in Production

Smart manufacturing plays an important role in I4.0/SM. Typical resources are converted into intelligent objects so they can feel, act, and behave in an intelligent environment [111]. This environment is possible due to ICT. ICT frequently has costly interruptions in SF that directly or indirectly affect the supply chain. In general, ICT-enabled interruptions affect individual productivity and thus decrease organizational productivity. Table 5 shows the methodological proposals to solve the ICT interruption challenges in the I4.0/SM context.

Table 5. SLR—ICT interruption.

Study Domain	Solution Methodology	Result	Industry Type
Study of intelligent manufacturing in the I4.0 context [111].	SLR.	Strategies to enable smart manufacturing.	Different industries
I4.0 issues in SMEs [154].	Review of applied literature.	Identification of deficiencies in SMEs for the adoption of I4.0.	Different industries
Use of I4.0 technologies to manage COVID-19 requirements [155].	SLR.	Identification of I4.0 technologies for supply management and COVID-19 detection.	Pharmaceutical
A reference model for design and improvement of smart factory [156].	Factory design and improvement model.	Dependency of activities, levels of manufacturing control, and software functions.	Electronics
Load balancing and energy scheduling in smart factory [157].	Energy-aware load-balancing programming model based on fog computing.	Optimum load balance.	Different industries
Real-time programming for smart factory based on effort learning [17].	Real-time scheduling-based reinforcement learning.	New model with better efficiency.	-
Reduced manufacturing conversion costs [158].	Define–measure–analyze–improve–control and quality control tools.	Identification and analysis of cost elements.	Manufacturing

According to Table 5, the methodological solutions include two research articles, two literature reviews, and three case studies. Regarding the SJR quality index and h5 index, the highest correspond to the *Journal of Cleaner Production* with 1.94 and 245. The most referenced article is that of Zhong et al. [111], with 1669 citations. The number of articles found was small, which indicates ample opportunities for methodological proposals to overcome this challenge. The largest number of contributions to the subgroup is five, corresponding to CC.

3.2.5. Protection of Industrial Know-How

I4.0/SM requires a workforce with new skills and competencies. With this transformation, knowledge management must connect and transmit information between company departments, facilities, devices, and systems and the workers themselves [159]. Standardization is essential for the adaptation of I4.0 technologies. Understanding the nature, causes, and impacts of collaborative technology trends will allow technologies to be standardized and licensed (patents related to I4.0). Table 6 shows the methodological proposals to solve the technical knowledge protection challenge in the I4.0/SM context.

Table 6. SLR—protect industrial know-how.

Study Domain	Solution Methodology	Result	Industry Type
Perception of knowledge management in the I4.0 era [159].	Qualitative analysis in maintenance activities.	Identification and classification of barriers in knowledge management.	Manufacturing
Accounting and reporting in I4.0 [110].	Qualitative analysis.	Empirical formulation in three levels for reports in I4.0.	Manufacturing
Landscape of IoT technology patents [160].	SLR.	Complete analysis of government patents for the USA, Europe, and China.	Different industries
Intellectual property counterfeiting I4.0 [161].	Qualitative analysis.	Intellectual property protection model.	Different industries

According to Table 6, the methodological solutions include three research articles and a literature review. Regarding the SJR quality index and h5 index, the highest correspond to the *Journal of Cleaner Production* with 1.94 and 245. The most referenced article corresponds to Trappey et al. [160], with 313 citations. The number of articles found was low, indicating the absence of studies to find policies and mechanisms that protect I4.0/SM technical knowledge. The largest number of subgroup contributions is three and corresponds to IoT.

3.2.6. Lack of Adequate Skills to Accelerate the March towards the Fourth Industrial Revolution

Currently, the lack of powerful tools remains a major obstacle to exploiting the full potential of I4.0. In particular, practical solutions that integrate formal and system methods are needed, crucial for I4.0 development [162]. Table 7 shows the methodological proposals to solve the lack of skills challenge in the I4.0/SM context.

Table 7. SLR—lack of skills.

Study Domain	Solution Methodology	Result	Industry Type
Future trends in I4.0 [162].	SLR.	Comparison of technological trends.	Manufacturing
Impact of technological, organizational, and environmental drivers on sustainable manufacturing practices [163].	Qualitative analysis and means of the partial least squares approach to the structural equation modeling.	Environmental pressures and support from management and employees positively influence sustainable manufacturing practices.	Different industries
Development and implementation of a virtual manufacturing system [164].	Design of a three-tier architecture information system.	Bidirectional integration between information systems for innovative and sustainable manufacturing.	Different industries
TBL in I4.0 [51].	Quantitative analysis.	I4.0 contributes positively to the economic, environmental, and social dimensions.	Manufacturing

Table 7. *Cont.*

Study Domain	Solution Methodology	Result	Industry Type
Adoption of I4.0 technologies in 10R advanced manufacturing [92].	Qualitative analysis and theoretical model.	Positive influence of 10R on sustainable development.	-
Promoters of sustainable manufacturing practices [165].	Graph theory and matrix approach.	Evaluation, prioritization, and classification of drivers of sustainable manufacturing practices.	Manufacturing
I4.0 technologies [129].	SLR.	Advances and experiences to enable I4.0.	Different industries
Sustainable manufacturing in a closed-loop supply chain [166].	Game theory and Nash bargaining.	Profit maximization and operational efficiency of the supply chain.	-
Scenarios and prospects of smart manufacturing systems for I4.0 [167].	Content analysis.	Identification of challenges and prospects.	-
Practical solutions for complex human–machine interactions [168].	Multi-layered modular solution.	Positive impact on learning curves.	-
Understanding the concept sustainable manufacturing [6].	SLR.	Inconsistencies in the understanding of the concept.	Different industries
Requirements for designing smart factory systems [169].	SLR.	Approaches and technical supports for smart factory.	-
SM framework powered by big data [170].	Linguistic interval-valued fuzzy reasoning method.	Obtaining the lowest predictive maintenance cost.	Manufacturing
Study of the smart factory concept using bibliometric tools [171].	Systematic literature network analysis.	Research directions and critical areas for smart factory development.	-
Identification of sustainable manufacturing enablers and barriers [172].	Maximum mean de-entropy algorithm, structural equation modeling, interpretive structural modeling.	Comprehensive sustainable framework.	Different industries

According to Table 7, the methodological solutions include eight research articles, four literature reviews, two case studies, and a survey. The *Journal of Cleaner Production* provides the most contributions with three studies. Regarding the SJR quality index and h5 index, the highest correspond to the *Journal of Resources, Conservation, and Recycling* with 2.47 and the *Journal of Cleaner Production* with 245. The most referenced article corresponds to Xu et al. [162], with 1880 citations. The industry with the greatest methodological advances is manufacturing, with four studies. The methodological proposals aim to find sustainable frameworks that identify enablers, barriers, and technologies for developing I4.0/SM. The largest number of subgroup contributions is seven and corresponds to CPS.

3.2.7. Redundancy Threat

Redundancy ensures a system's survival in the event of a failure. It is the ability to simultaneously transmit copies of data packets through multiple wireless links or network paths [173]. A resilient system must have duplicate components (physical redundancy) or more than one configuration for the operating system components (functional redundancy) [174]. Redundancy protocols depend on the network topology [175]. The higher the degree of redundancy, the greater the system resistance. Table 8 details the methodological contributions for solving redundancy challenges in the I4.0/SM context.

Table 8. SLR—redundancy.

Study Domain	Solution Methodology	Result	Industry Type
Redundancy and resiliency in CPS [174].	CPS meta-model and formal concept analysis.	Instantiation of the CPS meta-model.	-
An organizational framework focused on eliminating repetitive routines [176].	Content analysis.	Theoretical framework to analyze I4.0 applications.	Manufacturing
Impact of redundancy in the information technology industry [177].	Multipath TCP.	Increased reliability and latency.	Technology
I4.0 technologies that facilitate digital solutions [178].	SLR.	22 practices for sustainable manufacturing implementation.	Manufacturing
Security function for industrial inclinometers [179].	Open control area network, STM microcontroller.	Redundancy during the positioning process.	Extractive
Network topology with redundancy [180].	Analysis of reliability and natural connectivity.	Reliable and robust data transmission.	Aerospace

According to Table 8, the methodological solutions include two research articles, a literature review, and three case studies. Regarding the SJR quality index and h5 index, the highest correspond to the *International Journal of Production Economics* with 2.41 and *Sensors* with 179. The most referenced article is that of Frank et al. [178], with 1144 citations. The number of articles found was reduced, indicating a need for studies where redundancy is the axis in designing robust, reliable, and fault-resistant systems in I4.0/SM. The largest number of subgroup contributions is four, corresponding to CPS.

3.2.8. General Resistance to Change by Stakeholders

Traditional supply chains that have conventionally produced goods and services for many years naturally resist change. That is, the I4.0/SM implementation process encounters employees unwilling to change the way they work. These employees are reluctant to use new technologies and their associated practices [113]. Table 9 details the methodological contributions for solving the resistance to change challenge in the I4.0/SM context.

Table 9. SLR—resistance to change.

Study Domain	Solution Methodology	Result	Industry Type
Future I4.0 trends [85].	SLR.	Sustainable I4.0 framework.	Different industries
Barriers for I4.0 implementation [113].	Qualitative analysis and DEMATEL.	Identification of barriers in emerging and developed countries.	Different industries
Technology trends I4.0 [181].	Content analysis	I4.0 opportunities and challenges.	Agriculture and manufacturing
Changes in the I4.0 business model [182].	Qualitative analysis.	Key elements of the business model are significantly affected by I4.0.	Different industries
Key resources for I4.0 adoption [183].	SLR.	A theoretical model for identifying key transformation processes in adopting I4.0.	Manufacturing
Mapping of I4.0 technology trends [184].	Semantic relationships.	Shared semantics as a support tool for I4.0.	Collection services
I4.0 integration and environmentally sustainable manufacturing [185].	Content analysis and theoretical suggestions.	Conceptual framework with potential lines of research.	-

Table 9. *Cont.*

Study Domain	Solution Methodology	Result	Industry Type
Contribution of sustainable manufacturing in I4.0 [83].	SLR.	Positive impacts between the concepts of sustainable manufacturing and I4.0.	Manufacturing
Micro-smart factory connection via a digital twin [186].	Factory-as-a-service.	Cost reduction and production inefficiencies.	-
Artificial intelligence in entrepreneurship for I4.0 [187].	Qualitative analysis.	Verification of I4.0 use for social entrepreneurship.	-
Identification of I4.0 practices, cleaner production, and circular economy [188].	Delphi method, best-worst method, and multi-criteria decision making.	Framework for the evaluation and performance guide in the field sustainable.	Manufacturing
Artificial intelligence adoption driven by big data analytics [189]	Via institutional theory and resource-based vision theory.	Institutional pressures on artificial intelligence adoption and how it affects sustainable manufacturing and circular economy capabilities.	-

According to Table 9, the methodological solutions include nine research articles and three literature reviews. Regarding the SJR quality index and h5 index, the highest correspond to the *International Journal of Production Economics* with 2.47 and the *Journal of Cleaner Production* with 245. The most referenced article is by Kamble et al. [85], with 700 citations. The industry with the greatest methodological advances is manufacturing, with four studies. The methodological proposals qualitatively analyze the search of SU frameworks to identify barriers, opportunities, and key transformation processes in adopting I4/SM. The largest number of subgroup contributions is nine and corresponds to IoT.

3.2.9. Job Losses Due to Automated Processes and ICT Controlled Processes

The adaptation of traditional companies to I4.0 generates challenges in the education and development of competencies/skills expected of future employees. The labor market and human resource management will also be subject to change [190]. New government, industry, and training center policies are necessary for future employment in the I4.0/SM era. Table 10 details the methodological contributions to solving job loss challenges in the I4.0/SM context.

Table 10. SLR—job loss.

Study Domain	Solution Methodology	Result	Industry Type
I4.0 impact on employees [4].	Qualitative analysis.	Comprehensive research agenda on the I4.0 impact.	Different industries
Technological implementation and organizational changes [190].	Conceptual framework derived from the socio-technical perspective.	Adjusted organizational structure and new job profiles.	Manufacturing
I4.0 job profiles [191].	Text mining.	Labor profiles and profiles for information management.	Different industries
Skilled labor shortage analysis for I4.0 [192].	Concept study.	Urban production concept.	Different industries
I4.0 challenges [193].	Qualitative analysis and content analysis.	Prioritization of sustainable challenges in the supply chain.	Manufacturing
Impact I4.0 by 2030 [22].	SLR.	Relationship between Keynes's theory of technological unemployment and I4.0.	Different industries

According to Table 10, the methodological solutions include four research articles, a literature review, and a case study. Regarding the SJR quality index and h5 index, the highest correspond to the *International Journal of Information Management*, with 2.77 and 164. The most referenced article is by Luthra and Mangla [193], with 475 citations. The number of articles found was low, which indicates a need for studies where management frameworks are developed to support comprehensive training of human resources in the I4.0/SM era. The largest number of subgroup contributions is six and corresponds to AM.

3.3. Descriptive Analysis of the Studies

This section describes key trends defined based on existing study data. These trends allow us to observe scenarios that lead to new facts. The data were related, organized, and tabulated based on the research question.

Figure 3, using the VOSviewer software, summarizes the main keywords found in the SLR.

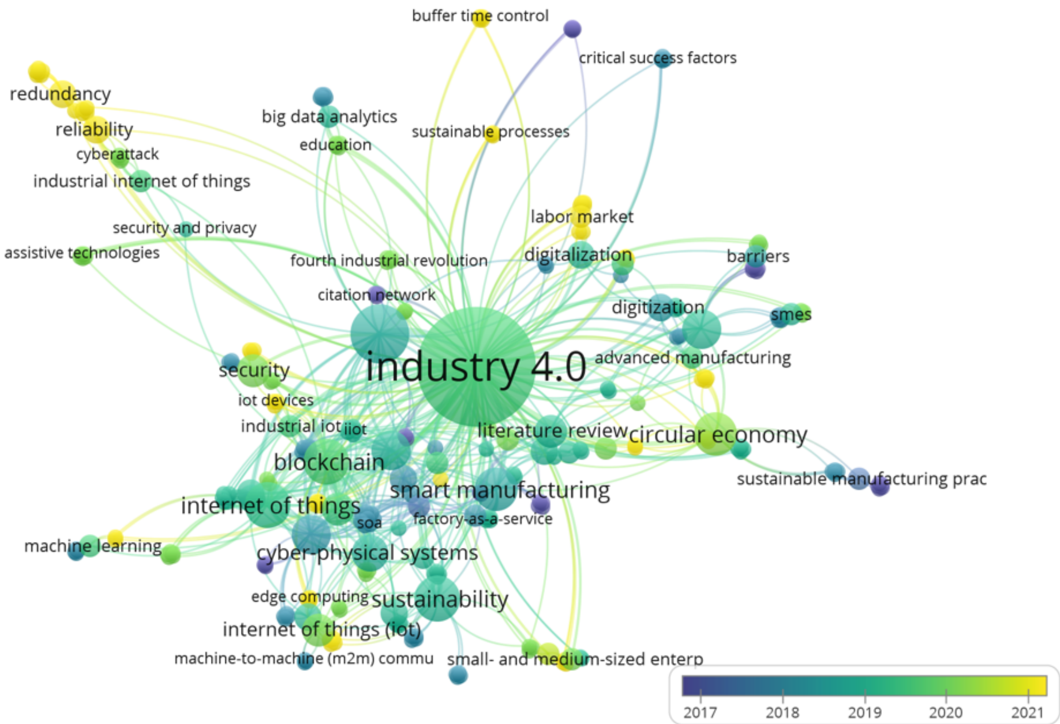

Figure 3. Co-occurrence of the keywords found.

Distribution of publications by study type: Research articles had the most proposals (51 studies), followed by literature reviews (25), case studies (16), and surveys (1) (Figure 4).

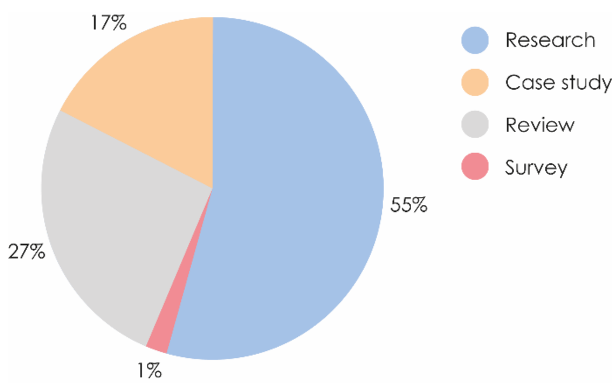

Figure 4. Distribution of study types.

Number of publications per subgroup: A total of four subgroups were used in the literature review. The IoT subgroup made the largest contribution (with 27 studies), followed by CPS (20), CC (12), and AM (8). Nineteen methodological proposals cover all subgroups, and eight proposals did not consider any subgroup but instead cover methodologies for evaluating and analyzing the challenge of the lack of adequate skills to accelerate the progress towards the fourth industrial revolution (Figure 5).

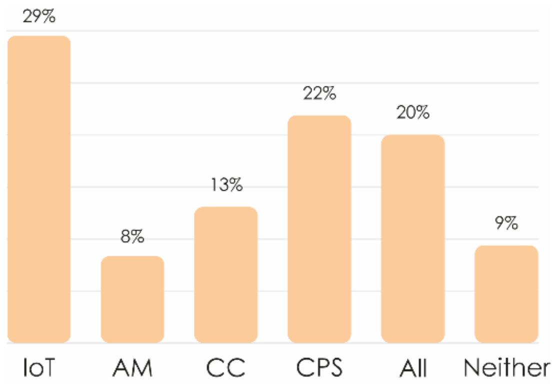

Figure 5. Distribution of studies by subgroup.

Number of publications per year: The research boom of the I40/SM theme is indisputable. In the past five years, there has been a growing interest in new and improved methodological proposals for developing the concept. We found that 21 high-impact articles were published in 2018 and 2020 for the proposed SLR (Figure 6).

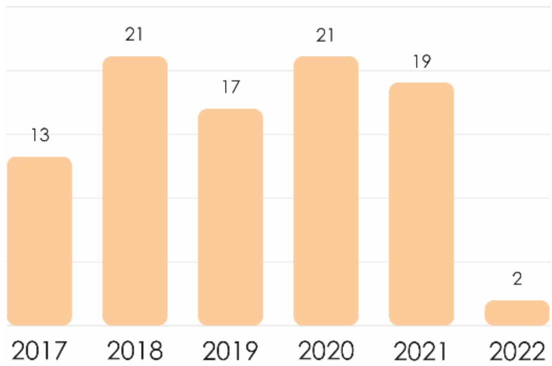

Figure 6. Distribution of studies by year of publication.

Figure 7 shows a positive trend in the sustainable organizational performance area, indicating that this research area is in constant development. The growing interest in sustainable manufacturing topics is a testimony to the relevance of sustainability, as well as the fact that more researchers recognize its importance. The notable increase in interest in the technological trends of IoT, AM, CC, and CPS linked to I4.0 is indisputable.

Number of publications by I4.0/SM challenge type: According to SLR, the integrity of production process challenges presents the highest number of methodological proposals, with 25 studies. The following challenges correspond to the lack of opportunities (15), information technology security (13), resistance to change (12), costly ICT interruptions (7), threat of redundancy and loss of jobs (6), reliability and stability of M2M communication (5), and protection of industrial know-how (4) (Figure 8).

Figures 9–11 show, in order, the distribution trends of the quality measures of the SJR index, the h5 index, and the distribution of the number of citations received by each reference as of 5 February 2022.

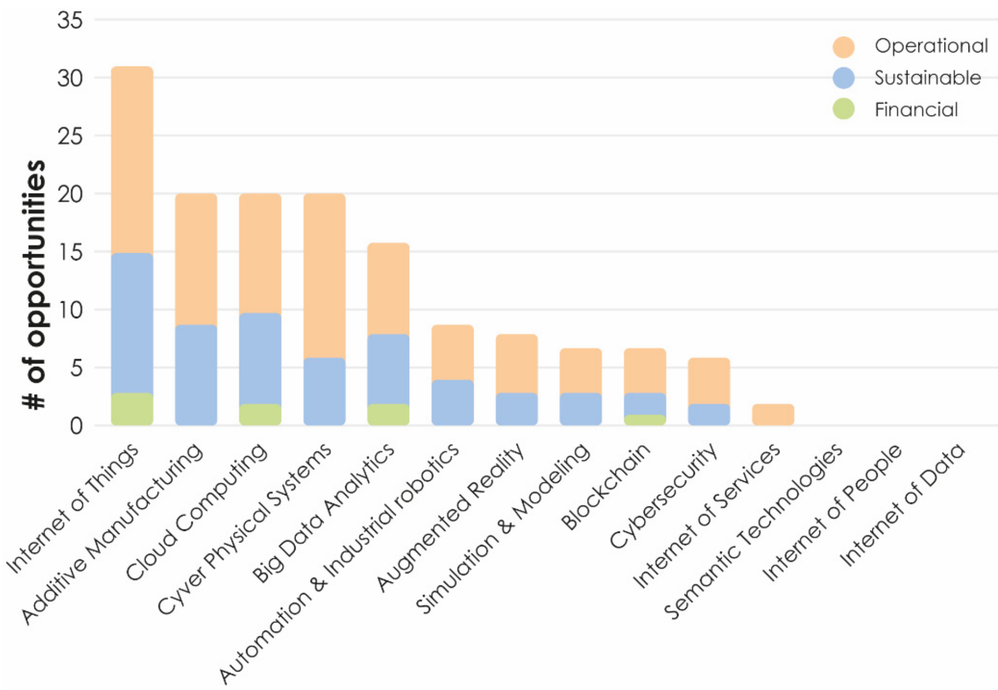

Figure 7. Distribution of opportunities in the areas of organizational performance for each technological trend linked to I4.0.

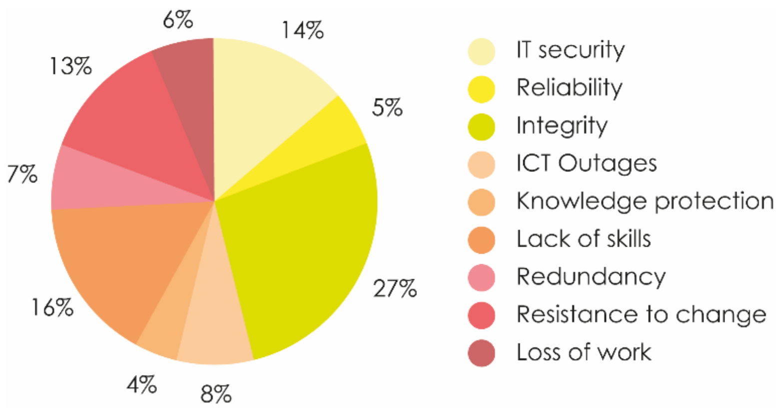

Figure 8. Distribution of studies by type of I4.0/SM challenge.

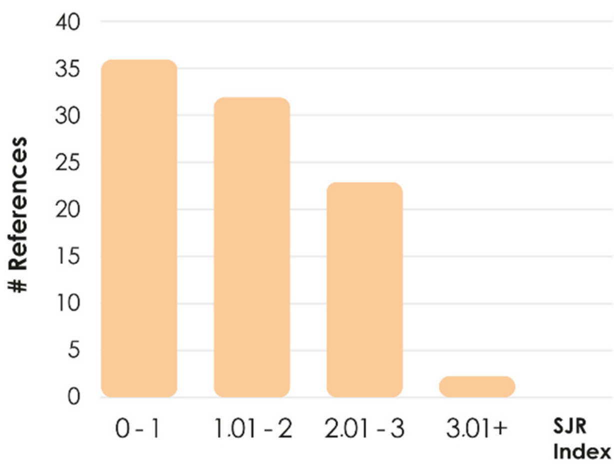

Figure 9. Distribution of the SJR index in SLR.

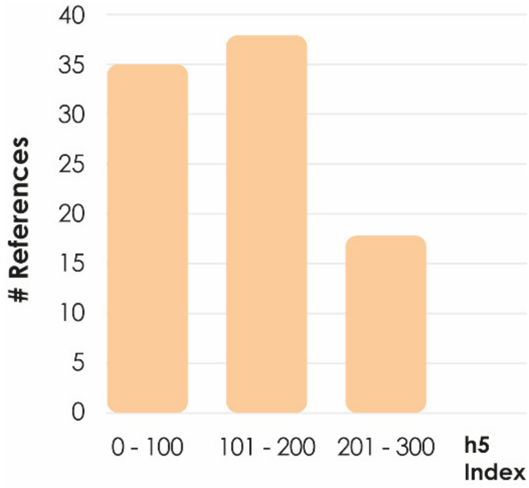

Figure 10. Distribution of the h5 index in SLR.

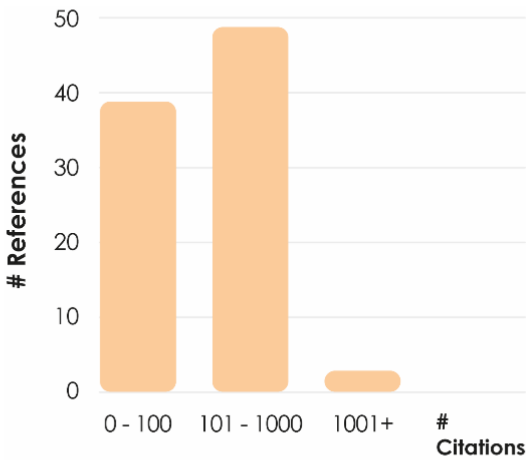

Figure 11. Distribution of SLR references by number of citations.

4. Discussion

Only four out of every ten companies achieved suitable progress in I4.0 implementation, varying significantly in different countries [194]. Most companies have not progressed or have achieved only limited progress due to various challenges in implementing I4.0. Therefore, there is a need for identify the barriers and their relationship, which could help in designing a mitigation strategy and, consequently, can lead to a smoother adoption of I4.0 [195]. According to Raj et al. [113], the lack of a digital strategy together with the scarcity of resources emerge as the most important barriers in both developed and developing economies. Additionally, difficulties arise in the diffusion of I4.0 technological innovation, mainly due to the lack of coordinated public policies regarding I4.0 (lack of standards and government regulation). The adoption of I4.0 requires proper strategic alignment of traditional supply chains to achieve a higher degree of implementation success. According to SLR, to properly allocate technology resources, organizations must capitalize on internal knowledge addressed by roadmaps and strategic planning. In addition, specialized consulting services are required to support decision makers in the allocation of resources.

The descriptive analysis of the studies reveals the accelerated development of new technological trends proposed by the fourth industrial revolution, where the integration of the I4.0/SM concepts provides a range of tools to support companies and manages information captured throughout the product or service cycle. According to the information in Table 1, these trends allow the search for opportunities to respond to sustainable manufacturing challenges.

The evolution towards I4.0/SM requires transforming production systems, moving from traditional factories to smart factories, and from traditional supply chains to digital supply networks. Smart factories and digital supply networks require a high degree of automation, integration, and extensive analysis and information sharing. Our SLR's forecast is at least 10 years to create a full I4.0/SM standard. This length of time may discourage small and medium-sized businesses from upgrading their systems due to their current investments. Transformation to I4.0/SM will require significant investments in new technologies, and the decision for such transformations will need to be made at the CEO level. For decision making, CEOs must rely on the main driving factors identified: expected benefits, market opportunities, labor problems, customer requirements, competition, and image quality.

The findings found in the SLR indicate that studies in I4.0/SM are a relatively new phenomenon, with countries such as India, Italy, and China leading the field (Figure S2). The range of opportunities is vast, but so are the barriers to empowerment.

SLR proposes that I4.0 reduces operating costs through digital integration. However, this reduction must compensate for the high cost of technological implementation; therefore, more comparative cost/benefit studies are required. I4.0 methodological contributions are necessary to evaluate the impact of optimizing supply chains, customer service, sustainable manufacturing, and recycling. Sustainability environmental studies must focus on searching for productive models where the central axes are climate change and the depletion of energy sources. Technologies linked to I4.0/SM have the potential to forecast production and reduce waste losses, distribution logistics, and energy consumption. However, more studies are required to evaluate and analyze the performance of the I4.0/SM in the processes of reuse, remanufacturing, and recycling of materials. Accordingly, conceptual frameworks are needed to allow common acceptance of 3R products (reused, remanufactured, or recycled). The conceptual definition will allow the implementation of commonly accepted legal frameworks among countries, companies, and consumers. Similarly, new 3R design tools or concepts, widely accepted and adopted by the industry, are required. These tools should use I4.0 technologies to optimize product life cycle design. Otherwise, new economic models are needed to incentive market demand, resulting in a basic 3R product offer. In addition, new integrated I4.0 models are required to optimize 3R circular manufacturing processes. Effective 3R management through I4.0 technologies will enable the successful integration of the circular economy and sustainable manufacturing concepts. Finally, I4.0 reverse logistics models are needed to achieve supply chains that foster the circular economy. Such integrated models close the circle of sustainability.

Future studies should focus on developing I4.0/SM integration frameworks capable of forming intelligent production networks that benefit from sharing resources, information, etc. In addition, it is necessary to address security protocols that, through I4.0, allow the sustainable management of chemical compounds considered dangerous or prohibited, using existing techniques such as detection, control, and monitoring analysis.

The development of the I4.0 concept is in full swing, but has various obstacles to overcome. The idea initially proposed a degree of automation to support productive human work. However, it has evolved, introducing technological applications that pose a degree of automation that replaces people in production processes in some areas. This is reaffirmed by SLR; the findings indicate that there is a limited existence of integral research plans that address the challenges related to the I4.0 impact on the future of employees/jobs.

The automatization and digitalization demanded by I4.0 result in simple, fast, and optimized supply chains, resulting in changes in production models. These new models have an impact on everything related to the labor market. I4.0 requires the comprehensive training of a qualified workforce in the areas of automation, data analysis, and artificial intelligence, being indispensable for companies to invest in professional development (intellectual capital of the organization).

Being aware of market changes is essential to understanding the importance of digital transformation. Traditional supply chains that cannot adapt to the digital era may cease to exist in the short term. Digital transformation processes must be continuous, involving the adaptation of the company's culture to new technologies. It is not just a matter of choosing new technologies or automating processes, but a considerable change in the way of thinking and the concepts of the company and its people.

I4.0 requires government policies to operate in different countries, but these legal frameworks that enable the use of technologies require integral business–society models to be approved. Therefore, I4.0 technology plays an important role, the key points being integration and collaboration as principles for new market trends. As soon as people understand the impacts of I4.0, the more effective digital transformation actions will be in the business world.

The adoption of I4.0 generates new business opportunities. I4.0/SM can create products considering the needs and desires of each consumer. Throughout this personalization, companies ensure greater satisfaction and loyalty of each customer. Our SLR found that the social dimension in I4.0 has barely been analyzed. Therefore, new studies are required to understand the impact of organizational changes, evaluate new management skills, create training models in digital technologies, evaluate unemployment in unskilled labor, and understand the impact of the imbalance in trade relations. Large manufacturers will be able to implement changes faster than small and medium-sized ones, and therefore, they will be able to analyze the impact of agribusiness 4. 0 and services 4.0 on the unemployed and how to help this workforce get back to work, as well as the creation of new hiring models and the impact of 5.0 on society concepts (human-centered society to provide harmony between economic development and related social issues) in developing countries, among others. Our SLR found several methodologies and metrics for impact measurement and evaluation of social outcomes. The main ones are the global reporting initiative, social return on investment, and common good balance sheets.

Another obstacle is the lack of a single conceptual framework that generalizes the study of the I4.0/SM concept, as the relevant research is very fragmented. From 2017 to 2022, different studies approached the I4.0 concept from multiple points of view with varying degrees of technical depth. These studies tried to find short-term solutions for conceptual frameworks, evaluation frameworks, strategies, marketing, corporate social responsibility, governance, data management, social acceptance, environmental impacts, enablers, and technological drivers, among others.

The new ICT paradigm combines communications technology and information technology to facilitate the issuance, access, and treatment of data from I4.0. However, the interoperability problem remains the central axis that requires more research and development of industrial applications. The solution to ICT challenges is the competitive key in all I4.0 scenarios.

ICT smart applications are currently implemented in various areas (medicine, hospitality, agriculture, business, supply chain, tourism, energy management, and logistics, among others). However, security and privacy issues in data transfer networks are still an important issue that we constantly discuss. Our SLR found different solutions aimed at improving security standards in the areas mentioned above. Solutions were found for some challenges; however, methodologies are lacking to address issues in network latency, traceability, scalability, redundancy, data storage, robustness, auditability, integration architectures, immutability, and digital policies, among others. According to SLR, Blockchain methodological proposals can address several of the mentioned problems.

For SLR, the identified technology trends of IoT, AM, CC, and CPS linked to I4.0/SM have very different applications and impacts in different industries, requiring multi-contextual approaches with the separation of technologies to provide additional information. These business-level trends mainly present challenges to software systems—in most cases, to closed-box systems that prevent M2M communication through IoT protocols. Standardization is essential for adapting to new technological trends. Although there is great viability for advancing I4.0/SM technology trends, many companies do not know how to capture the potential provided by IoT, AM, and CC technologies through sensors and big data analysis for creating the CPS concept.

These new technological trends allow for higher levels of production efficiency. They also have the potential to dramatically influence sustainable development through environmental, social, and economic dimensions. Our SLR in the selection of studies of the SU thematic area found that these three dimensions in I4.0 interact, overlap, and sometimes are conflicting, lacking sufficient guidance in scientific or practice literature.

From an ecological point of view in terms of costs, implementing environmental sustainability could be unfavorable for economic sustainability due to the additional investments necessary for clean production. However, when organizations do not support all three dimensions, they do not act sustainably. In the SLR, most organizations manage to have synergy between the environmental and economic sustainable dimensions but are still struggling to address the full TBL vision. I4.0 has a favorable impact on sustainability when (i) I4.0 technologies help manage product life cycles to achieve sustainable manufacturing; (ii) I4.0 technological advances remove critical factors for digital transformation, and the elimination of these factors allows for achieving sustainable environments; (iii) sustainability becomes one of the main elements of smart manufacturing, and these digital transformation processes must emphasize the implementation of sustainable development policies; (iv) it provides an understanding of the relationship between I4.0 and circular economy to achieve sustainable development objectives and comply with TBL; (v) it interrelates the use of I4.0 technologies to achieve sustainable supply chains; (vi) through I4.0 technologies, business models, and organizational structures are developed, providing new approaches for sustainable development; and (vii) it allows the development of green supply chains, among others [3].

Finally, resources for statistical process controls are increasingly useful in I4.0. This technique has evolved over time from monitoring and identifying variations manually to diagnosing them in real time with minimal human intervention. In the domain of statistical process control, the new I4.0/SM concept uses different machine learning algorithms and other intelligent approaches, namely, wavelet-based models, support vector machines, K-nearest neighbors, NN-based models, decision trees, fuzzy logic, and ES-based models, among others. I4.0, with its automation, connectivity, and digital access capabilities, will increase the efficiency and productivity of statistical process control. Currently, through the development of integrated statistical process control–artificial intelligence–CPS approaches, I4.0 is evolving towards intelligent statistical process control.

5. Conclusions

Despite the benefits that the adoption of I4.0 technologies brings to supply chains, there is still a long way to go. Performing a systematic literature review, we identified the main methodological contributions published between 2017 and 2022 that provide a solution to the nine challenges identified for Industry 4.0 implementation in the context of sustainable manufacturing. Additionally, 14 technological trends were identified and conceptualized. In total, 195 studies were used, 93 of which are part of the SLR. Countries such as India lead the research in I4.0/SM proposals, followed by Italy and China. Science Direct and IEEE databases with *Journal of Cleaner Production* (with 10), *International Journal of Production Economics* (with 6), and *IEEE Access* (with 6) make the largest contributions. The technologies with the highest number of mentions in the sustainable area correspond to the four technological trends: IoT, AM, CC, and CPS. These four technology trends have been well developed by researchers to enhance I4.0/SM capabilities.

With the present study, we aim propose an alternative methodology to guide the conceptual integration of I4.0 scientific literature, making it possible to search for long-term sustainable manufacturing methodological solutions with a high degree of specialization. The findings in the SLR suggest that the I4.0 literature is being carried out in a fragmented manner, meaning it is studied in isolation, where the effort that researchers make in all areas is not visible because the proposals are not entirely aligned with the objectives of the new I4.0/SM concept.

In turn, for performance evaluation and guidance frameworks in the sustainable field, these fragmented measurements make it difficult to have a comprehensive diagnosis of the I4.0 scientific literature that allows timely detection of the deficiencies and strengths of the new I4.0/SM concept.

The I4.0 concept is constantly evolving and developing. The new definition focuses on environmental, social, and economic dimensions, being necessary for the systemic synergy of I4.0 research towards sustainable manufacturing objectives. The literature's evolution and alignment have positively impacted the solution of the technological, business, and political challenges identified in I4.0/SM.

SLR shows that companies are more motivated to implement I4.0 to increase competitiveness rather than sustainability, especially regarding the social dimension. In addition, there is a demand to identify new I4.0 technological factors that act as drivers of the environmental and social dimensions associated with improved competitiveness. I4.0/SM must focus on the human being so it can reflect their requirements at both the environmental and social levels. In addition, further studies focused on the social component from the TBL perspective are needed in the I4.0 context to explore the benefits and advantages that digital transformation can bring to the environmental and social dimensions.

The technologies with the lowest number of mentions in the researched articles correspond to the technological trends of IoD, IoP, IoS, and semantic technologies. These trends have been overlooked as development opportunities for I4.0. Similarly, there are methodological gaps in the challenges—the threat of redundancy and loss of jobs, reliability and stability of M2M communication, and the protection of industrial know-how.

In the current context of industrial development, there are significant research opportunities in the sustainable area within the framework of I4.0 methodologies and technological trends. However, the sustainability concept has not received the necessary attention in the I4.0 literature. Our SLR found trends centered around specific conceptual frameworks for sustainable solutions targeting the circular economy. I4.0 transforms the entire value chain, revolutionizing AI, automation, and robotics. Meanwhile, CPS productive systems require integration between IoT, AM, CC, robotics, big data analysis, digital twins, and AR technologies. CPS is considered the convergence point of all I4.0 technologies.

SLR indicates that the implementation of I4.0/SM is a complex process. Most companies still have limitations in its adoption or have executed it in a limited way due to the various challenges. The main entry barriers identified in the SLR are implementation times, system configuration, adequate personnel, lack of adequate tools for rapid CPS prototyping, operator training, lack of knowledge, technical challenges, certifications, regulatory frameworks, employee resistance to change, and clarity of economic benefits, among others.

Ultimately, the SLR recommends that industrial organizations benefit from adopting I4.0 technology to improve their sustainability impact. However, each technology must be carefully evaluated, considering the type of challenge and the implementation barriers since the selected technology will influence the sustainability dimensions. Investment in I4.0/SM technologies must consider technology support, infrastructure, and system integrity. The methodology presented could be adapted to a specific I4.0 technology to simultaneously show the impact on environmental, economic, and social sustainability.

This study classifies a group of technology trends linked to I4.0. More specific work is required in the future, separating technologies to provide additional information. In addition, to measure the degree of I4.0/SM implementation, it is necessary to conceptually standardize 14.0/sustainable level indicators and I4.0/sustainable key performance indicators, together with evaluation frameworks and performance guides. Additionally, lean manufacturing in I4.0 can be explored at a strategic level and assess the changes needed for I4.0 adoption and their final impact. Finally, we must analyze, understand, and/or evaluate the role of artificial intelligence and machine learning in achieving I4.0/SM objectives.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su141811118/s1, Figure S1: Number of items identified per database, Table S1: Table of references, Figure S2: Number of publications per country where the studies were conducted.

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Abbreviations

AR	augmented reality
AM	additive manufacturing
CC	cloud computing
FI	financial
OP	operational
SU	sustainable
EOL	end-of-life
M2M	machine-to-machine
I4.0	Industry 4.0
SLR	systematic literature review
CPS	cyber-physical system
ICT	information and communications technology
IoS	Internet of Services
IoP	Internet of People
IoD	Internet of Data
IoT	Internet of Things
IIoT	industrial IoT
TBL	triple bottom line

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