

Review

# A General Outline of a Sustainable Supply Chain 4.0

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**Abstract:** This article presents a literature review to identify the current knowledge of supply chains 4.0 from the sustainability perspective. Reviewed papers were classified in terms of objectives, results, and sustainability approaches. Additionally, a critical discussion with the main results and recommendations for further research was carried out. Manufacturing supply chains have been contemplated but agri-food supply chains and chains related to diversified cropping systems have been also considered. In this way, 54 articles were identified and revised, and were classified according to the three main aspects of sustainability: economic, social, and environmental. The classification of articles indicated that more attention has been paid to the environmental aspect in the industry 4.0 (I4.0) context in the literature, while the social aspect has been paid less attention. Finally, reference frameworks were identified, along with the I4.0 models, algorithms, heuristics, metaheuristics, and technologies, which have enabled sustainability in supply chains.

**Keywords:** sustainability; industry 4.0; supply chain; review

## 1. Introduction

The fourth industrial revolution is expected to cause a tremendous industrialization growth and may disturb the sustainability of current industrial systems [1,2]. In addition, further impacts in terms of higher resources consumption, global warming, and climate change issues [3] are expected. In this sense, adopting management practices for production and supply chain systems that considers all the sustainability—economic, social, and environmental—aspects and exploits the digital transformation characteristics that industry 4.0 (I4.0) represents is a relevant theme that requires research and needs to be applied in manufacturing supply chains. The importance of incorporating sustainability in supply chains has been the focus of attention by researchers [4,5], however, few practical efforts were made within the context of a sustainable supply chain and I4.0 [4]. Regarding this, Duarte and Cruz-Machado [6] proposed a conceptual model that integrates I4.0 concepts into green and lean supply chains. In this context, many efforts have been made focusing on I4.0-related technologies and not I4.0 as a whole approach. Here, we address supply chain 4.0 as an extension of the I4.0 definition, incorporating value chain creation processes that comprise of vendors, producers, wholesalers, retailers, and end clients, that intends to synchronize demand and supply [7]. According to Luthra et al. [8], the majority of studies on I4.0 have considered the manufacturing sector context and ignored supply chain systems. To bridge this gap, this article presents a literature review on the sustainable supply chain 4.0 using the three afore-cited perspectives: social, environmental, and economic. In order to determine what has been done to date and who has worked on this research subject, a literature review was done and includes an analysis of 54 articles selected according to their novelty criteria, number of times cited, if they dealt with I4.0 on the whole, and the aspects that sustainability represents. Thus,

the main contributions of this paper are to: (1) provide a literature review on sustainable supply chains and I4.0; (2) organize the main insights in order to support and facilitate exchanges of the main supply chain 4.0 objectives, results, and sustainability approaches; and (3) examine the main contributions and limitations of the reviewed papers in order to identify recommendations for sustainable supply chain 4.0 future research works. This literature review can be useful for researchers and decision makers to clarify the state of the art of the addressed topic and define future research paths.

The rest of the article is set out as follows. Section 2 presents the structure of the methodology followed to conduct this article. Section 3 presents the literature review, which identifies the works related to sustainable supply chains and I4.0; the social, economic, and environmental aspects in the I4.0 context; the most relevant works that have dealt with sustainability; and I4.0 in general. Finally, Section 4 offers conclusions and future lines of work.

## 2. Review Methodology

The methodology proposed for this literature review started by selecting the databases: i.e., Science Direct, IEEE Explore, Scopus, Google Scholar, and Web of Science. The search criteria included filtering documents and articles by title and containing the following keywords always combined with the term Industry 4.0: sustain, sustainability, sustainable, agri, agro, econo, economic, social, human, operator, cost, environment, energy, waste, water, eco. Table 1 illustrates the data collection methodology.

**Table 1.** Data collection methodology.

Databases	Science Direct, IEEE Explore, Scopus, Google Scholar, and Web of Science.
Keywords	Industry 4.0, sustain, sustainability, sustainable, agri, agro, econo, economic, social, human, operator, cost, environment, energy, waste, water, eco
Document type	Articles and books
Date	No date filtered
Language	No language filtered
Search query	(TITLE (industry 4.0) AND TITLE-ABS-KEY (sustainable)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "sh"))
Initial search	256 documents
Provisional collection	58
Selected articles	54

Consequently, an initial search was conducted and collected provisional search results. Next, with this provisional information collected, it was filtered considering the following selection criteria: novelty, times cited, publication date, journal impact, abstract briefly reviewed, and sustainability approach. In case the provisional collection did not meet the selection criteria, the initial search was continued, iterating as long as every article in the literature was filtered. Otherwise, if an article was selected, it formed part of a definitive collection of search results and proceeded for deep evaluation and analysis. Next, each article was categorized by I4.0 category and sustainability approach. Figure 1 illustrates the described review methodology followed.

Table 2 summarizes the sources of the articles selected for the literature review of the supply chain 4.0 and sustainability.

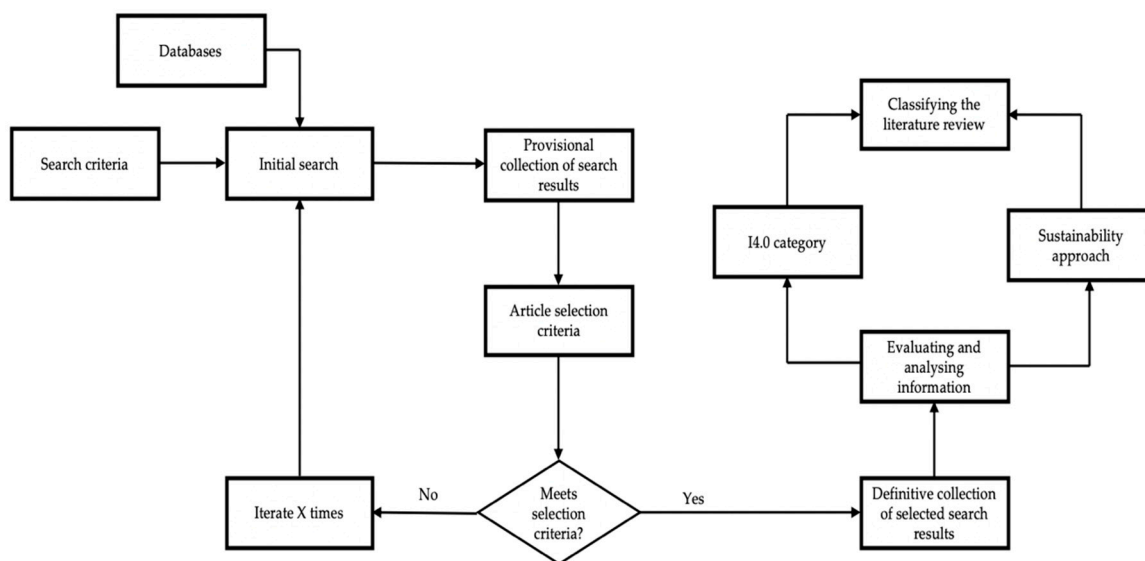


Figure 1. Structure of the methodology followed for the literature review.

Table 2. Sources of the selected articles.

Journal	Number
Sustainability	9
Proceedings	8
Process Safety and Environmental Protection	5
Computers and Industrial Engineering	4
DYNA	3
Procedia Manufacturing	3
International Journal of Production Research	2
Processes	2
International Journal of Precision Engineering and Manufacturing—Green Technology	2
Waste Management and Research	1
Procedia CIRP	1
International Journal of Innovation Management	1
Journal of Manufacturing Systems	1
IFAC-PapersOnLine	1
Technological Forecasting and Social Change	1
Energy Procedia	1
Benchmarking: An International Journal	1
International Series in Operations Research & Management Science	1
Journal of Sensors	1
Lecture Notes in Electrical Engineering	1
Journal of Manufacturing Technology Management	1
Journal of Cleaner Production	1
Energies	1
Studies in Computational Intelligence	1
British Food Journal	1
<b>Total</b>	<b>54</b>

### 3. Literature Review

#### 3.1. Taxonomy

The selected papers have been reviewed and classified by sustainability approach (EC: economic, ENV: environmental, and S: social), its main objectives, supply chain and Industry 4.0 approach (SC4.0), and results of each work (Table 3).

**Table 3.** Selected articles classification by approach and results of each work.

References	Sustainability Approach			SC4.0	Objective	Results
	EC	ENV	S			
[4]	X	X	X	X	Aimed to fill a research gap on sustainable supplier selection process within an I4.0 supply chain.	Proposed a multiagent system (MASs) approach for sustainable supplier selection of supply chains 4.0.
[8]	X	X	X	X	Review I4.0 initiatives to determine its key challenges for sustainable supply chains in the Indian manufacturing industry.	Validated key challenges with explanatory factor analysis (EFA) and analytical Hierarchy process (AHP).
[9]	X	X	X	X	Compare innovation policies under I4.0 and sustainability development transformation.	The study resulted in more efforts of China's political and legal regulatory aspects on the environmental approach.
[10]	X	X	X	X	Address the influence of the sustainability approach on business models.	Proposed a research agenda on how to create sustainable business models in the I4.0 context.
[11]	X	X	X		Aimed to study industrial value creation and present a comprehensive approach to challenges and benefits of industrial IoT (IIoT) in terms of sustainability.	Proposed that sustainable value creation in the context of IIoT requires consideration of technical, data, and public benefits and challenges.
[12]	X	X	X		Study the effects of I4.0 smart production systems on sustainability context in terms of energy efficiency.	Potential sustainability improvements in manufacturing companies linked with technology reaching a whole supply chain.
[13]	X	X	X	X	Review the aspects of ERP, SCM, IoT, and I4.0 and find opportunities in IoT embedded sustainable supply chain for I4.0.	Proposed a conceptual model for assessing the readiness of supply chains to meet the requirements of I4.0.
[14]	X	X	X	X	Aimed to identify potential sustainability barriers of pharma supply chains (PSC) and the implementation of I4.0 within PSC.	Reviewed 33 papers from 2008–2018, PSC- and I4.0-related, and identified major challenges that inhibit the inclusion of sustainability in PSCs.
[15]	X	X	X	X	Aimed to identify I4.0 enablers for a sustainable supply chain and propose a research framework for future research directions.	Identified 13 enablers that influence supply chain sustainability.
[16]	X	X	X	X	Reviewed new drivers for structural supply chain dynamics and resilience with the inclusion of sustainability, I4.0, and I4.0-characteristic self-adaptation.	The following drivers in adaptive supply chain management were proposed: adaptation, coordination, agility, and sustainability.
[17]	X	X	X		Study the implementation of a sustainable and intelligent material handling system for material distribution operations.	Designed and implemented a system proposing an agent-based algorithm for intelligent material handling (product or object differentiation).

Table 3. Cont.

References	Sustainability Approach			SC4.0	Objective	Results
	EC	ENV	S			
[18]	X	X	X		Analyse how I4.0 adoption contributed to every aspect of sustainability and its effects by a qualitative case study in a ceramic sector as a case study.	The study confirmed I4.0 applications support all sustainability aspects and improvements on productivity, product quality, energy consumption monitoring, safer work and less workload.
[19]	X	X	X		Review reference architectures for smart factories of I4.0 that consider the production of sustainable products and services.	Identified and analysed emerging I4.0 architectures: RAMI 4.0, IIRA, IBM Industry 4.0, and NIST smart manufacturing.
[20]	X		X		Review that aimed to develop a conceptual framework on how implementing gamification could tackle sustainability issues/barriers when transitioning from traditional processes to I4.0 sustainable processes.	Verified that sustainable manufacturing and I4.0 were the least approached on gamified applications.
[21]	X	X	X		Aimed to predict the relevant constructs for opportunities and challenges as drivers in I4.0 implementation and sustainability context.	Proposed a hypothesized research model and tested it. Revealed empirical insights from 746 German companies and interesting hypothesis relationships within challenges and opportunities in I4.0 implementation.
[22]	X	X			Identify current trends and future perspectives of sustainability and I4.0.	Identified the need for more studies on the validation of suggested I4.0 theories and concepts using simulation, prototypes, experimentation, etc. Identified a lack of studies concerning sustainability.
[23]	X	X	X		Aimed to identify the systematic impact of I4.0 technology developments and implementation of sustainable energy of the project Making Indonesia 4.0.	Proposed a conceptual model in the form of causal loop diagram conceptualisation of variables that support the integration of I4.0 and industrial sustainable energy in Indonesia.
[24]	X	X	X		Authors identified that VSM only considers economic aspects of sustainability and ignores environmental and social aspects, with this aim a sustainable value stream mapping (SVSM) was studied.	SVSM was applied in an apparel company and identified potential issues related to sustainability in production processes. Improvements in environmental and social aspects with the use of RFID technology.
[25]	X	X			Propose a sustainable layout with the use of big data in the I4.0 context.	Proposed a mathematical model that integrated aspects in the design of a facility layout. The proposed model is named sustainable robust stochastic cellular facility layout (Sustainable-RSCFL).
[26]	X	X	X		Aimed to assess opportunities driven by I4.0 in the process of sustainable development in the furniture industry in Poland.	Outlined the bridge between economic and social aspects of I4.0.

Table 3. Cont.

References	Sustainability Approach			SC4.0	Objective	Results
	EC	ENV	S			
[27]	X	X	X		Study the characteristics and requirements of SMEs for implementation of sustainability and I4.0.	Identified further potential of energy efficiency acquirable as a part of an entire supply chain.
[28]		X			Propose a framework of production planning and control considering carbon tax under I4.0 context and use the tire industry as a case study.	A mathematical programming model and I4.0-related technologies in production planning and control with the carbon tax.
[29]	X	X	X		Aimed to find a link between concepts of new product development processes, I4.0, and sustainable development.	Identified I4.0 technologies that should be considered within a framework of sustainable development.
[30]	X	X	X		Identify risks within I4.0 implementation in the context of sustainability and manufacturing industry.	Proposed an I4.0 sustainable risk framework. Results showed economic, environmental, and social risks caused by I4.0 implementation in SMEs.
[31]	X	X	X		Improve efficiency and working conditions in the smart factory of I4.0.	Developed an IoT based wearable named: OperaBLE for power awareness based on bluetooth low energy (BLE) and two algorithms. Low-frequency movement characterisation algorithm and adaptive heart rate algorithm.
[32]	X	X	X		Aimed to build a sustainable and flexible advanced HMI interfaces that enable adaptive and useful information to machine operators.	Authors presented 3 use cases of the hardware and software: HMI customised for 3D printers, real-time motor control from HMI, a digital twin of a robotic arm making use of real-time data.
[33]	X	X	X	X	Analyse challenges facing agriculture along a farming supply chain to allow the implementation of I4.0.	Authors suggested policymakers and decision makers invest in technological advances. Identified economic advantages to large enterprises but difficulties for SMEs for agriculture 4.0 adoption.
[34]	X	X	X	X	Aimed to improve sustainability management for the valorisation of agricultural waste integrating I4.0 into a supply chain design.	Proposed a five-step base approach combining big data of I4.0 and sustainability assessment. The approach was applied in the agro-food industry and identified great environmental impacts.
[35]	X	X	X		Aimed to understand the links between two paradigms, I4.0 and precision agriculture, in the context of its related technologies.	Identified the links between I4.0 and precision agriculture. Authors suggested that identification of these links makes it a useful tool that can have different impacts on theoretical and practice levels.
[36]	X	X			Aimed to offer solutions for I4.0 technologies development in terms of sensing, smart, and sustainable concepts for the agri-food sector.	Identified collaboration between human and technologies for agri-food production methods. Presented the technologies applied in the agri-food sector.

Table 3. Cont.

References	Sustainability Approach			SC4.0	Objective	Results
	EC	ENV	S			
[37]		X	X	X	Review I4.0 sustainability and related technologies.	Assessed the potential of sustainable value chain creation in I4.0 context based on experts' interviews.
[38]		X	X		Aimed to present ways to incorporate sustainability learning with the usage of KPIs in I4.0 virtual learning environment considering social and environmental aspects of sustainability.	Key difficulties of sustainability indicators are their unconstrained nature. Environmental and social aspects tend to transcend organisations.
[39]	X	X			Review the concept of energy management in terms of efficiency in the context of IoT technology/smart factories of I4.0.	Presented a set of phases for the adoption of energy management in smart factories.
[40]		X			Literature review with the aim of analysing sustainability impact and challenges of I4.0.	Indicated emerging I4.0 will cause opportunities when integrating sustainable development goals but real integration will occur with the use of an eco-innovation platform ensuring environmental performance.
[41]		X			The study had 3 objectives: present arguments related to I4.0 interface and environmentally sustainable manufacturing. discuss critical success factors (CSF) on I4.0 and environmental aspect, propose a framework for future integration of I4.0 and environmentally sustainable manufacturing and CSF.	I4.0 technologies can unlock the full potential of environmentally sustainable manufacturing practices. Proposed 12 research gaps for the integration of I4.0 and environmentally sustainable manufacturing.
[42]	X	X	X		Review how to enhance sustainability and energy efficiency in smart factories of I4.0.	Discussed promising I4.0 technologies. Solutions to sustainable manufacturing were summarized regarding renewable and clean energy, energy devices, and systems.
[43]	X	X	X		Aimed to analyse literature of potential barriers related to I4.0 implementation in manufacturing organisations.	Established relationships between barriers using interpretive structural modelling (IMS). Identified 12 significant barriers revealing effects on I4.0 adoption.
[44]	X	X			Propose a digital excitation system for the smart factories of I4.0.	The proposed simulation model is expected to increase the stability and economic effectiveness of an excitation system.
[45]		X			Explore gaps and overlaps between intergovernmental organizations' statements regarding the climate change effects on I4.0 technologies.	Identified the relevance of approaching energy and resource efficiency issues related to I4.0.



Table 3. Cont.

References	Sustainability Approach			SC4.0	Objective	Results
	EC	ENV	S			
[46]	X	X			Aimed to create an intelligent industry by measuring energy consumption optimisation at the machine and process level and its related costs in I4.0 context.	Proposed an IoT solution for energy consumption optimisation in the automotive industry. Presented implementation issues regarding installing the IIoT system in real environments.
[47]	X	X			Finding a system of systems concept for improving road construction efficiency in the context of lean and I4.0.	The concept of a system of systems uses lean principles for waste reduction and I4.0 concepts to address architectural concerns.
[48]	X	X			Enabling eventual programming in energy cloud platforms for management improvements and automation/control improvements.	Identified the correlations between energy consumption and CO2 concentration in working places.
[49]	X	X			Aimed to review the possibilities and concerns related to energy management and I4.0.	Identified the need for incorporating energy management in factory digitalisation projects. Identified factors driving the industry towards an intelligent energy management system.
[50]	X	X			Tackle connectivity and integration issues along a waste electrical and electronic equipment recycling and remanufacturing chain.	The study had 3 main contributions: extending digital twins that support WEEE/EEE manufacturing and remanufacturing, integrating I4.0 enablers in a digital twin context, developing product information models.
[51]	X	X			Tackle environmental issues regarding the textile industry classified as one of the world's major sources of industrial pollution.	The proposed mathematical model could be a decision model that allows managers in textile companies to evaluate the impacts on profit carbon emissions, energy recycling, waste reuse, and material quantity discounts.
[52]	X	X			Identify insights relationship between the cost for battery replacements and damage penalties in the context of I4.0.	Evaluated renewable energy sources to feed long-range (LoRa) nodes in industrial environments and their cost/benefits analysis.
[53]	X		X		Propose a green activity-based costing production planning model under I4.0. Aluminium-alloy wheel industry was used as a case study.	The ABC-based I4.0 model provided benefits on economic and environmental sustainability aspects under I4.0.
[54]	X	X			Analyse the variables that affect the adoption of precision agriculture technologies for smart water management in the context of agriculture and I4.0.	Proposed a conceptual model that integrated concepts of IoT, I4.0, theory of planned behaviour, precision agriculture, water and operations management.



Table 3. Cont.

References	Sustainability Approach			SC4.0	Objective	Results
	EC	ENV	S			
[55]	X	X			Study sustainability in material handling in the manufacturing sector and reviewed AGV technology.	Identified emerging research on AGV technology and improved economic aspect by the use of this technology and environmental aspect can be measured from AGV's and establish eco-indicators.
[56]	X	X	X		Identify future research directions related to maintenance and sustainable manufacturing in the I4.0 context.	Reviewed papers analysis findings showed a wide relevance of maintenance and sustainability.
[57]	X	X	X		Aimed to evaluate product sustainability in the context of circular economy and industry I4.0. Part 1.	Defined and discussed 3 elements for the proposed framework: life cycle analysis (ACV), cradle to cradle, and I4.0.
[58]	X	X	X		Aimed to evaluate product sustainability in the context of circular economy and I4.0 paradigm. Part 2.	Authors suggested that the proposed conceptual model will support sustainable smart product developments.
[59]	X				Propose a framework for warehouse resource management based on I4.0 technologies: RFID, sensors, artificial intelligence, autonomous vehicles, IoT, and high-performance computing.	Identified 3 improvements driven by the framework: improvement of working efficiency, reduction of operation costs, and time-saving in resource management activities.
[60]	X				Explore how I4.0 technologies can be integrated into a circular economy practice that established business models for reverse logistics (reuse and recycle waste).	Findings showed that circular manufacturing is an important factor to enhance productivity and waste and pollution reduction. I4.0 technologies play an important role in circular economies. Experts believe that I4.0 will cause a positive effect on the social aspect.

Regarding the I4.0 and the sustainable supply chain, Lin et al. [9] compared innovation policies of the sustainable I4.0 transformation-related projects called China Manufacturing 2025 and Taiwan Productivity 4.0. However, this work was limited to national and industrial level of I4.0, future works should focus on firm level. Man and Strandhagen [10] discussed different scenarios with the incorporation of I4.0 and sustainability included in business processes. They recommended that in order to measure the effect of sustainability strategies, the impact on the environmental aspect of sustainability can be measured through life cycle assessments (LCA). Thus, the following research lines were proposed: study how markets will shift to sustainable products in the context of I4.0 and how this could support sustainable supply chains, the creation of sustainable awareness of customers through I4.0 horizontal integration, achieving customer loyalty and satisfaction for sustainable I4.0 products, overcoming psychological of products obsolescence through I4.0, cost–benefit analysis of I4.0 solutions that support a sustainable supply chain, and research into the potential revenue models for I4.0 supported sustainable products.

Kiel et al. [11] presented a classification of the challenges and benefits of the Internet of Things (IoT) that focused on the sustainability of creating value. Waibel et al. [12] discussed the effects of smart production systems in a sustainable setting, in which they evaluated each sustainability aspect (economic, social, environmental, and technical) in terms of efficiency of resources. Manavalan

and Jayakrishna [13] reviewed the I4.0 requirements of a sustainable supply chain and analyzed different IoT aspects, supply chain management, and which software can be used to plan material resources in companies (ERP). These authors proposed a reference framework to evaluate the level of the supply chain's readiness in companies that pursue transformation towards I4.0. This reference framework comprises five supply chain management perspectives: businesses, technology, sustainable development, collaboration, and strategic management. The conceptual model addressed the criteria belonging to each sustainability enabler, the technology was only shown as a tool to reach the enablers (IoT, CPS, augmented reality, and big data). Additionally, the basic characteristic of a sustainable supply chain 4.0 is that organizations should realize closed loop life cycles for products.

Ghadimi et al. [4] proposed a model based on multiagent systems to automatically evaluate and select suppliers in the sustainability context and I4.0 supply chains, which consists of a three-layer system architecture: i.e., interface layer, technical layer, and data resources layer. These authors described how the developed model can act as a tool for I4.0 supply chains and described its advantages according to four I4.0 design principles [1]: (1) interconnection, which allows I4.0 supply chains to dynamically adapt to environments of the market and businesses; (2) transparent information, where several agents will be able to send and receive information in real time by different protocols; (3) decentralization, in which agents will have the capacity to communicate and make decisions themselves; (4) technical assistance, e.g., automating suppliers' selection process in a sustainable I4.0 supply chain.

Luthra and Mangla [8] presented a literature review that identified 18 I4.0 challenges, which they grouped as organizational, strategical, legal, and ethical challenges. These authors then validated challenges by an AHP (analytical hierarchy process) in the manufacturing sector in India. Within the context of sustainable supply chain 4.0 and from the organizational point of view, the authors addressed that technology and process innovation are fundamental in value chains.

Ding [14] offered a literature review to identify the barriers faced when including sustainability in the pharmaceutical supply chain: high costs and long usage times, little experience and training, reinforcing regulations, coordinating supply chains, and ineffective collaboration. Moreover, via the sustainable supply chains called Pharma 4.0, they identified how I4.0 can be applied to these supply chains to solve problems when including sustainability, which the authors divided into four aspects: increasing supply chains' flexibility, enhancing the effectiveness of coordination/communication of all the parties involved in a supply chain, reducing waste and pollution in different stages, and setting up an autonomous decision-making process.

Bag et al. [15] revised the literature in the sustainable and I4.0 supply chains context. They proposed a reference framework with which they identified 13 enablers that influenced sustainability in a supply chain. These enablers of a sustainable supply chain 4.0 are as follows: government support, third party audits, corporate governance, vertical integration, horizontal integration, change management, focus on human capital, information transparency, standardization and reference architecture, management commitment, improved IT security and standards, law and policy regarding employment, and support of research institutes and universities.

Ivanov [16] revised sustainability, I4.0, and self-adaptation as drivers for the structural dynamics of supply chains and resilience. This author considered that resilience in supply chains contains intersections with sustainable supply chains and analysed the factors affecting the structural design of resilient supply chains to eliminate the ripple effect and to enhance sustainability. Therefore, in supply chains' structural dynamics, I4.0 plays a key role as it facilitates flexible customized production at the expense of mass production. Yazdi et al. [17] conducted empirical research about OEE (overall effective equipment) and a sustainable manufacturing system in which they proposed an algorithm as a control architecture. Braccini and Margherita [18] investigated the supports that help to adopt I4.0 in a case study about a company that manufactures ceramics by dealing with sustainability on the whole. Moghaddam et al. [19] devised different reference architectures of sustainable smart I4.0 factories and dealt with manufacturing sustainable products. Paravizo et al. [20] proposed a conceptual

framework to develop gamified applications in the I4.0 field that focus on sustainable manufacturing. Müller et al. [21] put forward a search model with which to identify the opportunities and challenges of hypothetically implementing I4.0, which they applied to a sample of 746 German manufacturing companies and to five different industrial sectors. Kamble et al. [22] revised the I4.0 literature and built a reference framework of sustainability in the I4.0 context by taking 85 selected and classified articles as a basis. Hidayatno et al. [23] proposed a conceptual model to determine the impact of developing and implementing I4.0 technology with sustainable energy with the project “Making Indonesia 4.0”. They conceptualized the model by causal diagrams and using system dynamics to represent the variables that support I4.0 technologies. They developed this model within three sustainability components: environmental, social, and economic. The authors concluded that the model could be validated and presented quantitative and qualitative results using the sustainable energy data that were collected. Phuong and Guidat [24] presented a methodology to apply sustainable value stream mapping and a conceptual model to acquire and extract data using RFID technology. Kumar and Lamba [25] proposed a metaheuristic for a sustainable robust stochastic cellular facility layout problem. Wiśniewska-Szałek [26] assessed the opportunities that I4.0 provides when developing sustainability and presented a furniture industry case study. Müller and Voigt [27] compared the implementation of projects in Germany entitled “Industrie 4.0” and the project in China known as “Made in China 2025” in the sustainability context. This study was done using studies conducted in several SMEs in Germany and China. The results of this study revealed that the German SMEs perceived that I4.0 has a low impact, which benefits large companies more. The Chinese SMEs perceived social benefits. These authors contemplated that the energy efficiency potential obtained through the digitalization and interconnection of I4.0 must be considered by SMEs, which cannot be achieved as an individual organization, but as part of a supply chain as a whole. Tsai and Lu [28] proposed a framework to plan production and control with a carbon tax in the I4.0 setting. Bibaud-Alves et al. [29] provided a link among the development process concepts of new products, digital transformation, and sustainable development using an I4.0 approach. Birkel et al. [30] put forward a reference framework of the risks involved in implementing I4.0 into SMEs with a sustainability approach, i.e., environmental, social, and economic risks, as well as technical risks, risks with information technologies and legal/political risks. Roda-Sánchez et al. [31] proposed two power-aware algorithms with a flexibility approach to face the sustainability challenge in I4.0 (efficiency and working conditions). Ardanza et al. [32] presented a human–machine interface with efficient sustainable hardware/software for I4.0. In the context of agri-food supply chains and crop diversification, Zambon et al. [33] set out a framework of a system to manage agriculture 4.0 by the virtualization of an agro-food chain. Here, precision agriculture and IoT applied in the farming sector led to agriculture 4.0, which improved sustainability of crops and yields, increasing quality of working conditions, production, and processing.

Belaud et al. [34] proposed an approach to integrate I4.0 into a supply chain with the aim to improve sustainability management for valorization of agricultural 4.0 waste with the use of big data. Trivelli et al. [35] mapped precision agriculture technologies linked to I4.0 and developed a dictionary of terms that could be used as a basis of digitalized agri-food value chain. Miranda et al. [36] considered sensing, smart, and sustainable technologies as key characteristics of future sustainable products.

With respect to the social approach in the I4.0 environment, Stock et al. [37] offered a literature review based on creating value by an approach based on the social and environmental dimensions in the I4.0 context. These authors used “intelligent cube production”, made up of a smart product with RFID technology located in China (the Sino-German Research Institute) to assess and analyze the outcomes of the I4.0 potential in social and ecological domains. The environmental and social study assessment revealed that individual I4.0 technologies have a positive impact on resource management, such as RFID and 3d printing technologies. RFID can be used to store data of products life cycle and 3d printing leads to reduction of resources consumption. A lack of quantitative research on social and environmental impacts of I4.0 and sustainable development contributions was identified.

Chaim et al. [38] discussed the possibility of incorporating key performance indicators (KPIs) to evaluate sustainability in a virtual learning environment in the I4.0 context. Indicators were based on the classification offered in the work of [61], which consisted of classifying sustainability indicators in environmental stewardship (emissions, pollution, and resource consumption) and social well-being (employee, customer, and community).

In the environmental approach in sustainability and I4.0, the works by [39] stand out, which deal with how the IoT will improve the energy efficiency of smart factories and will determine the process by means of which this practice will be adopted in four phases: (i) implementing production processes and evaluation of today's energy management practices; (ii) monitoring and analyzing real-time uses by IoT technology; (iii) integrating data into energy management tools by energy decision support systems, simulation tools, etc.; (iv) defining sustainability strategies and production management practices to improve energy efficiency. Bonilla et al. [40] evaluated challenges and impacts when incorporating I4.0 using different I4.0 development scenarios, long-term sustainable development challenges, and operations with an environmental sustainability approach. Stock et al. [37] resorted to an environmental approach and I4.0. De Sousa Jabbour et al. [41] proposed a reference framework to set up the synergy between I4.0 and environmentally sustainable manufacturing. Meng et al. [42] revised the literature by considering sustainability and energy efficiency in smart factories to determine how they interact and benefit one another, and to also deal with any problems arising between both. Kamble et al. [43] analyzed the energy barriers that emerge when adopting I4.0 into production in India. Huh and Lee [44] set up a testbed and simulation for a lower-power digital "excitement" system for I4.0. Fritzsche et al. [45] revised the literature to identify gaps in intergovernmental organizations that study climate change and I4.0. Campo et al. [46] presented a solution by using the IoT for optimizing energy in an I4.0 domain and discussed applying it to real life. Axelsson et al. [47] pursued increasing efficiency and reducing waste when building roads using a lean approach and I4.0 with a "system of systems". Hernández-Luna et al. [48] presented a statistical analysis of correlations for energy management in an I4.0 environment. Medojevic et al. [49] revised the energy management literature in an I4.0 ecosystem and dealt with integrating both energy management and I4.0 and their related challenges. Wang and Wang [50] put forward and set up a system based on the digital version of a system, or "a digital twin", of I4.0 to recycle electrical waste and electronic devices. Tsai [51] proposed a mathematical model that considers environmental problems, ABC (activity-based costing) and TOC (theory of constraints) for the green planning and control of the textile industry. Sherazi et al. [52] presented a methodology to collect energy with a LoRaWAN (long-range wide area network) and analyzed its related costs for I4.0. Tsai et al. [53] suggested an optimization model for green production planning with the ABC classification and I4.0. It is worth mentioning that for the environmental aspect, searches to improve energy efficiency by means of the IoT technology in I4.0 were stressed, where sensors will enable energy use to be monitored in real time, and this information can be analyzed and shared through all the supply chain I4.0 links. Monteleone et al. [54] proposed a conceptual model for water management in the agriculture 4.0 context.

With the economic approach of sustainability and I4.0, Bechtsis et al. [55] dealt with materials manipulation processes with the help of AGV (automated guided vehicles) technology. Franciosi et al. [56] revised the literature about maintenance in sustainable I4.0 manufacturing and enabling technologies called maintenance 4.0. De las Heras García de Vinuesa et al. [57,58] proposed a reference framework to evaluate the sustainability of products by focusing on circular economy in the I4.0 context. Ma [59] suggested a reference framework to manage the resources of a management system for warehouses based on I4.0 enablers. Nascimento et al. [60] put forward a business model with circular economy to recycle waste according to an I4.0 approach.

### 3.2. Discussion

I4.0 could cause a growth in industrialization and disrupt the sustainability of existing manufacturing supply chains in terms of higher resource consumption, global warming, and climate

change issues. Therefore, it is relevant to the research of the sustainable supply chain 4.0, i.e., to adopt management practices for manufacturing supply chains that contemplate sustainability and address the digital transformation toward I4.0. Sustainability should be addressed in an integrated manner from its three perspectives: social, environmental, and economic. In this sense, the distribution of the 54 selected articles by approach is as follows: 50 (93%) of the reviewed papers have contemplated the sustainability from the environmental view, 48 (89%) from the economic view, and 34 (62%) from the social view. Also, it is important to highlight that only 10 (19%) papers have also addressed the concept of SC4.0 (Table 3).

We have identified that supply chains' sustainable practice drives towards: using sustainable energy and that the benefits of I4.0 in these chains involve companies being completely connected digitally, reducing the carbon footprint, and supporting decision makers in dynamic decision-making in real time [13]. Additionally, supply chains will have the characteristics to be flexible, sensitive, cost-effective and robust to be competitive in the long-term, sustainable, and resilient [16].

Concerning which characteristics are needed to enable a supply chain 4.0, I4.0 should allow the connection between the customer and supply chain digitally by providing information about smart products use and its status at different stages of the supply chain. Such characteristics enable visualization of the energy efficiency of the product they are using, preventive maintenance, and end-of-life monitoring, which allows recycling planning [10]. In this sense, it is recommended that the knowledge of challenges for the design, operation, control, and optimization for enabling sustainable business models by adopting accurate I4.0 technologies. Thus, the incorporation of characteristics such as sustainable products/operations, lean practices, and IT is required to achieve sustainability in industrial supply chains. The importance of the implication of I4.0 in a sustainable supply chain was identified through the adoption of continuous production processes and 3D printing technology, CPS, IoT, big data, and process analytical technologies. They improve productivity and flexibility of the manufacturing processes, enabling product mass customization and reducing waste of materials across product life cycles, consequently, making them more environmentally and energy efficient manufacturing [13,14].

Regarding the barriers for developing manufacturing sustainable supply chains 4.0, organizational challenges are the most critical ones, followed by legal/ethical issues, strategic challenges, and finally, technological challenges [8]. In this context, a supply chain 4.0 should become adaptive, self-organizational, and self-learning through the following drivers [16]: adaptation, coordination, agility, and sustainability. Thus, the impact of the I4.0 technological revolution, particularly of education and the standards required of the human factor, and the demand for highly skilled workers will change in many areas of companies [37]. Here, it is important to highlight the limitation of I4.0 as the inevitable investment on technology and efforts should be made on finding solutions regarding IT security, workforce with required skills, and information sharing in collaborative business models [13].

With respect to crop and value diversification, it is important to highlight the technologies oriented to the agri-food 4.0/agriculture 4.0 in the agri-food supply chains, i.e., virtualization, big data, map precision, and sensing smart, among others.

Finally, the importance of I4.0 design principles to create new reference models that will act as a basis to include each sustainability aspect has been detected. It has been determined that an intrinsic relationship exists between the reviewed works on the economic and environmental aspects of sustainability, while the social aspect appears to be the least addressed approach. Here, it is necessary to highlight the difficulty in designing sustainability indicators because of the unconstrained nature of the social factor, which transcends to companies towards suppliers, customers, and manufacturers [38]. Social issues can rely on indicators such as emissions, working conditions, and publicity/social acceptance. It is important to highlight the benefits in the social aspect, which is expected for a better integration and inclusion of employees. Challenges in this matter are related to the impacts on substitution of jobs by technological systems. One key aspect, namely I4.0 technologies, can help to improve these aspects.



#### 4. Conclusions

This article has analyzed the different sustainability aspects in supply chains in the digital transformation context that I4.0 represents and identified the challenges and advantages of adopting I4.0. We have identified different reference frameworks and conceptual models on supply chains 4.0 and sustainability. Only a few works that deal with the social approach of sustainability and I4.0 on the whole have been identified, given that most tend to focus mainly on enabling technologies to reduce costs and for monitoring. Contrarily, more works have been published with an approach related to economic and environmental aspects and I4.0. Therefore, there is a need for a reference sustainable and standardized I4.0 framework. This work has identified different projects that have adopted sustainability as part of their objectives: “Industrie 4.0”, “agri-food 4.0/agriculture 4.0”, “Making Indonesia 4.0”, “Taiwan Productivity 4.0”, “Made in China 2025”, “China Manufacturing 2025”, “Horizon 2020”, and “Thailand Sustainable Smart Industry, MSIE4.0”, among others. It has verified the sustainable manufacturing and sustainable supply chain 4.0 concepts, as well as models, algorithms, heuristics, and metaheuristics to deal with the sustainability and I4.0.

Future research lines should center on validating the different proposed conceptual models, reference sustainable frameworks and I4.0, mathematical models, and solution approaches to evaluate the impact of I4.0 enablers in a sustainable supply chain from the three perspectives—economic, environmental, and social—in an integrated manner. Thus, more applied research and real-world applications on the incorporation I4.0 into supply chains and manufacturing systems are recommended. Also, future research could focus on proposing solutions for challenges/barriers caused by agriculture 4.0/industry 4.0 adoption in the SMEs background. Applying novelty models on self-optimizing agricultural supply chain structures [62,63] in terms of cost of distribution and improving demand management, both contemplated within variable lead times scenarios (which may affect product obsolescence), could be a relevant research field. In this sense, a proposal and validation in a real world agri-food supply chain (where disruptions that most affect perishable products) related to crop diversification is a forthcoming work.

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