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Systematic Review

Technologies Associated with Industry 4.0 in Green Supply Chains: A Systematic Literature Review

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Abstract: This study aims to review the literature published in the last 15 years (2007–2022) that relates to Industry 4.0 and the green supply chain (GSC). This review identifies the enabling technologies for Industry 4.0 that are being applied to improve GSC practices and establishes the points of its future research agenda. A systematic literature review (SLR) of this topic was conducted using Web of Science and Scopus as databases. Our study combined descriptive and conceptual analysis, guided by three review questions. These questions were proposed to identify how Industry 4.0 technologies can enhance the development of GSCs. After refinement, 75 papers were analyzed. This research underlines what technologies of Industry 4.0 are being implemented to improve GSC aspects. In addition, it shows in which GSC practices the application of these technologies is being considered and what challenges of implementing Industry 4.0 in GSCs have been identified in the literature. Finally, all these findings enhance establishing a future research agenda. Current studies have focused on analyzing the benefits of implementing Industry 4.0 in GSCs. However, this paper delves into enabling technologies for Industry 4.0 and GSC practices and does not only discuss them in general terms.

Keywords: green manufacturing; Industry 4.0; supply chain management; sustainable production

Citation: Morella, P.; Lambán, M.P.; Royo, J.; Sánchez, J.C.; Latapia, J. Technologies Associated with Industry 4.0 in Green Supply Chains: A Systematic Literature Review. *Sustainability* **2023**, *15*, 9784. https://doi.org/10.3390/su15129784

Academic Editor: Claudio Sassanelli

Received: 27 April 2023
Revised: 6 June 2023
Accepted: 13 June 2023
Published: 19 June 2023

1. Introduction

In recent years, enterprises are more aware of their supply chains' social and environmental impacts [1]. Sustainability in the supply chain is recognized as a valuable and effective way to obtain economical, operational, and environmental performance [2], whereas the traditional supply chain is rarely focused on environmental protection and resource conservation [3].

This idea has boosted the term green supply chain (GSC) as an interesting way to integrate environmental thinking into the supply chain [4].

At the same time, manufacturing technology is being rapidly developed thanks to the advances in industrialization and informatization methods [5], known as Industry 4.0.

A considerable number of studies point out that Industry 4.0 initiatives can help industries to incorporate environmental protection and control initiatives for greening supply chains [6–10]. For this reason, we consider that a deeper analysis of this topic is interesting for researchers and scholars.

The analysis of the use of enabling technologies for greening the supply chain presented in previous studies has been conducted, it being a generalized version of the research from the authors' thesis, and it is guided by the following review questions (RQs):

RQ1: How does the literature describe the contribution of individual or combined Industry 4.0-related technologies to the implementation of a GSC?

RQ2: In which aspects of the GSC is the implementation of Industry 4.0-associated technologies being studied? What are the benefits of this implementation?

RQ3: What challenges of implementing technologies related to Industry 4.0 in a GSC have been identified from the literature?

At the beginning of the research, previous studies that assessed the relationship between Industry 4.0 and GSC were reviewed. This review enhanced the identification of their limitations.

One of the limitations was the number of papers analyzed, as well as the sources where they came from. As an example, the studies [11–13] analyzed less than 40 papers derived only from peer-reviewed sources. Moreover, bibliometric analyses, such as those conducted by [14–16], were only focused on the quantitative analysis of the topic. Although they highlighted the evolution of the relationship between Industry 4.0 and GSCs, they did not carry out deep research. Additionally, many of these reviews have focused on identifying the link between Industry 4.0 and GSC as general concepts. However, far too little attention has been paid to the use of technologies associated with Industry 4.0 and their usefulness in specific GSC aspects. As an example, [17] conducted a systematic literature review about the potentials of Industry 4.0 for supply chain management with respect to the triple bottom line, but they do not study which technologies are specifically more useful for environmental aspects. In addition, several authors recognized the importance of these cutting-edge technologies for greening the supply chain, but they focused only on a specific one. For example, [18] analyzed the use of big data in sustainable environments, whereas [19] highlighted the sustainable actions enabled by simulation technologies. Based on the above discussion, the purpose of this study is to provide an exhaustive review of the literature regarding the use of Industry 4.0-related technologies in GSCs and their implementation to achieve specific GSC aspects. Additionally, the challenges of this implementation and topics for the future research agenda are also identified.

The rest of this paper is organized as follows: Section 2 introduces the GSC aspects and the Industry 4.0 technologies and discusses the combination of both topics. Section 3 describes our research methodology. Section 4 presents the analysis of the literature. Finally, the paper ends with conclusions and proposals for future research agendas in Section 5.

2. Literature Review

This paper aims to study the existing research on the application of enabling technologies in Industry 4.0 to develop a GSC. Particularly, this section reviews these terms to conceptualize the terminology used in the SLR. Moreover, the previous studies about using these technologies to develop a GSC are identified in this section.

2.1. Green Supply Chain

A GSC was defined by [20] as "integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life". In comparison to a sustainable supply chain (SSC) that attends to environmental, social, and economic aspects, a GSC is focused on the environmental issues that integrate supply chain management, environmental protection, and resource optimization. For this reason, an SSC can be considered as an extension of a GSC that includes economic and social issues [21]. The difference between a GSC and an SSC is a key concept in understanding the scope of this work. It is the reason why we only address environmental issues in this study [22]. The concept of a GSC encompasses all the policies, processes, and procedures related to the reduction in negative impacts caused by supply chains. These activities that enable the implementation of a GSC are known as GSC practices [23]. They involve, for example, recycling, reducing energy consumption and waste, life cycle analysis, and improving energy efficiency and costs of life cycle, according to green standards [4].

Many scholars have grouped them, but there is not a consensus about the groups' distributions. Some authors correlated the GSC aspects with the echelons of supply chains, for example, ref. [24] distinguished between green procurement, green manufacturing, green design, and green distribution, whereas other authors added specific practice for packaging and legislation [25,26]. The authors of [27] asserted that a GSC covers all aspects from green purchasing to reverse logistics, including all the supply chain statements.

The categorization presented by [27,28] provided a large and comprehensive list of aspects and practices of a GSC; for this reason, it is used in this research to categorize the papers by GSC aspects as follows:

- Reverse logistics: Goods returned from consumers to manufacturers or distributors to achieve a more environmentally friendly world. Reverse logistics recovers the products at the end of their life and resells, reuses, or refurbishes their components [29–31].
- Green warehousing: implementing environmentally friendly practices in warehousing can save cost and energy [32].
- Green design: Product design that considers the environmental issues. This design reduces material and energy consumption. The environmental impacts of products during their life cycle are reduced too. Moreover, these products are designed to enable easy disassembly and, therefore, easy remanufacturing and recycling [30,33].
- Green manufacturing: manufacturing and production processes are re-engineered to reduce their environmental impacts, e.g., minimum waste generation, energy saving, or cleaner production [30].
- Carbon management: Carbon emissions are considered an important element in GSC because 80% of carbon emissions are produced by supply chains. Carbon footprint monitoring helps to identify how to reduce carbon footprint. This reduction means reducing manufacturing costs and energy consumption [34].

2.2. Industry 4.0 and Enabling Technologies

At the same time, information and communication technologies (ICTs) are rapidly developing. This is leading to a more digitized industry known as Industry 4.0, which could enhance the implementation of this GSC [8]. Industry 4.0 involves enabling technologies such as cyber–physical systems (CPSs), Internet of Things (IoT), cloud computing, and others related to the trend of industrial automation [35].

Among the enabling technologies, the CPS is considered the core technology of Industry 4.0. It integrates and coordinates physical and computational elements, enabling machine-to-machine communication and production optimization by decentralizing control systems [36]. The IoT allows communication between physical objects and their sharing to coordinate decisions too. In addition, it allows more visibility and better knowledge of the operations and assets of a company [37]. Big data can collect and analyze all the information acquired by these technologies for applications in statistical or predictive analysis [38]. This information can be provided to customers on demand thanks to cloud computing technology [39] that uses the internet and remote server to maintain data and applications [40]. The combination of these technologies is considered to improve efficiency, productivity, and competitiveness [41]. In comparison with traditional technologies, they enable the customization of each item of the same product thanks to their flexible lines and faster adaptation to changes or breakdowns [42].

Regarding industrial automation technologies, artificial intelligence (AI) replicates human intelligence through machines. AI technologies, such as machine learning and deep learning, help to develop challenging operations in industry that typically require human intelligence [43]. According to [44], "Blockchain is a distributed, immutable, transparent, secure and auditable ledger, which records all transactions executed and shares them among all participants". This technology allows information exchange in supply chains in a trustworthy, secure, and authenticated way [45]. Simulations enhance the design of synthesized models that simulate the properties of the implemented model [46,47]. Robots are also evolving into an autonomous, flexible, and cooperative technology that enables the interaction between the digital and physical worlds, reductions in costs and hazards, and advances in precision and quality [48,49] because they substitute the human resources that were in charge of those manufacturing process. In the same way, autonomous vehicles

(AVs) can help to manage production lines efficiently, handle warehouse inventories, and support intra- and inter-logistics services [50] that traditionally must be performed with forklifts. Finally, additive manufacturing (AM) is a versatile technology for flexible and personalized manufacturing systems that enables the design and manufacturing of more complex features than traditional manufacturing. Furthermore, it reduces material waste thanks to its additive capacity instead of removing material from raw material [51].

It is considered that supply chains can be improved by combining and integrating these new technologies. The combination of CPS, IoT, AI, cloud computing, and big data enable connectivity, interoperability, and decentralization [52]. This combination together with RFID (Radio Frequency Identification, a technology based on the use of the electromagnetic or electrostatic coupling in the RF portion of the electromagnetic spectrum to transmit signals [53]) can increase the flexibility and speed of supply chains. Additionally, ref. [54] asserts that the combination of AI, IoT, cloud computing, and machine learning technologies improves decision making.

2.3. GSC and Technologies That Enable Industry 4.0

The technologies associated with Industry 4.0 have a significant impact on GSCs and enable the adoption of GSC practices [55–57]. An example of this impact is the study of [58]. The author compared two supply chains: one used a traditional method and the other one used Industry 4.0 and its associated technologies. His study concluded that the advantages of applying Industry 4.0 together with coordination enable the leadership of this supply chain in terms of sustainability.

According to [59], digital transformation contributes positively to minimize waste, non-value-added activities, inefficiencies, and emissions. In particular, information exchange and real-time acquisition data improve productivity and flexibility and reduce waste of materials across product life cycles [60]. Therefore, they are crucial for the growth and improvement of green processes [61,62].

2.4. Gaps Identified in Literature Review

During our literature review study, we identified some gaps as opportunities for future research.

In summary, there is a lack of research about how technologies are helpful to develop a GSC. Moreover, there is an absence of literature reviews where the analysis is in-depth and qualitative, not only quantitative, as is the case of the analyses presented above. Finally, there is a shortage of cases in the implementation of technologies. These cases could contribute to more solid conclusions about the application of these to real environments. As an example, according to [22], GSC reduces the environmental damage of supply chain activities and improves organizational performance. Although the enterprises are aware of these benefits, there are not many successful cases presented in the literature.

3. Methodology

This study was conducted using the SLR approach. This is a common analysis to summarize the existing evidence concerning treatment or technology, identify gaps in current research, suggest areas for further investigation, and provide a framework/background to position new research activities [63]. In addition, an SLR enables us to identify, evaluate, and interpret all relevant and available information to analyze any topic of interest [64].

Following the guidelines in [63], this study combined a bibliometric overview of the literature identified around this topic and a conceptual analysis guided by specific RQs. Figure 1 illustrates the proposed research methodology.

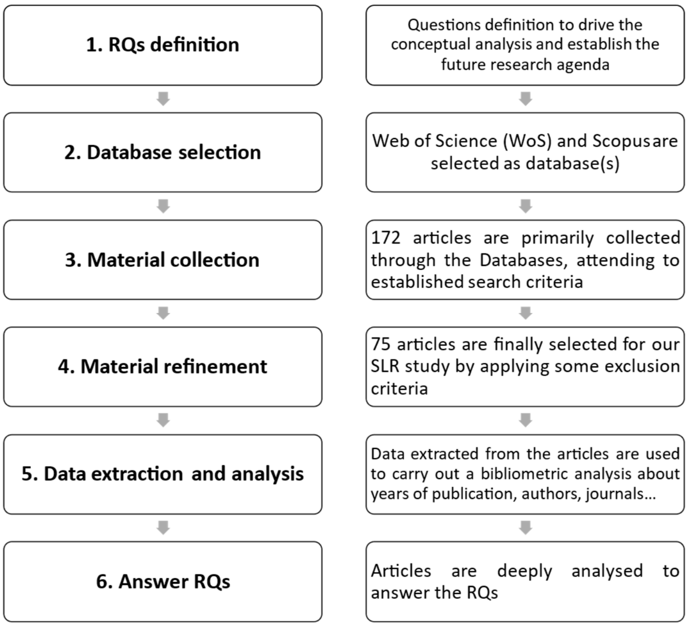

Figure 1. Research methodology procedures.

3.1. RQ Definition

The RQs defined in Section 1 enhance the development of this study and are used as guidance to summarize the current research on the implications of Industry 4.0 in GSCs (see Table 1).

Table 1. Review questions and motivations.

Review Question	Motivation
RQ1: how do individual or combined Industry 4.0-related technologies contribute to the implementation of a GSC in the literature?	There is not a specific literature review study about the use of technologies 4.0; therefore, our RQ1 intends to fill this gap. Furthermore, managers and scholars could easily identify how to obtain a green benefit from technologies associated with Industry 4.0.
RQ2: In which aspects of the GSC is the implementation of Industry 4.0-associated technologies being studied? What are the benefits of this implementation?	There is a wide range of aspects and practices involved in GSCs [28]. Therefore, it is interesting to know which of these aspects can be improved with the use of technologies related to 4.0.
RQ3: what challenges of implementing technologies related to Industry 4.0 in a GSC have been identified from the literature?	Challenge identification is crucial to succeed in implementation.

3.2. Database Selection

To identify the most relevant publications, two databases were used because some studies assert that using different databases improves the results obtained in literature reviews [65]. Web of Science (WoS) and Scopus are considered the major tools to evaluate research practices, and they are the most comprehensive sources of publication metadata [66]. For these reasons, both have been selected to develop this SLR.

3.3. Material Collection

To identify the literature, both GSC and Industry 4.0 terms should be represented by keywords. In the case of GSC, only the key word "green" was used because we wanted to avoid the term "sustainable" appearing. In the case of Industry 4.0, three different terms have been used as synonyms for the search. Regarding the time frame, 15 years was considered enough because the term Industry 4.0 appeared in 2011. Even so, we wanted to analyze a few years further back to see if the term "smart manufacturing" had a place in the older literature. Finally, we searched the following combination of keywords in both databases: "(green) and (supply chain OR supply-chain) and (Industry 4.0 OR I 4.0 OR smart manuf*)" from 2007 to 2022.

This SLR considered all fields of knowledge due to the multidisciplinary nature of Industry 4.0 research [67]. Furthermore, it is not limited to peer-reviewed journal publications since they are not the only source of relevant studies. For example, [68] asserted that using only peer-reviewed publications was not enough to provide a complete idea of their topic.

At this point, the search criteria framed our study around 172 papers related to Industry 4.0 and the green supply chain.

3.4. Material Refinement

Firstly, the duplicated papers and those that were not written in English were deleted, with 143 papers remaining. In the second step, three exclusion criteria (EC) were applied to ensure that the papers addressed the aim of the study. Then, all the abstracts were read. EC1 and EC2 excluded the papers that were not related to Industry 4.0 (EC1) or GSCs (EC2) or they used the term only to contextualize or exemplify some facts. As examples, ref. [69] presents green production as an advanced manufacturing mode but it is not related to advanced technologies, and [70] analyzes the impact of Industry 4.0 on logistics but without a green perspective. After full-text reading, EC3 excluded the papers about applications out of the GSC, such as building [71], chemical research [72], smart cities [73], or transportation [74]. In addition, EC3 discarded papers about the social dimension of sustainable supply chains, since it is not considered part of the GSC term [75] (e.g., [76]). After this refinement, 66 papers were identified within the scope of the research.

During full-text reading, the references cited by these papers were also reviewed to check that relevant papers of this topic were not missed, following a backward snowballing methodology. Thus, 4 papers that did not appear in the initial search were identified as interesting for the research topic and therefore were added [77–80]. Furthermore, based on previous studies' research, we added 5 papers that were interesting for the research, although they did not appear in the database search. Three of them complemented the research on the challenges of implementing Industry 4.0 and its constituent technologies in GSCs [81–83], whereas the other two were related to specific aspects of GSCs [11,84]. Finally, 75 papers were selected for the systematic review (see Figure 2 for retrieved publications).

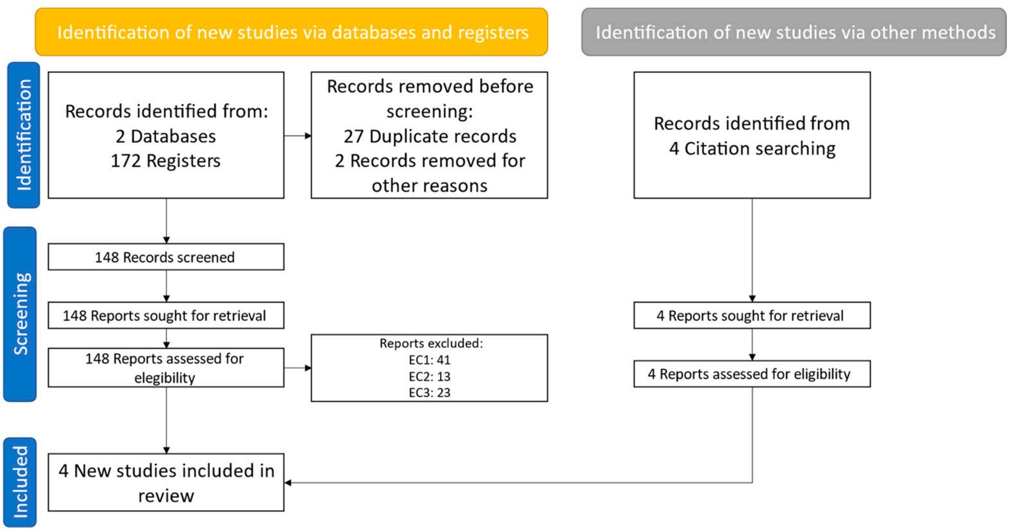

Figure 2. PRISMA (see Supplementary Materials) flow diagram.

After that, we proved the saturation of our search strategy to demonstrate that the majority of relevant works were included.

Saturation can be defined as the stage in which there are no new ideas originating from the searched data [85]. In this case, we used the data saturation methodology explained in [86]. This methodology looks for a saturation point to demonstrate that the search for new work did not add new information on the topic.

The index keywords were used to evaluate whether new information appeared in a paper or not due to their standardization and their capability to synthesize themes. The index keywords were counted only the first time they appeared within a paper. Therefore, we could see how many papers added new insights to our research and if the data saturation point had been achieved with the current search or if it was necessary to continue. As can be seen in Figure 3, new index keywords were found until paper number 56. After that, there were no new major topics included in the papers. Therefore, it can be concluded that our search strategy included most of the relevant papers associated with technologies 4.0 and GSC.

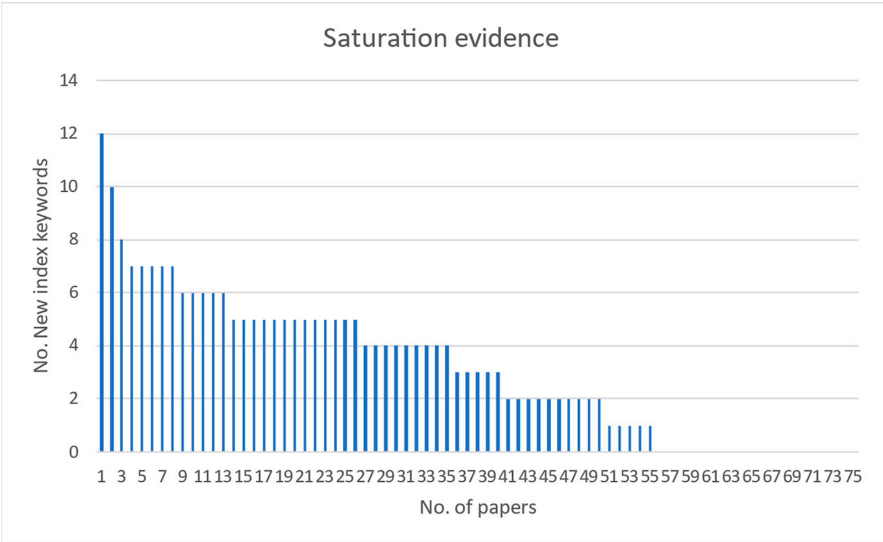

Figure 3. Saturation evidence for the search strategy.

3.5. Data Extraction and Analysis

First, a descriptive analysis was carried out to analyze the following aspects: distribution of papers by year of publication, journal, and type. After that, a qualitative analysis in line with the RQs was conducted, and papers were categorized according to GSC aspects and technologies 4.0 to enhance the identification of key themes. Papers in which themes overlapped were reviewed under all of them.

Papers were classified according to both topics (GSC and Industry 4.0). In the case of GSC aspects, they were categorized as follows, according to the classification made by [28]:

- Reverse logistic;
- Green warehousing;
- Green design;
- Green manufacturing;
- Carbon emissions management.

Regarding technologies associated with 4.0, the papers were classified by technology, including AI, AM, autonomous vehicles, automation and robots, big data, blockchain, cloud computing, CPS, simulations, IoT, and RFID. The combination of both categorizations enhanced the linkage between GSC aspects and technologies related to 4.0 necessary to answer the RQs.

4. Literature Review Analysis

4.1. Descriptive Analysis

Authors should discuss the results of their studies and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

The 75 publications were classified by source of publication, year, and journal.

Analyzing the type of publications (see Figure 4), the dominant type is journal article, contributing 81% of the papers. Moreover, almost 10% of the papers are not peer-reviewed papers. This figure is not very large because most of the papers are articles that belong to journals where peer review is widespread.

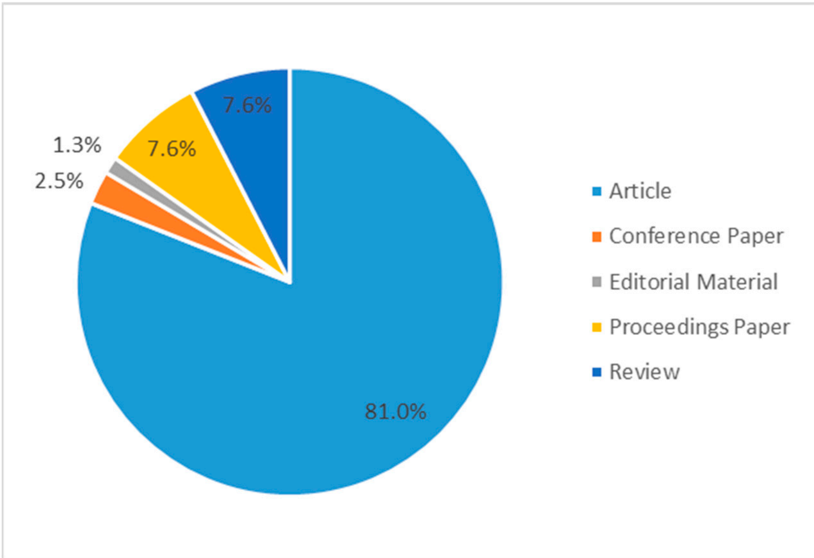

Figure 4. Types of publications.

Figure 5 shows the types of publications across the years; before 2017, our researched topic appears only in proceedings papers, and articles do not appear until 2017. Note that our period of analysis stretches from 2007 to 2022; however, the first paper appears in 2011, corresponding with the appearance of the term Industry 4.0 during Hannover Messe [37]. This distribution shows a growing significance given to the research about Industry 4.0 together with GSC in the literature in the last 3 years. This finding confirms the growing acknowledgment of combining Industry 4.0 with GSC in the scientific community.

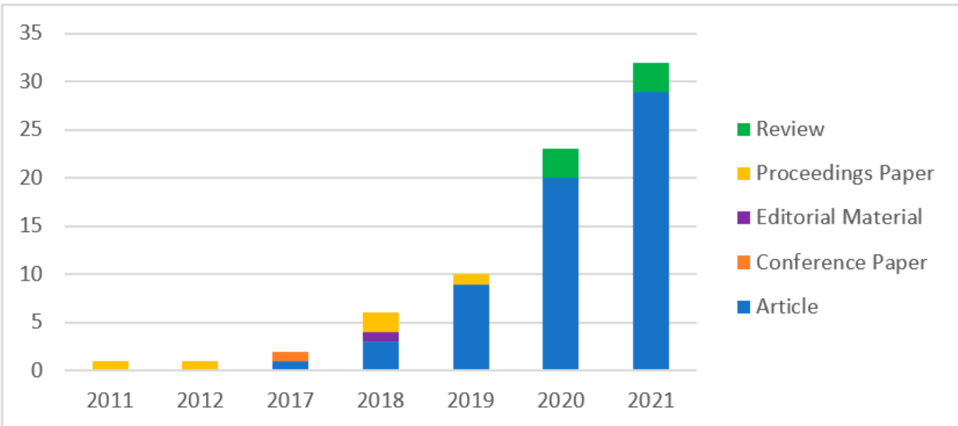

Figure 5. Types of publications across the years.

In addition, it must be highlighted that the reviews mentioned in Section 1 analyzed the literature until 2018, when there were not many contributions about this topic [12,13,87], or their studies were limited to a few years. For example, ref. [11] carried out a study only during the period 2017–2020. This evidences the necessity of conducting an SLR on this topic.

Focusing on the distribution by journal type, numerous journals have published papers about the implementation of Industry 4.0 in GSCs (75 papers published by 46 journals). The top 10 journals (see Figure 6) contribute about 50 % of the publications (37 of the 75 papers). The analysis shows that journals focused on sustainability (e.g., Sustainability, Resources, Conservation and Recycling, and Journal of Cleaner Production) and manufacturing and operations (e.g., Production Planning and Control, International Journal of Production Research) have a special interest in this topic.

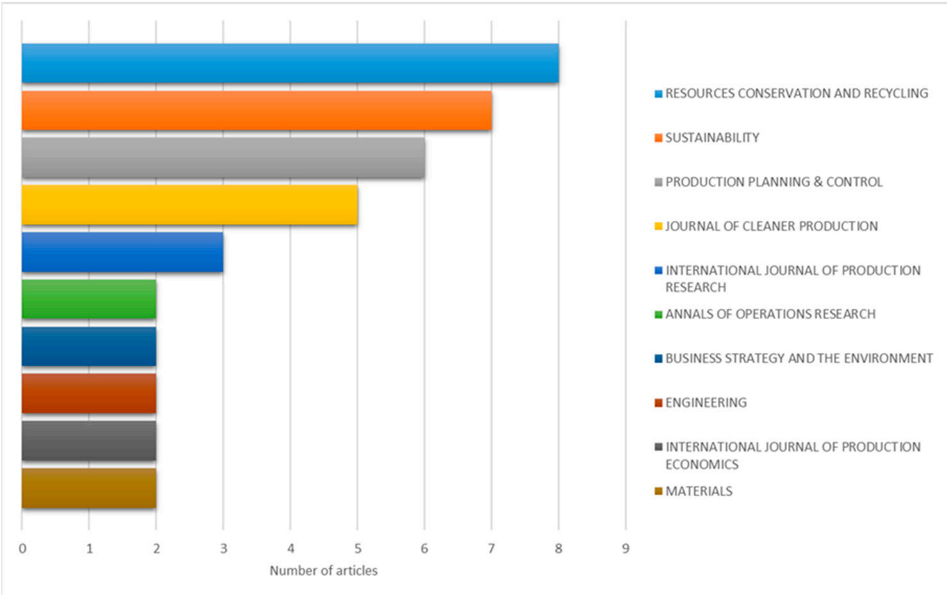

Figure 6. Paper classification by journal.

4.2. Content Analysis

In this section, the three RQs are addressed, and therefore, we present the outcomes from the qualitative analysis.

4.2.1. RQ1: How Does the Literature Describe the Contribution of Individual or Combined Industry 4.0-Related Technologies to the Implementation of a GSC?

This section aims to highlight which Industry 4.0-enabling technologies are the most studied in the literature for implementation in a GSC. Analyzing the classification of papers based on the technologies described in Section 2, it is shown that 11 different technologies have been identified in 45 of the 75 papers. Among the most mentioned technologies are the IoT, big data, CPS, and AM (see Figure 7 and Table 2). From this classification, it turned out that there are technologies that are usually implemented individually (e.g., AM), whereas technologies such as RFID or CPS are implemented as a combination of technologies.

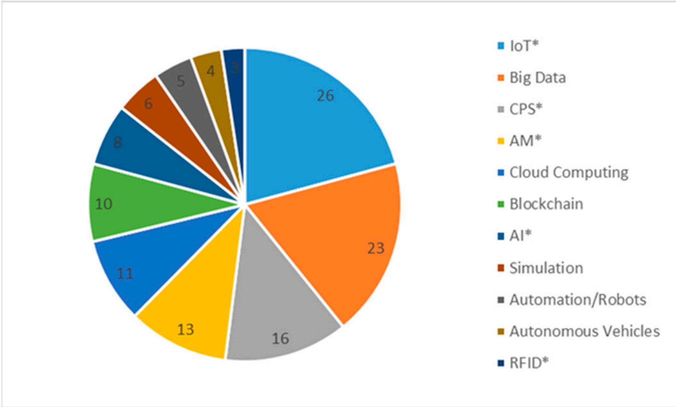

Figure 7. Most studied technologies associated with 4.0. * Artificial intelligence (AI), additive manufacturing (AM), cyber–physical system (CPS), Internet of Things (IoT), RFID (Radio Frequency Identification).

Table 2. Paper distribution by Industry 4.0 technologies.

Individual Technologies	
AI	[81,88–92]
AM	[1,11,12,92–100]
Autonomous vehicles	[92–94,98]
Automation/robotics	[92–94,97,98]
Big data	[11,92,96,101–104]
Blockchain	[57,92,96,105–108]
Cloud computing	[11,92]
IoT	[79,92,96,98,109]
Simulation	[12,92,94,110]
Combined technologies	
IoT and big data	[111,112]
IoT and CPS	[78,113]
IoT and RFID	[114,115]
IoT, big data, and CPS	[16]
IoT, big data, and cloud computing	[80]
IoT, big data, CPS, and cloud computing	[116–119]
IoT, big data, CPS, cloud computing, and AI	[106]
IoT, big data, CPS, cloud computing, and simulation	[120]
IoT, CPS, big data, cloud computing, simulations, AI, AM, and autonomous vehicles	[97]

A deeper analysis allows us to characterize the use of these technologies in a green environment.

Internet of Things

The IoT is conceived as a tool to facilitate the information flow through the entire GSC. The IoT plays an important role in the data acquisition and analysis related to inventory, transportation, facilities, and customers. For instance, IoT devices installed in material handling equipment allow us to know if equipment characteristics are beyond boundaries, for example the speed [109]. Another example is presented in [79], where the IoT identifies and classifies the components of products to manage recovery operations. In addition, this data collection can be useful in energy management and, therefore, in reducing energy consumption. As it is suggested by [108], the IoT can collect energy consumption information for its visualization. After that, decision-makers can use this information to manage energy-efficient practices. Overall, the IoT enables the real-time exchange of information with reliability [12], improving the efficiency and quality of production processes and decision making [92].

Big data

Research findings indicate that big data is an important technology to develop a competitive and green supply chain. The statistical survey conducted by [101] suggests that an appropriate infrastructure of big data can provide a competitive advantage for GSCs. In the same way, the analysis conducted by [102] using a descriptive qualitative method approach in which source and data collection is conducted through company observation, documentation, and interviews with key company managers. This analysis allows them to pose the following hypotheses: "Big data analytics have a positive relationship with I4.0 adoption" and "Sustainable manufacturing has a positive relationship with I4.0 adoption". In short, the study asserts that the use of big data allows the management of more transparent energy consumption and recycling of resources. The same idea of energy consumption management and optimization through big data technology is presented in [96]. Moreover, big data can help managers through better visualization of the information for decision making [103], analyzing market trends [98], or even comparing the impact on the supply chain before and after implementing GSC aspects [104].

Additive manufacturing

AM enhances a circular production system, since the materials used in AM processes can be recycled [1,92,100]. Apart from that, it is considered as a key technology for reducing cost, energy, and material waste [9,11,93,99] because of its capability for working just-in-time and the elimination of machine setups due to changeovers. Furthermore, it enables a decentralization of the production and shorter distances between end users and manufacturers, reducing transport cost and environmental impact [98,100].

Cloud Computing

In the same way, cloud computing technologies facilitate the sharing of information during the entire life cycle of products [92], providing real-time information about raw material status and production capacity. This can be used for achieving GSC practices, such as waste management [98].

Blockchain

Although blockchain has found little application in supply chains, it has great potential to increase transparency, reliability, and availability of information [107]. The quantitative, questionnaire-based study conducted by [105] determines that blockchain technology promotes and enables the tracking of pro-environmental behavior. This technology makes it possible to obtain, manage, and use data on a product throughout its life cycle, resulting in better product design, more efficient production planning, and environmentally responsible end-of-life recovery [98]. This behavior leads to improved green supply chain practices. In addition, traceability serves to increase stakeholder confidence in green supply chains [96], for example, by tracking the environmental quality of materials [92] or reducing rework by knowing the full traceability of defective products, which reduces resource use and greenhouse gas emissions [57]. In addition, the actual carbon footprint of products can be tracked, and the exact amount of carbon tax to be charged to each company can be determined [108]. Ultimately, blockchain technology ensures environmentally friendly product design and production [121].

Artificial Intelligence

Once the information is acquired, AI plays an important role in decision making [92]. The articles dealing with AI tools present different case studies. They build on previous experiences to create models that detect possible failure patterns. One of the studies has developed a model that predicts chiller operating efficiency and a chiller health assessment model. This prediction allows meeting the chiller load demand and minimizing electricity consumption given the existing infrastructure [91]. Another study presents a system that makes decisions to meet production targets in a production plant in the presence of uncertainties [89]. Finally, ref. [81] proposes the use of AI to solve technical challenges related to process safety. For example, knowledge-based reasoning for process safety or dynamic risk assessment. Hence, these models minimize energy consumption and enable more efficient decision making.

Simulations

Simulations can be useful in testing and validating tools and systems [110]. This technology allows the measurement of process efficiency before its implementation through the simulation of activities [92]. For example, simulating and testing activities that are supposed to reduce energy consumption [12].

Robots

Following the idea of process efficiency, robotics technology is a key element to improve efficiency by reducing resources and errors. Therefore, its implementation can minimize energy consumption and material waste [92,93].

Autonomous vehicles

Autonomous vehicles integrate production, logistics, and planning movements. This integration enables the optimization of movements, reducing fuel consumption and emissions [93]. Moreover, their use improves material handling and reduces carbon emissions, improving environmental performance [108].

Combination of technologies

Considering the combination of technologies involved in Industry 4.0, 23 of the 75 papers have been studied. Note that the technologies studied more in combination are enabling technologies, such as IoT, CPS, cloud computing, and big data.

They are considered key technologies for smart and sustainable factories (as suggested in [16]) because they enable the treatment of data to achieve valuable information that can be seen through cloud platforms [12,80,106,118]. This enhances the development of indicators to avoid waste and reduce emissions [116] and the monitorization of energy consumption, equipment status, or product quality [120].

As case studies, [119,122] combined these four technologies to develop energy monitoring systems and KPIs by acquiring real-time data, whereas [111] implemented big data and IoT technologies to check the quality of products, improving decision making and reducing waste.

Another repeated combination of technologies is IoT and RFID to record real-time information during the entire product lifecycle, reducing the complexity of the recycling process [114,115]. Adding RFID can improve tracing and tracking in reverse logistics, lowering carbon emissions during transportation [95].

Finally, [97] concluded that integrating all of these technologies (IoT, CPS, big data, cloud computing, simulations, AI, AM, and autonomous vehicles) enables human–machine collaboration to automate the process economically and environmentally.

4.2.2. RQ2: In Which Aspects of the GSC Is the Implementation of Industry 4.0 Technologies Being Studied in? What Are the Benefits of This Implementation?

This section aims to identify which technologies associated with Industry 4.0 are used for each GSC practice. Within the sample of sixty-seven papers that specifically talk about GSC aspects (identified in Section 2), five different aspects have been found: reverse logistic, green warehousing, green design, green manufacturing, and carbon management (see Figure 8). These five aspects are developed in the following subsections.

Green manufacturing

According to Figure 8, the most studied aspect of GSC within the selected papers is green manufacturing, which appears in 46 of the 67 papers.

As we defined in the literature review section, green manufacturing tries to diminish the environmental impact of production processes. Most of the papers focus on energy consumption due to its high impact in green manufacturing [123]; 70% of the energy consumption in industries belongs to machines [124].

Scholars present AM as a smart production system capable of reducing energy consumption, since it reduces the difficulty of manufacturing complex 3D parts, which results in low energy utilization [1,93,94,97,99].

Others point out that one of the keys of investment to lower energy consumption during manufacturing is robotic development [93]. Moreover, robots reduce the number of human resources and, therefore, the heating and lighting costs, as a transition to a “lights out factory” [125].

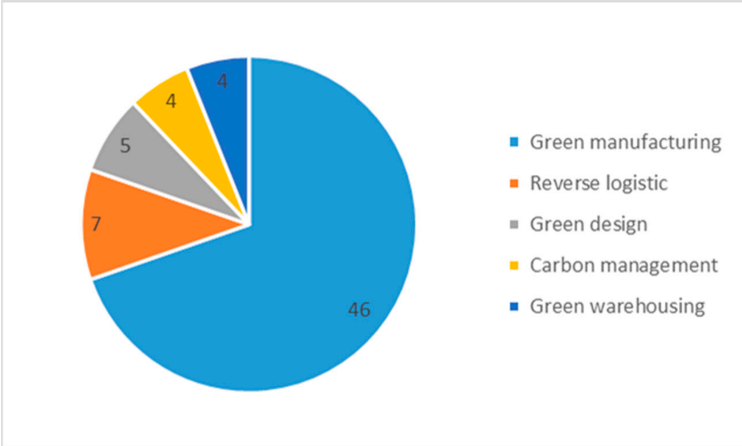

Figure 8. GSC aspects most frequently studied.

Furthermore, the use of CPSs and the IoT enables the real-time monitorization and, therefore, the optimization of energy consumption [94], whereas simulations can reduce energy consumption by simulating activities instead of developing them in the physical world [12,91].

Another interesting green manufacturing practice is the adoption of a lean production, which is known as lean and green. Although [126] in their literature review and [127] in their quantitative measurement do not identify the relation between smart factories and the lean and green supply chain, other authors consider that the purposes of implementing Industry 4.0-associated technologies (efficiency, productivity, flexibility, and transparency) must be also considered in lean and green [128]. In the same way, ref. [88] consider that Industry 4.0 technologies enhance the reduction in delivery times, deliver high quality products, minimize waste, and enhance risk aversion, considered lean terms. These terms reduce carbon footprint and GHG emissions at the same time. The authors of [117] revealed that lean terms and Industry 4.0 enabling technologies are beneficial for achieving optimizing and cleaner production. In this case, they reduced the lead time by 25.60% and the carbon dioxide, methane, and nitrous oxide emissions by 55%. The authors of [129] identify efficiency improvement and an increase in flexibility as the outcomes of integrating Industry 4.0 with lean and green practices. Finally, ref. [130] presents a roadmap for integrating lean and green with Industry 4.0 technologies because they consider this as crucial for developing viable GSCs.

Among all the technologies, CPS, IoT, big data, and cloud computing enable higher effectiveness and resource efficiency [116] and are crucial due to the high level of information sharing required by lean and green supply chains [83,118,131].

Finally, green manufacturing aims also to gain production efficiency, which is considered one of the benefits of implementing Industry 4.0 [11,77,106].

According to several authors, adopting CPS, IoT, big data, and cloud computing technologies for real-time data acquisition enhances and speeds up decision making, improving scheduling and operational efficiency [62,78,80,111,112,132].

Our study identifies three cases of AI implementation for this purpose, where AI detects potential failures and enables quicker decision making [81,89,103].

Simulations are also considered interesting for making strategic decisions because risks can be assessed before the implementation of the strategy [113,121,133].

Green design

With respect to green design, three different practices have been detected.

Design for recycling is described by [11] as “Designing in a manner that will enable waste materials with specified properties to be recovered and used again in the manufacturing process or by others is essential”.

This practice has been identified in two papers using AM. First, AM enables the recycling of waste materials to be used as raw material [100]. The second point is the design of new green products. Here, the capability of AM in manufacturing complex and high-resolution features which often cannot be achieved within the constraints of traditional manufacturing methods is crucial [94].

Green design also consists in designing products which reduce the consumption of materials and energy [134]. In this sense, ref. [94] suggest that simulation technologies can introduce product innovations for an eco-friendlier product, saving energy and material consumption.

Finally, ref. [105] propose the use of blockchain to reduce the negative environmental effects of products, which is another purpose of green design, by sharing raw material information in a more secure, reliable, and trusted way.

Reverse logistic

Reverse logistic is a GSC aspect that covers the level of recovery and return of used products through operations such as tracking and tracing [1].

All the papers which studied this aspect of GSCs suggest that the IoT enhances information management [11,79]. The combination of the IoT with RFID tags enables the information record of products through their life cycle and tracks them in real-time, reducing the uncertainty and complexity of the product recycling process [114,115]). The authors of [9] add CPS and cloud computing technologies to the IoT and RFID to improve these track-and-trace operations by acquiring and sharing information about products and processes.

Carbon management

Another GSC aspect identified in this study is carbon management, particularly in relation to carbon reduction targets. Therefore, the monitorization of carbon footprint is attracting more attention in the manufacturing environment [120]. Technologies such as CPS, IoT, cloud computing, and big data are necessary to achieve this monitorization, since they enable the acquisition of real-time information.

In this sense, the case studies analyzed which consider this aspect of GSC agree on developing KPIs for monitoring carbon emissions. The authors of [10] developed four indicators that together assess carbon dioxide damage based on technology-induced logistics performance indices, economic growth, industry value added, and high-tech industry. The case study reported in [119] evaluated the six big losses of Nakajima in carbon footprint units.

Green warehousing

With regard to green warehousing aspects, two interesting practices have been identified. The first practice is the decrease in inventory levels. CPS, IoT, big data, and cloud computing technologies with the help of AI can adjust the allocations and routes of goods knowing in real-time the available resources and space, as suggested by [98].

The other practice proposes the use of technologies to optimize material flows. In particular, autonomous vehicles are considered efficient in material handling operations due to the reduction in human intervention [108]. Moreover, the acquisition of real-time data thanks to the IoT enables faster decision making, thus accelerating material flows. The information collected about material call actions can be used to optimize material flows [92,125].

To summarize, Table 3 illustrates the relationships found in the literature between Industry 4.0 cutting-edge technologies and GSC aspects divided by practices. The value inside the summary cells shows how many papers have cited the implementation of each technology to improve a GSC practice. The results show that RFID is only being considered by scholars in reverse logistic practices, whereas AM is covered in all the GSC aspects except for carbon emissions management. Furthermore, researchers foresee the use of technologies involved in real-time data acquisition and processing, such as CPS, IoT, big data, or cloud computing, as tools to improve efficiency and lean practices in GSCs.

Table 3. Industry 4.0 technologies divided by GSC aspects.

	Reverse Logistic	**Green Design**			**Green Manufacturing**			**Carbon Emissions Management**	**Green Warehousing**	
Industry 4.0 technology	Recovery of the company's end-of-life items	Design of products for reduced consumption of materi-als/energy	Intend to reduce products' negative effects on the environment during their entire life cycle	Design of products for reuse, recycling, and recovery of materials and component parts	Generate minimum waste and reduce environmental pollution	Lean production	Lower raw material costs, gain production efficiency, and improve their corporate image	Carbon reduction targets	Material flow optimization	Decrease inventory levels
AI					[91]	[90,117]	[81,89,106]		[92]	[98]
AM	[9]			[11,94,100]	[1,12,93,97,99]	[95]	[96]		[92]	[98]
Automation/robots					[93]				[92]	[98]
Autonomous vehicles					[93,97]				[92]	[98]
Big data					[12,97]	[88,90,116–118]	[11,80,96,101, 103,106,111,112]	[119,120]		
Blockchain			[105]			[90]	[57,106,121]		[92,108]	[98]
Cloud computing	[9]				[97]	[116–118]	[11,80]	[119,120]	[92]	[98]

Table 3. *Cont.*

	Reverse Logistic	Green Design			Green Manufacturing			Carbon Emissions Management	Green Warehousing	
CPS	[9]				[12,94,97]	[116–118]	[11,78,106,113]	[119,120,135]		[98]
IoT	[9,11,114]				[12,94,97,99]	[88,116–118]	[11,78,96,106, 111–113]	[119,120,135]	[92]	[98]
RFID	[9,114,115]									
Simulation		[94]			[12,97]			[120]	[92]	
Unspecified	[136]	[134]			[93,123,125,137]	[83,122,126–131,138]	[77,132,133,139, 140]	[10]	[125]	
Total	13	2	1	3	25	29	35	12	10	8

4.2.3. RQ3: What Challenges of Implementing Industry 4.0 Technologies in a GSC Have Been Identified from the Literature?

Researchers are studying the benefits of implementing Industry 4.0 in a GSC; however, little attention is focused on the challenges of this implementation. For this reason, this section aims to present the findings about this topic that have been found in six out of the seventy-five papers studied. The analysis of the papers reveals that challenges can be classified into economic, educational, and policy challenges and regulatory frameworks (see Table 4).

Table 4. Challenges identified in the literature.

Challenges	References
Economic challenges	[98,141,142]
Educational challenges	[83,129,142,143]
Policy challenges	[98,141]

Economic challenges

The initial high investment cost of Industry 4.0 is identified by scholars as the main economic challenge due to the uncertainty of digitization economic benefits. Case studies analyzing the technology's implementation in a GSC do not show evidence about the economic benefits; therefore, the possibility of a lack of recovery or financial losses presents a threat to managers [98,141,142].

Educational challenges

Educational challenges come from the current lack of expertise in technical knowledge to implement and understand these new technologies and from an absence of environmental awareness [83,129,142,143]. The literature proposes models of implementation, but there are few successful case studies presented and even fewer implemented in industrial environments. Moreover, [142] points out that sometimes managers are not able to assess this implementation or they directly denote a lack of vision of its benefits, although they should handle the challenges and motivate their employees [144]. In this way, [83,141,142] argued that this challenge is related to a resistance to culture change motivated by uncertainty and the risk of losing their employment.

Policy challenges

As a final point, government failure to support process automation through technologies associated with Industry 4.0 [83,145] has been identified as one of the main policy challenges. In addition, there is no evidence in the studied literature of protocols, standards, and guidelines for implementing Industry 4.0 technologies in GSCs or for measuring the benefits obtained from this implementation.

5. Discussion

After analyzing and studying the articles on Industry 4.0 and GSCs, we propose the following points as the future research agenda:

- More successful case studies on the implementation of technologies are needed. This research shows that many authors support the theory that 4.0 technologies can benefit GSCs, but more case studies and applications in real environments are needed to reinforce the idea proposed in theory.
- Our study does not approach the social dimension of supply chains since it studies GSCs and not sustainable supply chains. Further research could analyze the implementation of Industry 4.0-associated technologies in sustainable supply chains to address and integrate the social dimension.
- Considering the importance of implementing technologies associated with Industry 4.0 for greening the supply chain and how they are being extrapolated to other areas, such as everyday life, it would be interesting to study the transfer of this concept to other sectors such as healthcare or agri-food.

- This study has identified a lack of standardization in technology implementation and performance measurements. Further studies could focus on developing standards and protocols for introducing and measuring green issues, as well as for implementing new technologies. In addition, future research could be dedicated to studying and developing indicators that measure the economic or environmental benefits of implementing 4.0 technologies.
- It is necessary to extend the study of challenges found in the implementation of 4.0 technologies. This study analyzes the challenges of implementing Industry 4.0-related technologies in a GSC to establish a roadmap for facing these challenges.

6. Conclusions and Future Research Agenda

This research aims to analyze the applications of implementing Industry 4.0 and its constituent technologies to improve GSC aspects. The main findings, limitations, and points for future research are presented in this section.

The research topic that combines Industry 4.0 and GSCs has experienced growing attention in recent years. Studies in the past have highlighted the benefits of Industry 4.0 for greening the supply chain. However, little attention has been paid to the use of technologies associated with 4.0 to develop specific GSC aspects. Our study detects a tendency to combine the technologies known as enabling technologies (CPS, IoT, cloud computing, and big data) due to their capability for improving the information flows. Otherwise, AM was foreseen by several authors as a promising technology to develop more efficient production and work with recycled materials. Moreover, the literature indicates that researchers are paying close attention to monitoring and reducing energy consumption, probably due to the large amount of energy used in the manufacturing process. However, it is necessary to extend the research about the benefits of Industry 4.0 for greening the supply chain, as suggested in the discussion section.

Managerial implications

Regarding managerial implications, the allocation of GSC aspects into categories can serve as an overview of the existing practices for greening supply chains. Consequently, our study will help practitioners to identify the most suitable technologies regarding the GSC aspect that they would like to improve. In addition, they can identify which green benefits can be obtained with technologies already implemented. Moreover, the barriers identified in our research may be worthwhile for practitioners to address from the outset. They should focus on combating resistance to change and working to ensure that employees understand the importance of new technologies and their application in overcoming the environmental problems generated by supply chains.

Theoretical implications

As a theoretical implication, our study provides scholars with a source where they can find relevant articles, depending on the technology or green issue they are interested in. Additionally, in this paper, future researchers can identify relevant areas of study on the adoption and combination of new technologies that should be further analyzed and expanded for greening the supply chains.

Limitations

We note certain limitations in this study. First, a large number of relevant papers about the challenges of implementing Industry 4.0 enabling technologies were not identified in the initial search; thus, we have added three papers to enrich that search. However, other relevant papers on this topic may have been overlooked. Second, our research has focused on technologies under the term Industry 4.0, but research on enabling technologies or the application of technologies outside the context of Industry 4.0 has not been included.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15129784/s1. PRISMA checklist. Reference [146] is cited in the supplementary materials.

Author Contributions: Conceptualization, P.M. and M.P.L.; methodology, P.M. and M.P.L.; validation, P.M. and M.P.L.; formal analysis, P.M. and M.P.L.; investigation, P.M., M.P.L., J.R., J.C.S. and J.L.; data curation, P.M.; writing—original draft preparation, P.M.; writing—review and editing, M.P.L.; supervision, J.R. and J.C.S.; project administration, J.R. and J.C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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