Received: 13 June 2022 | Revised: 15 December 2022 | Accepted: 29 December 2022

DOI: 10.1002/bse.3358

RESEARCH ARTICLE

Business Strategy and the Environment WILEY

Uncovering Industry 4.0 technology attributes in sustainable supply chain 4.0: A systematic literature review

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Funding information
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Abstract

Industry 4.0 technologies are transforming supply chain management from a linear model to what is known as supply chain 4.0, where operations are integrated, and flows stream in multiple directions. The study aims to explore the attributes of Industry 4.0 technologies and their impact to drive sustainability values. The findings were generated after a systematic literature review of 71 articles on various sustainability dimensions and multiple Industry 4.0 technologies. The study provides a review of the most studied technologies in the sustainable supply chain context and categorizes their attributes as well as their relevance to sustainability. The results show that advances in technologies such as Blockchain and Internet of Things have increased the potential for supply chains to reach sustainability values.

The study expands the existing literature and encourages businesses and the scientific community to investigate the power of Industry 4.0 technologies for sustainability.

It presents limitations and directions for future research.

KEYWORDS
Blockchain, Industry 4.0, SCOR 12.0, supply chain 4.0, sustainability performance

1 | INTRODUCTION

The latest special report from the Intergovernmental Panel on Climate Change (IPPC, 2019) indicates that global warming is likely to increase to 1.5°C between 2030 and 2052, a change that is causing irreversible damage to the earth. Social issues also threaten societies and states, and the current COVID-19 pandemic puts companies' economic and financial status at higher risk. The world's community has recognized the need to resolve the challenge of sustainability development, which led companies to adopt comprehensive and long-lasting strategies to help sustainability value creation in their supply chains (Narimissa et al., 2020).

Industry 4.0 technologies have taken on great proportions in the supply chain management field. It is defined as the fourth industrial revolution that is characterized by wireless connectivity and sensors with the power to collect big data, enable visibility, and empower business systems (Awan et al., 2021). It brings together advanced technologies such as Blockchain, Internet of Things (IoT), additive manufacturing, 3D printing, artificial intelligence, robotics, and cybersecurity, which drive supply chain 4.0 (Mak & Max Shen, 2021). In different sectors and industries, companies are responding to the need to integrate Industry 4.0 technologies into the process of digitizing their supply chains (Liu et al., 2020). This is referred to as Industry 4.0-based digital supply chains or supply chain 4.0 (Frazzon et al., 2019).

Abbreviations: AI, Artificial Intelligence; AM, Additive Manufacturing; BC, Blockchain; GHG, greenhouse gas; I4.0, Industry 4.0; IAV, Intelligent Autonomous Vehicles; IoT, Internet of Things; ODSs, ozone-depleting substances; RFID, Radio Frequency Identification; SC, supply chain; SCOR, Supply Chain Operations Reference; SDGs, Sustainable Development Goals; SLR, systematic literature review; SSC4.0, sustainable supply chain 4.0.

Supply chain 4.0 is an integrated ecosystem that is the result of digitalization and integration of smart technologies into its operations (Frazzon et al., 2019). Practitioners are experiencing this adoption, and the multiple benefits of the transition to an Industry 4.0 driven supply chain are identified (Awan et al., 2021; Ghobakhloo et al., 2021; Sislian & Jaegler, 2022). For instance, Blockchain technology is generating immense political and regulatory debate as it presents controversies in terms of sustainability (Nurgazina et al., 2021). It can help solve many challenges such as computing scope 3 emissions that require strong traceability, high coordination, collaboration, visibility, and trust between all supply chain parties (Chiarini, 2021; Farsan et al., 2018). However, the debate is over the nature of the consensus mechanism of Blockchain that requires high electricity power. Scientists are working constantly to make the Proof-of-Stake protocol more widespread in the use of Blockchain, as is less energy consuming (Ftserussel, 2022).

A holistic understanding of the attributes of supply chain 4.0 technologies and their impact on sustainability performance is lacking (França et al., 2020; Kamble, Gunasekaran, Ghadge, & Raut, 2020). Studies focus on the impact of technologies more broadly, listing their impact on sustainability (Furstenau et al., 2020) or focusing on their impact on a particular industry or a specific pillar of sustainability (Mangla et al., 2022; Yu et al., 2022). Therefore, a thorough examination is needed to uncover sustainability performance under the application of Industry 4.0 technologies to explore the technological aspects that align the relationship of the three sustainability pillars and to understand their contribution.

This article fills this gap by bringing another perspective to the topic and goes further by identifying the most studied technologies in the context of sustainability and listing their attributes. In addition, it provides a critical theoretical look at the importance of strategic technology adoption and the importance of performance measurement in driving sustainability performance. It systematically analyzes 71 articles and answers the following research questions:

1. What are the Industry 4.0 technological attributes that drive sustainability performance?
2. What are the sustainability values created by these attributes?
3. Is supply chain 4.0 the enabling structure to meet the sustainability challenge?

The paper is structured as follows. Section 2 explains the position of the paper within the literature. In Section 3, the research methodology is summarized. It explains the steps followed to perform the systematic literature review (SLR). Section 4 covers descriptive results. Section 5 presents the results of the SLR and discusses them. Section 6 brings a discussion. Finally, Section 7 addresses the theoretical and managerial implications. It concludes the paper and identifies the limitations of the study, as well as avenues for future research.

2 | POSITIONING

The interplay between sustainability and Industry 4.0 technologies is the subject of a quite abundant but recent literature in which academia is making a significant contribution to keep pace with the rapid evolution of industries and policies.

The research on the selected databases shows that there is an additional field of research to cover the attributes and enablers of Industry 4.0 technologies in relation to sustainability values. Previous studies have examined the relationship between Industry 4.0 and sustainability from different perspectives (Edwin Cheng et al., 2021; Mangla et al., 2022), focusing mainly on technologies and their impact on sustainability practices (Govindan et al., 2022), without going further in discovering what lies behind the power of these technologies, especially their attributes.

On the other hand, the "fourth industrial revolution" is emerging with multiple capabilities that are attracting companies to discover implementation opportunities. At the same time, academics are conducting extensive research in different contexts to develop frameworks that would facilitate their implementation.

The novelty of the topic motivates our research. We aim to study technology drivers and their implications for sustainability. The goal is to understand the links between technological attributes and sustainability values. The results would contribute to develop new business strategies regarding potential applications in different supply chain processes.

Second, while other studies highlight the relationship between Industry 4.0 and sustainability practices, this study presents the multiple attributes of the emerging Industry 4.0 technologies and relates them to contributions to sustainability, such as Blockchain-based traceability to improve carbon footprint (Kouhizadeh et al., 2021) or IoT-enabled real-time data flow, to enhance waste management, recycling, reuse, recovery, and remanufacturing (Garcia-Muiña et al., 2019). The resulting categorization presented in Table 4 may help future research and applications to perceive anticipated sustainability outcomes on the implementation of a specific technology in a specific process.

Third, this research responds to the call in the literature to show the growing importance of Industry 4.0 technologies in meeting changing business requirements (Awan et al., 2021; Naz et al., 2022). The analysis would bring to the practice a perspective on technology attributes and how they might relate to desired sustainability initiatives.

The study selection is broad to cover studies spanning different industries, technologies and capabilities that contribute to sustainability. Moreover, its relevance is based on the novelty of the studied articles mainly published between 2018 and 2022. The study also covers a large part of Blockchain technology and discovers its benefits as it has a huge impact on industries and creates huge debates and discussions in the field.

3 | REVIEW METHODOLOGY

In this study, we take the advantage of using a SLR approach to holistically understand the studied phenomena (Thomé et al., 2016). The use of this methodology is intended to understand the attributes of

Industry 4.0 that drive sustainability practices in different contexts and industries. Moreover, its nature allows reproducible findings that may benefit academics and organizations.

This paper follows transparently the three steps of building a SLR developed by (Tranfield et al., 2003).

The review planning is the first stage, which involves developing the review protocol. It specifies the preliminary research questions, relevant keywords and strings, search methods, and quality assessment. The second stage is the selection of studies, which consists of five main stages: (1) identification of relevant articles, (2) exclusion of studies by title, (3) exclusion of articles by reading abstracts, (4) use of quality assessment to obtain relevant articles, and (5) snowballing to obtain other relevant articles. The third and last stage is to develop the data extraction form and draft the synthesis that summarizes the results of the systematic approach. All stages are carried out with the contribution of the authors involved in the determination and validation of the selection of articles.

3.1 | Stage 1: review protocol

A summary of the review protocol is presented in Table 1.

The research focuses on qualitative and quantitative studies published from 2006 to 2022. The reason behind this selection is that new Industry 4.0 technologies have become popular in the field of supply chains over the last decade. For example, Blockchain emerged in 2009 but has recently gained popularity in supply chains and, more recently, in sustainability studies (Kopyto et al., 2020; Kouhizadeh et al., 2021; Nakamoto, 2009).

TABLE 1 Description of the research process for the systematic literature review

Stage 1: review protocol	
Preliminary research questions	(1) What are the Industry 4.0 technological attributes? (2) What are the sustainability values created by these attributes? (3) Is supply chain 4.0 the enabling structure to meet the sustainability challenge?
Strings	("Digital supply chain" OR "Supply chain 4.0" OR "Industry4.0") AND ("sustainability" OR "sustainable supply chain management")
Language of search	English
Filters	Subject areas: decision sciences, business, management and accounting, and social sciences
Time span	From 2006 to 2021
Reference types	Journal papers (review articles and research articles)
Databases	Scopus and ScienceDirect
Quality assessment criteria	Credibility, dependability, confirmability, transferability, and reflexivity

The online search adopts and combines specific keywords that set the selection of studies. Two categories of keywords are defined. One related to the context of supply chain 4.0: (i) digital supply chain, (ii) digitalization, (iii) Industry 4.0, and (iv) supply chain 4.0; and the second group related to sustainability: (i) sustainability, (ii) sustainable supply chain, and (iii) green supply chain. At least two of these keywords are listed in titles, keywords, or abstracts of the articles. Moreover, the search is executed through the following string: ("Digital supply chain" OR "Supply chain 4.0" OR "Industry4.0") AND ("sustainability" OR "sustainable supply chain management"). The string is broad so as not to limit the results to a specific technology or a specific pillar of sustainability. For example, articles on green supply chain were generated, even though this term was not included in the string. In addition, the use of the terms "digital supply chain," "Industry 4.0," and "Supply Chain 4.0" in the search string generated articles covering different technologies in different contexts regarding sustainability.

The final step in the review planning is the quality assessment process. It provides criteria to support our confidence that the results of a particular study could make a significant contribution to our study (Kitchenham et al., 2001). The assessment is based on five criteria defined by Stenfors et al. (2020) that are credibility, reliability, confirmability, transferability, and reflexivity.

Taken together, all articles retained after Step 3 (Figure 1) were rated ($n = 142$) on a Likert scale: 1 defined as very poor, 2 as poor, 3 as fair, 4 as good, and 5 very good. The article was excluded under a mean score of 2.5.

3.2 | Stage 2: study selection

The second phase of the research methodology involved a six-step process as described in Figure 1.

The aim of this process is to develop a data extraction form, set in Microsoft Excel, that records key elements of each article.

The primary search provides a total of 230 articles. During the search process, certain types of articles were omitted (editorials, mini-reviews, book chapters, and conference papers), and the search focused on articles from the following subject areas: decision sciences, business, management and accounting, and social sciences.

A thorough review is conducted, considering the titles and abstracts of the selected papers to check their relevance to the scope of the study. Eventually, some articles are excluded as they did not simultaneously cover the two categories (Industry 4.0 technologies and sustainable supply chains).

To further refine the results, a second filtering of the 142 selected articles is performed. The evaluation generated 62 articles. Simultaneously, a snowball technique is used to ensure that additional knowledge in the context of the research questions could be captured from additional sources. A total of nine articles are retrieved. The last step consists of the completion of the data extraction sheet, which consists of the analysis of 71 articles.

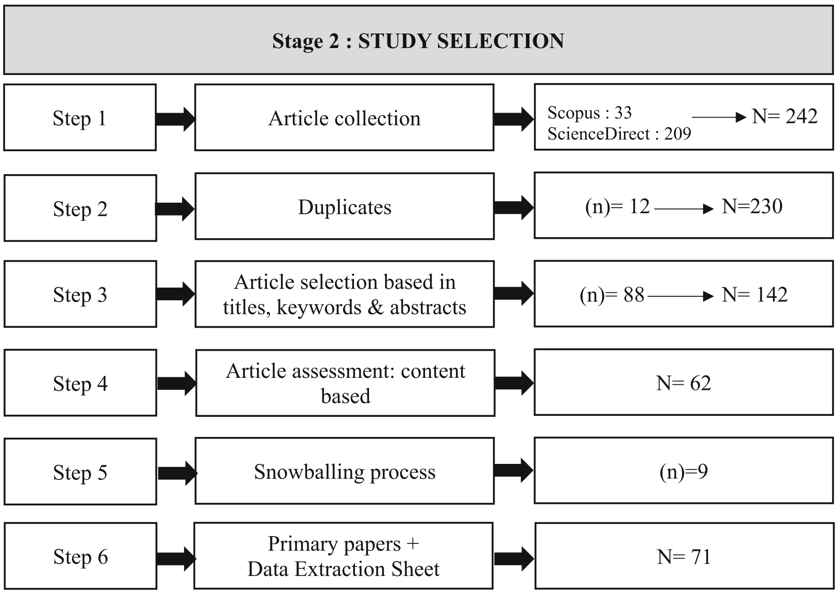

FIGURE 1 Description of the study selection process to build the data extraction sheet

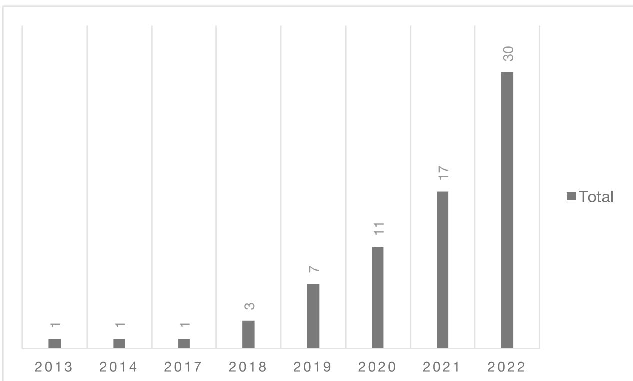

FIGURE 2 Distribution of publications per year

4 | DESCRIPTIVE RESULTS

Although the collection of articles focuses on the last 15 years based on the emergence of Industry 4.0 technologies, the research generates articles that span the period from 2013 to 2022. As illustrated in Figure 2, year 2022 has seen an increase in publications in this field, a peak with 30 studies, comparing to 17 articles in 2021 and 11 articles in 2020.

The studies are widely distributed across several journals (Table 2): Computers in Industry, International Journal of Production Economics, and Technological Forecasting and Social Change with nine articles each and Business Strategy and the Environment with seven articles.

These journals have either a strong focus on sustainability or new technologies, and digitalization development. They include articles with different approaches and perspectives. Quantitative research and SLRs are the most common in these journals (Table 3), and we observe a drastic increase in the quantitative methodology in 2022 (Figure 3), which leads us to believe that these technologies are starting to be concretely implemented in industries.

Few studies used qualitative methods, mainly to draw literature reviews to uncover opportunities for new technologies in the context of sustainable supply chains, to offer solutions and innovative directions to address the sustainability challenge.

The review generates discussions revolving around five main advanced technologies (Figure 4). Blockchain technology appears in 20 articles, IoT in 10 articles, artificial intelligence and big data in six articles, 3D printing/additive manufacturing in five articles, and finally intelligent autonomous vehicles (IAVs) in one article. The remaining articles discuss the contributions of Industry 4.0 technologies and sustainability by addressing several technologies simultaneously.

Lastly, a VosViewer analysis is conducted to detect the main clusters of the topic from the most cited keywords in titles and abstracts. The results generated are presented in Figure 5. Two main clusters were displayed (Cluster 1—sustainability, digitalization, supply chain, and digital supply chain and Cluster 2—Industry 4.0, Blockchain, IoT, and artificial intelligence), which justify the relevance of these emerging technologies to the context of sustainable supply chain 4.0.

5 | FINDINGS

This section outlines the key constructs to answer the research questions.

5.1 | Supply chain 4.0 and sustainability

The emergence of Industry 4.0 technologies has led researchers to focus on exploring their use. A report by Capgemini published in 2018 indicates that Industry 4.0 technologies can optimize operations of value chains (Capgemini, 2018). Supply chain 4.0 can be seen as a process that enables the adaptation of Industry 4.0 technologies with the human and environmental dimensions to make sustainability at the core of business development (Cañas et al., 2020).

In addition, supply chain 4.0 is powered by Industry 4.0 technologies, which empowers the supply chain through massive data and strong cooperation and synchronization between digital networks, software, and hardware (Büyüközkan & Göçer, 2018). The benefits of Industry 4.0 technologies in supply chain 4.0 can be wide-ranging: improved energy and cost efficiency, improved customer satisfaction (Chan et al., 2018), market disintermediation and sustainable manufacturing, faster transactions (Lezoche et al., 2020; Raj et al., 2022), accurate forecasting, and real-time (Greif et al., 2020), transparent, and flexible information flows (Hofmann & Rüsch, 2017).

In addition, the literature highlights other technological outcomes that optimize sustainability performance in supply chains (Table 4). Awan et al. (2021) refer to previous studies to summarize stakeholders' interest and expectations in Industry 4.0. The authors demonstrate that Industry 4.0 capabilities have great potential on economic efficiencies, social goals, and green activities. For some authors, Industry 4.0 technologies are relevant to decrease transactional costs (Christou et al., 2022; Garrido-Hidalgo et al., 2019; Phuyal et al., 2020), optimize companies' value creation (Beaulieu & Bentahar, 2021), enable transparency of monetary and energy flows during the production process, reduce carbon emissions, etc. (Baumers et al., 2013; Fernando et al., 2021; Mohammed et al., 2022).

Lezoche et al. (2020) explore how emerging technologies would transform the agri-food supply chains. The authors state that the adoption of advanced technologies enables smart agricultural supply

TABLE 2 Journal distribution

Journal name	Number of selected papers
Computers in Industry	9
International Journal of Production Economics	9
Technological Forecasting and Social Change	9
Business Strategy and the Environment	7
Transportation Research Part E: Logistics and Transportation Review	6
Computers & Industrial Engineering	5
Sustainability (Switzerland)	3
Technology in Society	2
Journal of Cleaner Production	2
International Journal of Information Management	2
TQM Journal	1
Sustainable Futures	1
Supply Chain Management	1
Journal of Industrial Information Integration	1
Journal of Industrial Ecology	1
Journal of Environmental Management	1
Journal of Engineering and Technology Management	1
Journal of Business Research	1
International Journal of Supply Chain Management	1
International Journal of Production Research	1
International Journal of Precision Engineering and Manufacturing - Green Technology	1
International Business Review	1
Industrial Marketing Management	1
IEEE Access	1
Current Research in Environmental Sustainability	1
Cleaner Logistics and Supply Chain	1
Annals of Operations Research	1
Total	71

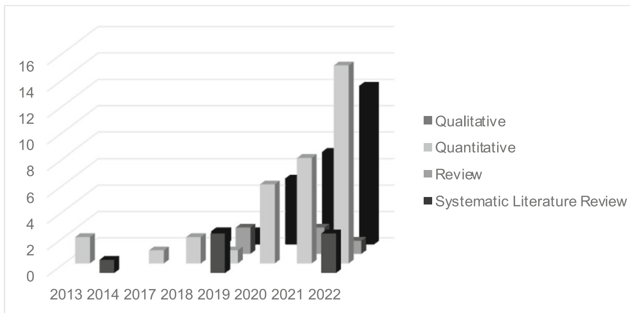

FIGURE 3 Distribution of methodologies by articles and by year

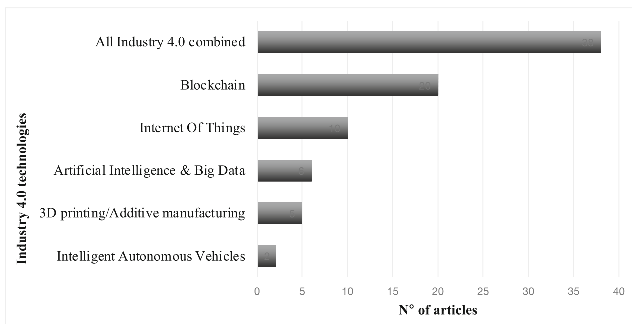

FIGURE 4 Industry 4.0 technology focus by article

TABLE 3 Overview of the methodologies covered in the selected articles

Methodologies	Quantitative	Qualitative	Review	Systematic literature review
Number of articles	33	7	5	26

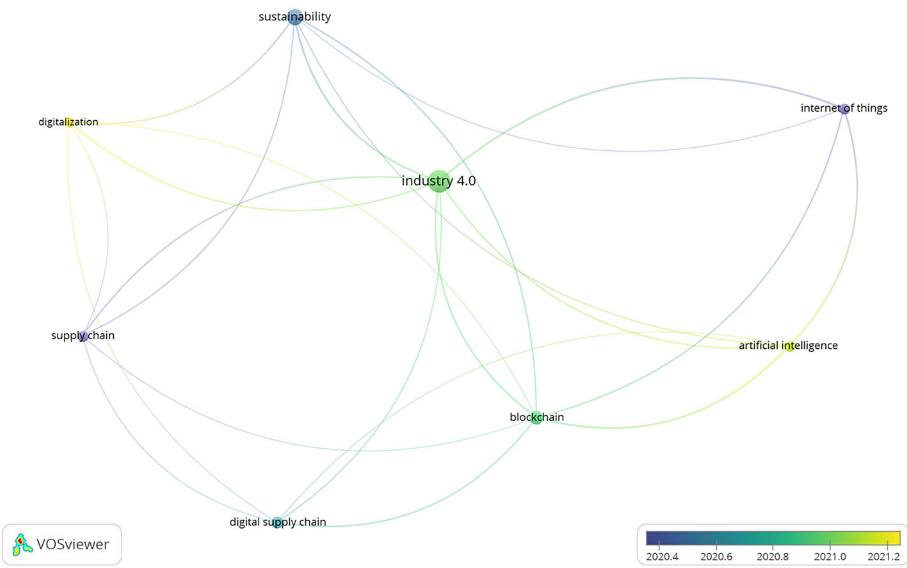

FIGURE 5 Vosviewer cluster analysis by keywords occurrence

chains to meet important agricultural goals including economizing water, maintaining soil, reducing CO_2 equivalent, and boosting productivity. In addition, Kamble, Gunasekaran, Ghadge, and Raut (2020) investigate the enablers of Blockchain technology, they assert that Blockchain technology has a great potential to provide traceability, empower smallholder farmers, reduce intermediaries, and allow stakeholders to mitigate, monitor, and assess the risks in the agricultural supply chains, while alleviating rural distress and social sustainability.

5.2 | Industry 4.0 technologies as a catalyst for supply chains sustainability

5.2.1 | Blockchain integration

Blockchain technology has become a common buzzword. It consists of continuous blocks of data in a shared, decentralized network managed by mathematical algorithms. This feature is referred to as the consensus mechanism by which data is processed. Through this mechanism, Blockchain regulates access and instantly detects and prevents malicious activities and invalid input (Kamble, Gunasekaran, Ghadge, & Raut, 2020).

In a company's supply chain, Blockchain allows storage of data and transparent transmission of flows with the benefit of traceability, privacy, security, and transparency (Yadav & Prakash Singh, 2022; Zhao et al., 2019). Entrepreneurs and academics see great potential of this technology and estimate that it can be an ultimate tool to achieve the 17 Sustainable Development Goals (Aravindaraj & Rajan Chinna, 2022; Jiang et al., 2022). Smart contracts are one of the well-known features of Blockchain. They provide the capacity of automating transactions and contracts through self-executing systems that initiate transactions automatically when they receive a pre-defined order (Raj et al., 2022; Tsolakis et al., 2022).

According to Kopyto et al. (2020), there is a 64% probability that smart contracts displace supply chain transactional operations by 2035. Additionally, this Blockchain attribute contributes to economic sustainability by improving operations' efficiency and payoff accuracy (Belhadi et al., 2022; Kamble et al., 2022). Blockchain-based traceability is another feature, which has great potential to contribute to green supply chains. It can improve the measurement of carbon footprints, which are usually hard to assess (Fernando et al., 2021; Kamble, Gunasekaran, & Gawankar, 2020). Zhao et al. (2019) state that Blockchain is being studied and tested to enhance water sustainability.

This technology has a powerful foundation for supply chain mapping and designing low-carbon products, production operations, and transportation (Rejeb & Rejeb, 2020; Satyro et al., 2022). In practice, entities report the volume of emissions produced, Blockchain attributes give collaborators the ability to cooperate and trade their excess greenhouse gas (GHG) emission rate (Kopyto et al., 2020).

5.2.2 | IoT integration

Besides Blockchain, researchers define the IoT as another advanced technology in the digital era that will revolutionize supply chains (Manavalan & Jayakrishna, 2019). It is internet-based and uses the internet to enable digital items to communicate and exchange data in a timely manner throughout the supply chain (Hopkins, 2021; Sharma & Joshi, 2020).

Moreover, to further define this technology, Manavalan and Jayakrishna (2019) consider that it is a system that connects sensors and actuators, for example, Radio Frequency IDentification (RFID) tags and mobile phones, to the internet. These physical systems constantly stream enormous flow of data to the network for processing in the dedicated task, for example, smart industry, smart warehouses, and smart transportation (Christou et al., 2022; Perussi

TABLE 4 Industry 4.0 technologies: their attributes and contributions to supply chains' sustainability performance

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Arunmozhi et al. (2022)	Sislian and Jaegler (2022)	Tsolakis et al. (2022)	Cole et al. (2019)	KambleKamble, Gunasekaran, and Gawankar (2020)	Lezoche et al. (2020)
Blockchain	Self-executing smart contracts Shared ledger Immutable system Transparent and secure building blocks Blocks of records Timely data recording	Improved productivity						
		Sustainability performance	x					
		Faster transactions			x			x
		Operational cost reduction		x			x	
		Elevating operational efficiencies					x	
		Agility, adaptability, and alignment						
		Visibility of business rules and transactions		x	x	x	x	x
		Market disintermediation					x	x
		Value creation opportunities						
		Anticipated-based financing and automated payments						
		Traceability of products and operation		x		x		x
		Security of data and transactions		x	x	x		
		Tool for quantifying social risks						
		Potential to reach the 17 SDGs						
		Efficient use of energy						x
		Carbon footprint measurement/ mitigation						
		Humanitarian supply chain						
		Water management						
		Trust between parties and collaboration			x	x		x
		Reduced waste and delays		x				x
		Inclusivity of small and medium enterprises			x			
		Energy management and carbon trading						
		Food safety						
		Efficient supplier selection						

TABLE 4 (Continued)

Industry 4.0 technologies	Zhao et al. (2019)	Fernando et al. (2021)	Kopyto et al. (2020)	Aoun et al. (2021)	Kamble, Gunasekaran, and Sharma (2020)	Raj et al. (2022)	Yadav and Prakash Singh (2022)
Blockchain							
							x
						x	
	x					x	x
	x				x		
				x	x		
				x	x	x	
						x	
	x	x	x		x	x	x
	x	x		x	x	x	x
			x				
	x						
		x	x				
	x						
				x	x	x	
							x
		x	x				x
					x		
							x

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Tsolakis et al. (2021)	Rad et al. (2022)	Bager et al. (2022)	Jiang et al. (2022)	Khan et al. (2021)	Mangla et al. (2022)	Hofmann and Rüsch (2017)
Blockchain	Self-executing smart contracts Shared ledger Immutable system Transparent and secure building blocks Blocks of records Timely data recording	Improved productivity			x				
		Sustainability performance	x				x	x	
		Visibility of business rules and transactions	x		x		x	x	
		Value creation opportunities			x				
		Anticipated-based financing and automated payments			x		x		
		Traceability of products and operation	x	x	x		x	x	
		Security of data and transactions		x	x		x	x	
		Tool for quantifying social risks							x
		Potential to reach the 17 SDGs	x			x			
		Trust between parties and collaboration	x					x	
		Reduced waste and delays					x		
		Inclusivity of small and medium enterprises			x				
		Energy management and carbon trading					x		
		Food safety	x						

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Perussi et al. (2019)	Kamble, Gunasekaran, Ghadge, and Raut (2020)	Lezoche et al. (2020)	Greif et al. (2020)	Garrido-Hidalgo et al. (2019)
Internet of Things	Robustness Intuitiveness Scalability Interlinkage With physical and other Technologies Connectivity with intelligent autonomous vehicles Automated systems and wireless Communication Data sensing	Higher productivity	x			x	
		Efficient reverse logistics					x
		Closed loop SCM					
		Circular economy performance					
		Minimized operational costs			x	x	x
		Waste mitigation			x		
		Product quality			x		
		Good working environment					
		Visibility of data and traceability		x			x

(Continues)

TABLE 4 (Continued)

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Perussi et al. (2019)	Kamble, Gunasekaran, Ghadge, and Raut (2020)	Lezoche et al. (2020)	Greif et al. (2020)	Garrido-Hidalgo et al. (2019)
		Advanced sustainability measurement (big data)				x	
		Accurate forecasting				x	
		Real-time detection of systems misfunctioning	x				
		Reduced carbon emissions	x		x	x	
		Operational efficiencies and increased margins	x		x		
		Collaboration and coordination between parties		x			x
		Autonomous operations	x		x		
		Good customer relationship				x	

Industry 4.0 technologies	Phuyal et al. (2020)	Christou et al. (2022)	Manavalan and Jayakrishna (2019)	Bag et al. (2021)	Awan et al. (2021)
Internet of Things	x	x			
		x	x		
				x	x
	x	x			x
					x
	x		x	x	
				x	
		x			
			x		
			x	x	x
		x			

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Baumers et al. (2013)	Chan et al. (2018)	Rad et al. (2022)	Liu et al. (2020)	Yoon et al. (2014)
3D printing/additive manufacturing	Electrically powered technology Rapid prototyping Flexible design Print on demand	Reduction of production cost and time		x			
		Product customization		x			
		Responsiveness and flexibility		x			
		Reduced lead times		x			
		Energy flows monitoring	x		x		
		Increased visibility for life cycle inventory assessment	x			x	
		Eco friendly product designs	x				x
		Improved environmental performance			x		

Industry 4.0 technologies	Contribution for sustainability values	Simonetto et al. (2022)	Kamble et al. (2022)	Yang et al. (2021)	Li et al. (2020)	Sharma and Joshi (2020)	Yevu et al. (2021)
Article referring to several I4.0 technologies combined	Autonomy in industrial manufacturing and transportation		x		x		
	Sustainability performance				x		x
	Economic benefits						
	Social benefits						
	Environmental benefits						
	Integration/coordination among stakeholders			x			
	Good impact on SCOR processes						
	Improved relationships with suppliers/clients					x	
	Quality products and quick deliveries		x				
	Increased service levels					x	
	Intellectual property						
	Reduced lead times						
	Sustainable practices and digital innovation		x	x		x	
	Enhancing products/product safety						
	Reduce CO_2 emissions, waste, and energy cost			x			x
	Closed loop SC/circular economy	x					
	Resource allocation		x				
	Safety		x				
	Operational cost reduction		x				

TABLE 4 (Continued)

Industry 4.0 technologies	Contribution for sustainability values	Simonetto et al. (2022)	Kamble et al. (2022)	Yang et al. (2021)	Li et al. (2020)	Sharma and Joshi (2020)	Yevu et al. (2021)
	Increased efficiencies		x				x
	Real-time dynamic decision making	x					x
	Overall performance						
	Predictive analysis						
	Augmented value creation						
	Real time information tracking						
	Potential to reach SDGs						

Industry 4.0 technologies	Naseem and Yang (2021)	Cañas et al. (2020)	Ramirez-Peña et al. (2020)	Lukinskiy et al. (2022)	Ahi et al. (2022)
Article referring to several I4.0 technologies combined	x			x	
	x	x			
					x
				x	x
	x				
	x				
					x
		x	x		
			x		
	x		x		
	x			x	
		x		x	

Industry 4.0 technologies	Contribution for sustainability values	Yu et al. (2021)	Tang and Veelenturf (2019)	Belhadi et al. (2022)	Sheth and Kusiak (2022)	Kamble, Gunasekaran, Ghadge, and Raut (2020)	Furstenau et al. (2022)	Spieske and Birkel (2021)	Saha et al. (2022)	Hofmann and Rüsch (2017)	Mohammed et al. (2022)	Beaulieu and Bentahar (2021)
Article referring to several I4.0 technologies combined	Autonomy in industrial manufacturing and transportation				x							x
	Sustainability performance					x			x			x
	Economic benefits	x				x					x	
	Social benefits					x						
	Environmental benefits	x	x			x					x	
	Integration/ coordination among stakeholders	x									x	
	Good impact on SCOR processes								x			
	Improved relationships with suppliers/clients						x				x	
	Quality products and quick deliveries		x			x	x		x			x
	Increased service levels		x									
	Intellectual property											
	Reduced lead times									x		x
	Sustainable practices and digital innovation											
	Enhancing products/ product safety		x									
	Reduce CO_2 emissions, waste, and energy cost		x	x								
	Closed loop SC/circular economy			x								
	Resource allocation			x								
	Safety		x									
		x				x					x	

(Continues)

TABLE 4 (Continued)

Industry 4.0 technologies	Contribution for sustainability values	Yu et al. (2021)	Tang and Veelenturf (2019)	Belhadi et al. (2022)	Sheth and Kusiak (2022)	Kamble, Gunasekaran, Ghadge, and Raut (2020)	Furstenau et al. (2022)	Spieske and Birkel (2021)	Saha et al. (2022)	Hofmann and Rüsch (2017)	Mohammed et al. (2022)	Beaulieu and Bentahar (2021)
	Operational cost reduction											
	Increased efficiencies				x		x	x	x			
	Real-time dynamic decision making						x		x	x		
	Overall performance					x	x			x		
	Predictive analysis						x	x	x	x		x
	Augmented value creation									x		x
	Real time information tracking											
	Potential to reach SDGs											

Industry 4.0 technologies	Contribution for sustainability values	Lopes de Sousa Jabbour et al. (2022)	Hopkins (2021)	Sharma et al. (2022)	Raut et al. (2021)	Saunila et al. (2019)	Ivanov et al. (2022)	Aravindaraj and Rajan Chinna (2022)	Piccarozzi et al. (2022)	Büyüközkan and Göçer (2018)	Farajpour et al. (2022)
Article referring to several I4.0 technologies combined	Autonomy in industrial manufacturing and transportation									x	
	Sustainability performance		x	x					x		
	Economic benefits	x	x			x			x	x	
	Social benefits		x					x	x		
	Environmental benefits	x	x	x				x	x		
	Integration/coordination among stakeholders									x	x
	Good impact on SCOR processes										
	Improved relationships with suppliers/clients										x

TABLE 4 (Continued)

Industry 4.0 technologies	Contribution for sustainability values	Lopes de Sousa Jabbour et al. (2022)	Hopkins (2021)	Sharma et al. (2022)	Raut et al. (2021)	Saunila et al. (2019)	Ivanov et al. (2022)	Aravindaraj and Rajan Chinna (2022)	Piccarozzi et al. (2022)	Büyüközkan and Göçer (2018)	Farajpour et al. (2022)
	Quality products and quick deliveries								x		
	Increased service levels								x		x
	Intellectual property										
	Reduced lead times										
	Sustainable practices and digital innovation				x					x	
	Enhancing products/ product safety										
	Reduce CO_2 emissions, waste, and energy cost				x			x	x		
	Closed loop SC/circular economy										
	Resource allocation										
	Safety	x									
	Operational cost reduction		x				x	x	x		x
	Increased efficiencies										
	Real-time dynamic decision making										x
	Overall performance	x					x			x	
	Predictive analysis		x				x			x	
	Augmented value creation								x		x
	Real time information tracking		x	x			x				
	Potential to reach SDGs							x			

Industry 4.0 technologies	Contribution for sustainability values	Govindan et al. (2022)	Barata (2021)	Qader et al. (2022)	Yu et al. (2021)	Agrawal et al. (2022)	Ghobakhloo et al. (2021)
Article referring to several I4.0 technologies combined	Autonomy in industrial manufacturing and transportation					x	
	Sustainability performance		x				
	Economic benefits		x				
	Social benefits		x				
	Environmental benefits		x		x	x	x
	Integration/coordination among stakeholders				x		x
	Good impact on SCOR processes						
	Improved relationships with suppliers/clients						
	Quality products and quick deliveries	x					
	Increased service levels	x			x		
	Intellectual property						
	Reduced lead times	x					
	Sustainable practices and digital innovation						x
	Enhancing products/product safety					x	x
	Reduce CO_2 emissions, waste, and energy cost	x	x	x		x	
	Closed loop SC/circular economy					x	
	Resource allocation						
	Safety				x		
	Operational cost reduction	x		x		x	
	Increased efficiencies						
	Real-time dynamic decision making			x			
	Overall performance	x			x		
	Predictive analysis	x					
	Augmented value creation	x					
	Real time information tracking	x					x
	Potential to reach SDGs						

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Tsolakis et al. (2022)	Lezoche et al. (2020)	Raut et al. (2021)	Rad et al. (2022)	Edwin Cheng et al. (2021)	Tseng et al. (2022)
Artificial intelligence and big data	Facilitates supply chain network design Automated and optimal decision making Self-correction of supply chain operations Work with drones and machine learning algorithms	Efficiency and productivity	x		x			
		Automated sorting of products	x					x
		Transparency and traceability across international trade	x			x		
		Reduced errors	x	x				
		Enhanced forecasting and demand management	x	x				
		Reliable predictions		x				
		Water and resource management		x	x			
		Fraud detection		x				
		Environmental protection		x	x		x	x
		Efficient planning		x				
		Automated decision-making		x	x			
		Reduced operational costs		x	x	x		
		Sustainability performance			x			
		Reduced waste			x			
		Circular economy					x	
		Efficient material reuse and recovery						x

Industry 4.0 technologies	Attributes	Contribution for sustainability values	Perussi et al. (2019)	Bechtsis et al. (2018)
Intelligent autonomous vehicles	Automatic interactions Automated sensing Digitally connected Enable synchronized production and logistics	Coordinated operations		x
		Material flow optimization		x
		Sustainability performance evaluation		x
		Efficient planning and scheduling		x
		Higher productivity	x	
		Real-time detection of systems misfunctioning	x	
		Reduced carbon emissions	x	x
		Operational efficiencies and increased margins	x	
		Autonomous operations	x	

Abbreviations: SCM, Supply Chain Management; SCOR, supply chain operations reference; SDGs, Sustainable Development Goals.

TABLE 5 SCOR 12.0 an evolution from "green" to "sustainable"

Green SCOR 11.0 "metrics"	Sustainable SCOR 12.0 "metrics"
Carbon footprint	Scope 1, 2, and 3 GHG emissions Ozone-depleting substances (ODSs)
% recycled products	New definitions of recycled and reclaimed items
Liquid emissions	Water discharge and hazardous or nonhazardous emissions
Solid emissions	Hazardous or nonhazardous emissions

Abbreviations: GHG, greenhouse gas; SCOR, supply chain operations reference.
Source: Supply Chain Council Report (SCC, 2017).

et al., 2019). Furthermore, IoT is referred to as the physical internet as it holds a great potential with its interoperability capacity to understand major technologies such as RFID tags, Blockchain, and artificial intelligence (Agrawal et al., 2022). For instance, Kopyto et al. (2020) convene a panel of international experts in which panelists have agreed that IoT has a great potential to become the standard in traceability when combined with Blockchain.

IoT facilitates the generation of massive data throughout the processes of the entire supply chain that contributes to keeping track of the quality of the value chain leading to waste reduction, good economic performance, and strong customer relationship (Bag et al., 2021; Lezoche et al., 2020).

Awan et al. (2021) explore stakeholders' interests and expectations regarding the benefits of IoT for the circular economy. At the organizational level, they expect IoT to facilitate the generation of real-time data on waste generation, recycling, reuse, recovery, and remanufacturing, which enable companies to reap economic and environmental benefits (Barata, 2021; Raut et al., 2021). IoT strengthens transportation and inventory management through smart inventory management (Liu et al., 2020), route planning, and automated synchronized scheduling (Garrido-Hidalgo et al., 2019; Greif et al., 2020).

IoT is effective in deploying and evaluating reverse supply chain operations to help stakeholders better manage resources through real-time inventory data flow and low-cost, low-energy operations (Garrido-Hidalgo et al., 2019; Simonetto et al., 2022). Besides that, IoT has great potential in the circular economy as it facilitates information management during the product's end-of-life (Garrido-Hidalgo et al., 2019).

5.2.3 | 3D printing/additive manufacturing

3D printing is commonly referred to as additive manufacturing, direct digital manufacturing, and rapid manufacturing. As defined by Baumers et al. (2013), additive manufacturing involves a set of electrically powered technologies with the capacity to assemble materials to produce complex items in a one-step numerical process, eliminating the need for any equipment or machinery.

Some authors state that it challenges social sustainability performance by limiting jobs, increasing counterfeiting, and challenging intellectual property (Chan et al., 2018). Moreover, energy consumption may be an area of concern from an environmental sustainability perspective, as is estimated to be 100 times higher in 3D printing as compared to traditional production processes (Yoon et al., 2014).

Despite these challenges, Baumers et al. (2013) state that utilizing the machine to its full capacity boosts process efficiency. This technology has the potential to drive faster production and contributes to a cleaner, responsive, performing, and flexible supply chain (Chan et al., 2018; Sharma & Joshi, 2020). It is effective for increasing manufacturing flexibility, reducing lead times, improving product customization, and decreasing inventory levels (Liu et al., 2020; Yoon et al., 2014). These features have great potential for economic sustainability, performance customer, and service efficiency (Rad et al., 2022).

From an environmental perspective, the adoption of additive manufacturing can bring transparency of financials and resources during the manufacturing phase (Liu et al., 2020). This allows companies to provide their customers with reliable data on the energy embedded into their product components during the manufacturing phase (Piccarozzi et al., 2022), unlike traditional supply chains where these data are typically not available. Moreover, this transparency and visibility helps the company better assess its manufacturing emissions for life cycle inventory assessment and design products that reduce energy consumption (Baumers et al., 2013; Cole et al., 2019).

5.2.4 | Artificial intelligence, big data, and IAVs on supply chain sustainability performance

Advanced analytics and artificial intelligence are key elements that characterize the new digital age. Although the research on artificial intelligence in sustainable supply chain management is very limited, it remains an innovation with promising potential (Tseng et al., 2022).

It is a computing system capable of executing tasks that demand human intelligence (Saha et al., 2022; Sheth & Kusiak, 2022). Predictive analytics allows companies to step ahead of demand, (Govindan et al., 2022; Spieske & Birkel, 2021) and therefore align its capacities to avoid delays, excess production, and inefficient loadings (Raut et al., 2021).

Lezoche et al. (2020) point out that big data analytics strengthen trust, flexibility, collaboration, and control. It also supports agile supply chains with operational compliance, business performance, and efficient management flow (Lukinskiy et al., 2022).

Other emerging technologies are cited in the selected articles and are defined as triggers for a "new industrial revolution." Robotics and IAVs are ground-breaking, they can perform mundane, repetitive tasks in an efficient and consistent manner (Phuyal et al., 2020). Robotics and IAVs are widely used in the distribution process, such as in warehouses and distribution centers (Bechtsis et al., 2018). They help entities to become more sustainable in a way that fosters lower emissions, streamlines costs, and improves social welfare (Perussi et al., 2019).

5.3 | Business I4.0 technological transformation toward sustainability

Companies are investigating Industry 4.0 technologies to discover new ways to build sustainability strategies and sustain effective resource management, which creates a growing interest by academicians in examining how these companies are developing their sustainability performance in an integrated supply chain context powered by Industry 4.0 technologies.

For firms to achieve sustainable performance with these technologies, the literature draws on dynamic capabilities theory to mention the importance of technology integration (Yang et al., 2021), which involves incorporating sustainability practices as well as Industry 4.0 technologies into business models. Industry 4.0 technologies have attributes that allow companies in a volatile business environment to integrate, create, and redefine resources for sustainability to compete (Bleady et al., 2018). Therefore, we emphasize the importance of integrating technology into the supply chain operations reference (SCOR) model processes to gain visibility across the various aspects of planning and operations (Saha et al., 2022).

The SCOR model is defined by the Supply Chain Council (SCC, 2017) to uncover managerial practices to drive supply chain excellence and performance. It builds on six supply chain processes (plan–procure–manufacture–deliver–return–enable) and sets metrics and strategic goals to maintain business performance (Dissanayake & Cross, 2018). In its latest version, SCOR 12.0 has incorporated Industry 4.0 technologies such as Blockchain, IoT, and additive manufacturing as emerging practices to exploit new business opportunities (SCC, 2017).

The aforementioned technologies are not crystal balls (Bager et al., 2022) but rather require a well-defined adoption framework that defines and connects technology attributes to business objectives in order to generate the right strategies to generate value across the three pillars of sustainability.

Firms can gain competitive advantage based on key strategic capabilities that support sustainability development. These capabilities are based on key sources, including reducing inputs (Yevu et al., 2021), reducing costs (Naseem & Yang, 2021), improving stakeholders' collaboration (Ahi et al., 2022), developing a shared vision, and focusing on the economic, social, and environmental aspects of sustainability (Ramirez-Peña et al., 2020).

Technology platforms and automated tools are crucial in providing advanced functionalities and fostering automation within the digital environment (Tang & Veelenturf, 2019). These technology attributes integrate business models and the six SCOR processes to drive efficiencies at each level of the chain. Corporate sustainability performance may rely on these technologies that hold power of synchronization (e.g., sensors, RFID, and software) to extract data across all business processes, which will be used to optimize production, internal and external processes, and logistics (Govindan et al., 2022; Piccarozzi et al., 2022). The big data generated are the key to monitor and drive the chain toward operational efficiencies, reduced costs (labor cost, lead time, and operational cost), and increased profits, which sustains economic performance (Barata, 2021).

6 | DISCUSSION

Supply chain 4.0 is powered by I4.0 technology; however, authors argue that their benefits are driven by adequate integration into business models and supply chain processes to drive new sustainability practices (Kamble, Gunasekaran, Ghadge, & Raut, 2020).

Yu et al. (2022) recognize the importance of collaboration between different functional areas of the company to align with organizational goals and improve performance. In this regard, technology should be seen as an enabler to be defined, deployed, and managed in the supply chain (Ghobakhloo et al., 2021).

Saberi et al. (2019) argue that the use of Industry 4.0 technologies promotes a significant level of process integration. In addition, Thramboulidis and Christoulakis (2016) consider the composition of cyber-physical, cyber, human components, and IoT as essential components for the integration of the technologies. In addition, the authors emphasize the requirement for collaboration and trust among stakeholders to achieve the visibility, traceability, and real-time transactions that have been selected as the key attributes for achieving economic efficiencies, social goals, and green operations (Hopkins, 2021).

In contrast to these benefits, many barriers are uncovered as hindrances to technology application, for example, lack of skills and investment barriers, cost, technological barriers, data barriers, and organizational related barriers (Aoun et al., 2021). However, the study indicates that promising operational and business efficiencies are reasons enough to invest time, money, and effort in discovering these technologies to prepare companies for the future to achieve sustainability goals (Khan et al., 2021; Tsolakis et al., 2021).

In this study, Table 4 summarizes the sustainable capabilities and values associated with the different technologies studied. Scholars believe that the agenda is economically driven with an emphasis on operational and production efficiencies (Li et al., 2020). From a social perspective, security, reduced inequality, quality, and trust between parties are enabled by technological attributes (Mangla et al., 2022; Tsolakis et al., 2021), such as smart contracts, 3D printing automation, and IAV (Beltrami et al., 2021; Tsolakis et al., 2021). Similarly, these attributes optimize ecological footprints and enable the identification of carbon tax and the transfer of carbon credits (Arunmozhi et al., 2022; Khan et al., 2021).

Authors also discuss that several technologies should be integrated in the same process to boost performance (Kopyto et al., 2020). For instance, robots, sensors, IoT, and Blockchain can be integrated seamlessly to generate new opportunities by making connections between data, people, and devices.

The literature on sustainability lacks managerial guidelines that can help understand technology implementation, namely, the adoption, integration, and measurement (Saunila et al., 2019). In fact, the transition to a supply chain 4.0 ecosystem comes with managerial and financial challenges.

Adopting modern technologies helps achieve complex sustainability goals such as measuring scope 3 emissions (Kouhizadeh & Sarkis, 2018), assessing social aspects, and improving financial auditing. Supply chain performance assessment involves the use of financial and nonfinancial metrics related to business processes (SCC, 2017). SCOR 12.0 addresses the lack of standardized metrics and incorporates new supply chain performance factors and addresses topics such as metadata, IoT, Blockchain, additive manufacturing, and other disruptive technologies (SCC, 2017). The model introduces new metrics to assess sustainability performance in the new I4.0 context (Table 5). This framework is given for companies to control the multiplicity of indicators and select the performance indicators that best suit their objectives.

Although these technologies promise greater benefits, aligning the right technology with sustainability goals remains a challenging task. Corporate guidelines, policies, and business plans must fully address Industry 4.0 requirements and therefore must be considered as mediators to increase technology integration into business operations to improve process sustainability performance.

7 | CONCLUSION

Supply chain 4.0 is a connected ecosystem powered by integrated planning and execution systems, visibility of logistics operations, autonomous operations, smart sourcing and warehousing, efficient and rapid management of spare parts, and advanced big data analytics (Mohammed et al., 2022; Perussi et al., 2019).

We emphasize that the transformation toward supply chain 4.0 harmonizes the sustainability challenges and solves complexities such as carbon footprint measurement, data visibility and traceability, cost management, social empowerment, and closed loop supply chain (Barata, 2021; Beaulieu & Bentahar, 2021; Lopes de Sousa Jabbour et al., 2022).

Moving toward a digital ecosystem requires joint technology standards, partner-aligned strategies, and a systematic implementation (Ding, 2018). Besides, companies should align economic, environmental, and social potentials to reach global optimization and cover the risks of technology implementation. In this context, companies find themselves in a new industrial paradigm that transforms their traditional value creation. Stakeholders become integrated in the same network, which result in high degree of cooperation and coordination that would benefit the supply chain with visibility and transparency of data needed for managing business processes, enhancing automation and innovation of decisions, and developing new business leads (Ahi et al., 2022).

The study provides a bibliometric analysis of 71 articles that discuss the sustainable benefits of Industry 4.0 technologies by focusing on two main themes, that is, the attributes of Industry 4.0 technologies and the capabilities that drive corporate sustainability values.

The findings reveal that "sustainable supply chain 4.0" and "Industry 4.0 technologies" are two emerging topics that can change business strategies to move companies toward sustainability performance.

7.1 | Implications

The study captures recent advanced technologies and their attributes to drive process integrations toward sustainability goals.

Managers will acknowledge the role of modern technologies such as Blockchain, IoT, big data, and robotics that could potentially have significant income in their sustainability plans. The results encourage practitioners to follow innovative business thinking to drive effective strategies tailored to their sustainability goals.

Managers must recognize the importance of adequate integration and measurement to achieve results. Consistent collaboration and cooperation among stakeholders are required to maintain the data flow, which is paramount to the functioning of these technologies. In addition, companies should shift their focus on human resource development toward innovative and collaborative thinking that impacts social sustainability.

7.2 | Limitations

The research can be approached with some limitations to consider:

1. The article is evolving in a topic of discussion; it is recent but evolving at a rapid pace. Therefore, some studies may have been omitted from the analysis.
2. The analyzed articles did not cover the term supply chain 4.0 but rather focused on Industry 4.0, digitalization, and digital technologies, which led the authors to analyze the articles independently to avoid confusion. Therefore, there is a need for a standardized framework of supply chain 4.0 and sustainability.
3. Technologies such as artificial intelligence, data analytics, and IAV did not emerge in the search as much as Blockchain and IoT, making them less explored in this context.
4. The study could have included a conceptual framework to direct the empirical work.

7.3 | Future research avenues

Empirical work is needed to evaluate and estimate the significance of implementing Industry 4.0 technologies in a real case supply chain. Besides, future studies can draw on data-driven approaches to analyze and assess the outcome of technology integration and its impact on economic, environmental, and social sustainability performance in supply chain 4.0.

Furthermore, the benefits and challenges of these technologies can be investigated on a larger scale to better understand their effective integration into sustainable supply chains. The impact of supply chain 4.0 on achieving the 17 Sustainable Development Goals can also be explored.

Organizational information theory can also be more developed to study the strategic driven forces for efficient collaboration between stakeholders in supply chain 4.0.

Future studies can develop models to test the sustainability performance impact of a particular business strategy on SCOR processes in an I4.0 context.

ACKNOWLEDGMENTS

The authors thank the journal for considering this research.

CONFLICT OF INTEREST

The authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article.

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How to cite this article: Srhir, S., Jaegler, A., & Montoya-Torres, J. R. (2023). Uncovering Industry 4.0 technology attributes in sustainable supply chain 4.0: A systematic literature review. *Business Strategy and the Environment*, *32*(7), 4143–4166. https://doi.org/10.1002/bse.3358