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Review article

Net zero supply chain performance and industry 4.0 technologies: Past review and present introspective analysis for future research directions

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ABSTRACT

Interest in applying Industry 4.0 technologies in supply chain operations has increased significantly due to the urgent need to combat climate change and achieve net-zero emissions. This study aims to thoroughly comprehend how Industry 4.0 technologies affect the efficiency of net-zero supply chains. To do so, the study systematically reviews the existing research using 68 academic papers that are thematically analysed and classified by potentials associated with Industry 4.0 in the context of net zero supply chain performance. The findings of this systematic literature review highlight the multifaceted role of Industry 4.0 technologies in achieving net-zero supply chain performance. However, the study also identifies challenges related to policy, technology, economy, and markets to harness these technologies effectively. A conceptual framework is proposed to help organizations strategically leverage Industry 4.0 technologies for sustainable supply chain performance. By identifying knowledge gaps, the review provides a roadmap for future research to explore the complex dynamics at the intersection of Industry 4.0 and sustainability. Practically, the study offers valuable insights for supply chain managers and policymakers on the opportunities and challenges associated with adopting Industry 4.0 technologies for sustainable practices. With the goal of achieving net-zero supply chain performance, this paper emphasizes the importance of a holistic, integrated approach to technology adoption and sustainability strategies.

1. Introduction

Greenhouse gas (GHG) emissions have a significant impact on both human life and nature, as has been increasingly clear in recent years [1]. Viral and nonviral diseases, as well as other societal upheavals, are thought to be brought on by the increase in GHG [2]. By the year 2100, global surface temperatures are projected to increase by 3–4 °C in comparison to the averages from 1986 to 2005 [3]. According to researchers, if current trends continue, mean close-surface air average temperatures would climb by 1.5 C by 2052 [4]. At the start of the 20th century, there was a sharp increase in the amount of fuel used by various industrial processes, which led to a global increase in GHG emissions [5,6]. Moreover, supply chain (SC) emissions are far higher than other direct and indirect pollutants [7].

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Table 1
Comparison of past literature review studies and our study's focus.

Author(s)	Focus of study	No. of reviewed articles	OP/OC
[25]	A review of Internet of Things (IoT) embedded sustainable supply chain for Industry 4.0 requirements	N/A	OP
[26]	Review of articles concerned with blockchain impact on sustainable food supply chain to achieve net zero	55	OP
[27]	Investigating potential interventions on disruptive impacts of Industry 4.0 technologies in circular supply chains: Evidence from SMEs of an emerging economy	N/A	OC + OP
[20]	A systematic review of Industry 4.0 technology attributes in sustainable supply chain 4.0	71	OP
Our Study	A systematic review of Industry 4.0 technologies literature in net zero supply chain performance	68	OP + OC

*N/A = not applied, OP = operational parameters, OC = operational cost.

The World Meteorological Organization predicts a nearly 50/50 chance that the average global temperature will unexpectedly exceed 1.5 °C in the next five years [8]. It would be reasonable to anticipate that the scientific community would support the work done by policymakers.

Constructing a model that satisfies the profitability goals and the organization's sustainability is the main challenge in developing a sustainable SC [9]. Furthermore, the idea of a net-zero business strategy has a broad scope and can include targets such as zero waste, zero plastics, etc., in addition to zero emissions, which makes it challenging for organizations to develop an efficient sustainability policy that simultaneously fulfils several criteria [10]. The necessity to switch to net zero supply chain (NZSC) methods has become crucial as a result of the achievement of the established target of carbon neutrality in various industries and pressure from governments around the world. In this context [11], defined NZSC as an integrated and environmentally friendly approach to supply chain management that aims to balance the GHG emissions produced over the course of a product's or service's entire lifecycle with comparable emissions removals, reductions, or offsetting measures.

The concept of Industry 4.0 (I4.0) has caused a change in research and business attention toward cutting-edge digital technology [12]. Industry 4.0 is characterized by the incorporation of its fundamental concepts, such as the Internet of things, cyber-physical systems, big data analytics, cloud computing, artificial intelligence, and additive manufacturing, within and between companies [13,14]. According to several studies [15,16], I4.0 technologies are anticipated to enable real-time SC optimization, create interrelated manufacturing processes, and enable the customization of production, goods, and services throughout the supply chain. A single modification or update cannot significantly reduce the industry's GHG emissions [17].

The first law of thermodynamics and energy conservation principles are the cornerstones of an NZSC [18]. Technologies from I4.0, such as sensor-driven data acquisition and real-time analytics, align with energy conservation principles [19]. They make it possible to precisely monitor and optimize energy usage throughout the SC, significantly reducing energy losses and waste [20]. When used to control thermal processes such as heating, cooling, and refrigeration, I4.0 technologies resonate with the thermodynamic aspiration of reducing entropy generation while increasing overall system efficiency [21]. Incorporating I4.0 technologies emphasizes their inherent compatibility with fundamental physical principles by utilizing data-driven decisions to optimize fluid flow and reduce turbulence [22]. These technologies embrace electromagnetic physics, allowing for more effective energy and information transmission while reducing electromagnetic interference in SC operations [23]. Thus, establishing the foundation of our investigation in fundamental physics enhances the scientific rigor of our research and offers an insightful framework for thoroughly illuminating how I4.0 technologies create NZSCs.

The decarbonizing industry entails redesigning goods and industrial processes in favour of cleaner and greener versions [24]. An SLR that jointly (a) includes multiple key I4.0 technologies, (b) summarizes their challenges and benefits for NZSC performance in a general context, and (c) takes into account the key success factors that maximize benefits or reduce challenges is still lacking. There is still a dearth of literature on the area of NZSCs covered by I4.0, and no noteworthy reviews in this area have been discovered. This necessitates making an exception when doing a thorough literature assessment on I4.0 in the NZSC. The use of I4.0 technologies in NZSC contexts has been examined in previous literature review studies, which are summarized in Table 1. Furthermore, it illustrates how the focus of this study differs from that of earlier studies.

Earlier SLRs in this field have concentrated on particular technologies (such as mobile technologies [28]), NZSCs in particular industries such as zero-emission transport [29], and particular aspects of NZSCs, e.g., net-zero carbon cities [30], GHG emissions [6], and the circular economy of rare earth components [31]. The literature on the NZSC is extensive but still developing [32,33]. To fully utilize this literature and use it as a guide for performing solid research on the I4.0 features of the NZSC, a systematic literature review (SLR) is needed. To achieve NZSC performance, the SLR aims to capture the most recent theoretical advancements and insights that are pertinent to the current landscape of I4.0 technologies. Since I4.0 technologies and supply chain management sustainability initiatives are both dynamic and evolving during this time, it makes sense to concentrate the SLR on materials published in the last decade - between 2013 and 2023. This span of time includes a crucial decade marked by quick advances in connectivity, automation, and digitalization technologies, which are essential elements of I4.0. Furthermore, this time period is crucial for determining how the integration of these technologies into SC operations will affect sustainability, especially in terms of achieving NZSC performance. Furthermore, the urgency of addressing climate change and sustainability was reinforced by international agendas such as the Paris Agreement and the Sustainable Development Goals (SDGs), which increased the importance of SC sustainability practices. The current study ensures that the synthesis of prior knowledge takes recent developments into account and offers a thorough understanding of the subject matter in light of the most recent business and environmental dynamics. More precisely, the following research questions are addressed in this study:

RQ 1. How has the literature on I4.0 changed over time in the field of net zero supply chains?

RQ 2. What are the potential benefits, critical factors, and challenges associated with I4.0 studies conducted from a net zero supply chain perspective?

RQ 3. What are the current gaps in the literature that can serve as a roadmap for future studies and improve the management of the digital net zero supply chain?

Our SLR offers answers to these research questions for the 14 I4.0 core technologies, including artificial intelligence (AI), Internet of Things (IoT), cyber-physical systems (CPS), cloud computing (CC), Internet of Services (IoS), additive manufacturing (AM), advanced robotics (ARs), radio frequency identification (RFID) technology, big data & analytics (BDA), augmented reality (AR), vertical integration, horizontal integration, cyber security (CS), and blockchain (BC). We establish a framework that takes into account how the performance of the NZSC is impacted by the 14 fundamental technologies, their challenges, benefits, and key success factors.

This SLR forges new ground in study at the nexus of I4.0 technologies and sustainable supply chain management by providing a thorough analysis that goes beyond the purview of previous research. This work stands out because it incorporates the most recent and cutting-edge research, ensuring a current comprehension of the intricate relationships between I4.0 and NZSC. Furthermore, our review adopts an interdisciplinary approach to offer a multifaceted perspective, fusing ideas from various disciplines such as industrial engineering, environmental science, and economics. This integrated approach identifies significant research gaps and provides practitioners and policymakers with valuable recommendations for navigating the changing environment of sustainable supply chains in the I4.0 era.

From a practical perspective, the SLR offers actionable insights for SC managers, policymakers, and industry stakeholders. It highlights best practices, challenges, and potential strategies for leveraging I4.0 technologies to enhance sustainability performance within supply chains. Furthermore, it underscores the importance of a systemic approach to technology implementation and sustainability integration, emphasizing the need for organizations to align their digitalization efforts with broader net-zero objectives. Overall, the review serves as a valuable resource for those seeking to navigate the complex terrain of I4.0 technologies in the context of sustainable supply chain management, facilitating informed decision-making and the development of effective strategies to address pressing environmental challenges.

As a result, the main goals of this study are to categorize the articles by summarizing them according to their dominant themes, examine the changes in the published literature over time, and provide recommendations for future research to help global researchers and practitioners. The study makes a significant contribution to the literature in the sustainability area. In this area, extensive worldwide research is ongoing; thus, this SLR can significantly impact how knowledge is shared, how people act, and how different sectors work together to address the critical problems of sustainability and SC performance in the context of I4.0 technologies by providing a thorough overview of key concepts and their fundamental relationships. Likewise, the current study has the potential to reach and help a broad audience, ranging from people and businesses to policymakers and researchers, and it will assist in creating a future that is more technologically advanced and sustainable.

The remainder of this paper is organized as follows. First, Section 2 is dedicated to prior literature review studies. The SLR method is presented in Section 3. In Section 4, the descriptive and thematic findings are provided. The synthesis of findings and development of a framework are discussed in Section 5. Section 6 addresses the future research scope. Finally, the conclusion and implications for practitioners and researchers are presented in Section 7.

The crucial role of each section lies in how they all work together to advance knowledge of I4.0 technologies in the context of the NZSC. This work is compelling because it provides insightful information, encourages interdisciplinary discussion, and offers academics and practitioners a road map for navigating the changing field of sustainable supply chain management in the age of I4.0.

2. Review of the literature

In Table 2, we define the key concepts connected to the determined domain.

2.1. Supply chain in context to the net-zero economy

It is crucial to monitor worldwide GHG emissions in light of growing worries about global warming and the hazards it poses to nature as a result of human activities. Therefore, it is necessary to establish the groundwork for a low-carbon shift in the infrastructure linked to each SC unit [40]. Due to the necessity to reduce GHG emissions, the idea of emissions regulations known as "Net Zero Carbon Emissions" (NZCE) was developed. The concept of "NZCE" refers to subtracting the precise volume of carbon dioxide emitted into the atmosphere by every specific activity [41]. The conceptual model of net zero in various fields is necessary since it is more than simply a theoretical hypothesis but rather a framework for climate change mitigation efforts [42].

Even though there are initiatives to transition from conventional SC operations to an NZSC, the infrastructural change is more

Table 2
Definition of key concepts.

Reference	Description
Industry 4.0	
[34]	Industry 4.0 gives businesses the ability to increase economic values including their efficiency, flexibility, and particularly revenue growth.
[35]	The emergence of Industry 4.0 and the deployment of its underlying technologies have sparked interest in the possibility of achieving various operational quality standards.
[36]	Adopting Industry 4.0 requires significant capital investment, which is typically more viable for high-value-added goods and services found in advanced economies.
Net zero supply chain	
[37]	The ideal place for supply chains may change under the new goal of net-zero emissions supply chains from being near to demand hubs to regions where zero-emissions energy is affordable and easily accessible.
[38]	The growth of the green economy is an essential tool for decarbonization and directly advances the NZSC climate plan.
[26]	Innovation is essential for improving green SC efficiency and expediting the switch to net-zero supply chains.
[39]	The adoption of new business models for CE technologies within an ecosystem that encourages resource-efficient activities would necessitate strategies to mobilize money to achieve NZSC.

difficult than policymakers anticipated. The implementation of this change in SC operations faces several challenges, from budgetary limitations to policy development. Before creating a framework to accomplish NZSC, it is crucial to address these concerns [33]. These difficulties can be broadly categorized into four categories: execution, transparency, support, and supplier interaction [43]. There is a plethora of literature on performance in low-carbon industrial systems and revamping SC procedures [44,45]. Moreover, the impediments that currently stand in the way of accomplishing NZSC should be eliminated with priority. The key stages to establishing the NZSC are shown in Table 3.

2.2. Industry 4.0 in net zero supply chain

Industry 4.0 has the potential to speed up efforts to protect the environment and maintain natural resources by identifying several factors, including CO2 sinking, energy emission reductions, monitoring deforestation, greener transportation networks, forecasting weather, and effective SC management [53,54]. Enhancing value generation from waste, increasing energy and material efficiency, and applying biomimicry concepts by switching from nonrenewable to renewable energy sources are all goals of sustainable SC activities. This is improved by key I4.0 technologies, including AI, IoT, and BC technology [55]. The reallocation of all economic sectors is necessary to obtain net-zero emissions, and there will also need to be successful solutions such as SC digitalization. By assisting in the closing, slowing, narrowing, intensifying, and dematerialization of resource loops [56]. Supply chains that are fueled by digital technology, data innovation, and a talented workforce can promote resilience and sustainability [57]. Significant technical advancements and the advent of several new digital technologies coincide with the need to cut emissions and may enable the industry sector to undergo radical changes. There is a line of research that attempts to connect these phenomena by examining how much I4.0 can do to combat climate change [58,59]. However, the results are mixed; some find that I4.0 has a favorable impact on climate change, while others discover a negative impact or even no impact.

3. Research methodology

3.1. PRISMA-based systematic literature review

This present review was conducted using the preferred reporting items for systematic reviews and meta-analyses (PRISMA). The review process is a flowchart that consists of four steps: identification, screening, eligibility, and inclusion. The attractiveness of PRISMA is that it provides a wonderful opportunity to discuss emergent topics and a reproducible research approach that illustrates the full review process [60]. This method was selected since it could provide knowledge of the current and widely recognized concepts and industry trends while also providing answers to the review questions. For this systematic review, we searched the papers using three databases, i.e., Scopus, Web of Science and EBSCO databases, since they offer a wider variety of academic sources and helped us obtain a more thorough understanding of the research we wanted to conduct. We employed a set of keywords in addition to a database search within article titles and keywords to conduct our investigation. Notwithstanding this, the quantity of publications examined is still too great to adequately assess and evaluate, necessitating the addition of further inclusion criteria. There were 68 articles overall that satisfied the requirements for perceived integrity and relevance. The criteria were created, as indicated in Table 4, to assist in screening articles and to significantly reduce the number and complexity of reviews.

To ensure the validity and strength of the conclusions drawn from our comprehensive literature review, we rigorously applied quality control (QC) and quality assurance (QA) procedures to the data gathered throughout the study. We first established strict inclusion and exclusion criteria during the data collection phase to reduce the risk of bias. These criteria were used to weed out irrelevant or poor-quality sources. A systematic and standardized data extraction form was also used to maintain consistency in

Table 3
The key stages to achieving a net zero supply chain.

Key step	Description	Reference
Rethink product design	Instead of just improving current procedures, returning to the drawing board and reviewing product design. Tinkering at the margins will not produce NZSCs; instead, a thorough reevaluation of manufacturing processes may be necessary.	[46]
Embrace collaboration	Supply networks are asymmetrical, with high-quality talent, and knowledge, and less developed SMEs that need assistance along the chain. To prosper, everyone must work together and share resources, technologies, investments, and knowledge.	[47]
Build the capabilities required for change.	The gaps in knowledge and skills that the transformation will reveal will affect SME suppliers the most. Training and capability development will hasten the transformation.	[48]
Support climate technologies	R&D investments must be made today, along with close industry, academia, and financial collaboration, to speed up bringing innovations to market at scale by 2050.	[49]
Structure better data development	To provide consistent, transparent, and reliable environmental, social, and widely available governance measures, platforms that can collect operational data from across the SC must be developed.	[50]
Think about policy and standards broadly	Businesses are held to constantly altering expectations by their stakeholders as a result of a historical absence of consistency in guidelines, and market efficiency, which increases cost and complexity. SCs span international borders, necessitating regulations that uphold a high yet practical common standard.	[51]
Enable financing	Banks must have access to mechanisms that allow them to collaborate and coinvest with corporations and create public–private partnerships. This necessitates the use of proper data structures that allow for the traceability and transparency of financial resources.	[52]

Table 4
The methodical process for finding and selecting relevant papers.

No.	Approach
1	**Define the subject area** Impact of industry 4.0 on net zero supply chain performance
2	**Keyword search string** o *Keyword search term* {"industry 4.0″ OR (“internet of things” OR IoT) OR (“artificial intelligence” or AI) OR “big data” OR “Cyber-Physical Systems” OR “business intelligence” OR “cloud computing” OR “smart factory” OR “virtual reality” OR “green technology*" OR “technology*"} AND {"e-logistics" OR “digital supply chain” OR “logistics 4.0″ OR “supply-chain*" OR “supply chain*"} AND {"net zero*" OR “net-zero*" OR “decarbonize*" OR “net zero emission*" OR “net zero economy*"}
3	**Search Databases** o SCOPUS, Web of Science and EBSCO.
4	**Primary Criteria** o Inclusionary: Peer-reviewed, Journal articles, published in English, articles should be published in journals devoted to NZSC and I4.0 technologies OR in ABDC/ABS ranking. o Period: 2013–2023. o Exclusionary: Proceedings/conference papers, Working papers, Industry/Company reports, Editorials, Market reports and News reports.
5	**Secondary Criteria** o Inclusionary: Articles discussing I4.0 technology issues that are entirely or partially related to NZSC that are pertinent to the research goal o Exclusionary: Irrelevant research objectives, Not I4.0 in NZSC-related

recording pertinent data from selected studies. Therefore, as part of the screening process, we manually reviewed papers as part of our quality control process to ensure that they were relevant to the topic. Articles that were not included were then excluded. Disagreements were settled by discussion and agreement. Thematic and content analysis methods were used during the synthesis phase to find recurring themes and patterns in the selected studies. Iteratively, peer debriefings were held regularly to confirm the research papers that had been identified and ensure that they accurately captured the body of knowledge as a whole.

A summary of the selection procedure for papers is shown in Fig. 1.

3.2. Results

In this section, we present the descriptive findings associated with the publishing year and the content analysis that identified the challenges, benefits, and key success factors of I4.0 technologies concerning NZSC performance.

3.2.1. Distribution of publications

For this systematic review, Fig. 2 examined the publication of research studies by year. The figure demonstrates how the number of

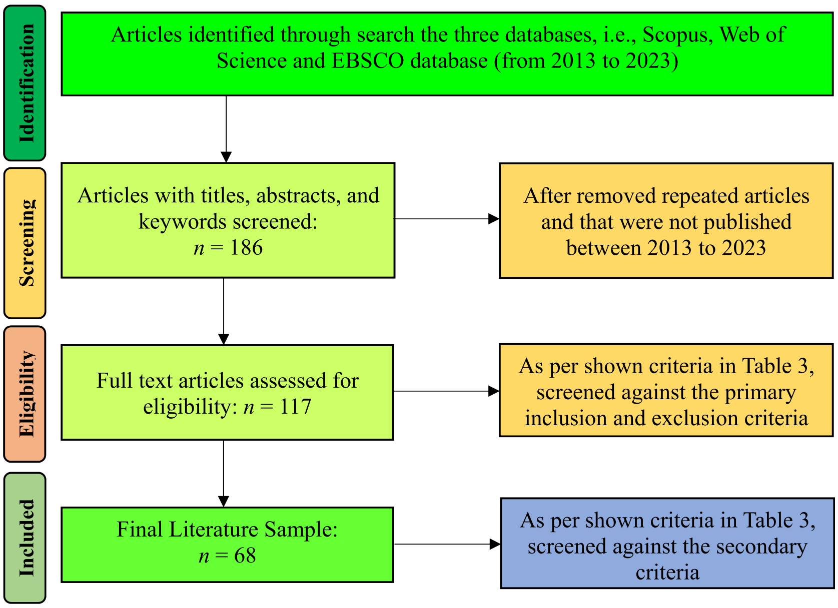

Fig. 1. Process applied to choose the articles for this study.

studies focusing on I4.0 technologies and their impact on NZECs has grown over time. The publication of articles on I4.0 technologies related to NZECs is becoming increasingly of a priority. Moreover, we looked into the types of I4.0 technologies that researchers favour for their research. We examined the I4.0 technologies that were implemented, which can help us determine what kind of net zero technologies are employed more regularly by academics for the research. We discovered that the majority of the studies on the influence of the NZSC revolve around artificial intelligence. A total of 22 % of the articles used in this study were AI-based. Furthermore, 12 % of research in the same vein was based on CPS technology (see Fig. 3). However, it is clear that blockchain, which has not yet been extensively studied, is the technology that academics prefer the least. The areas targeted for power supplies, net zero energy sources, and infrastructure are improved with the aid of these technologies to lower and evaluate the carbon footprint utilizing tuning and training technologies.

Furthermore, we made an effort to graph the different industrial fields where I4.0 technologies were used to advance the NZSC. Fig. 4 shows that Manufacturing employs I4.0 technologies at a higher rate than any other industry. Moreover, 22 % of the time, I4.0 technologies are employed in the service sectors, such as society, business, consumer, and public services, to reduce the GHG emissions of these sectors. Although it has historically been thought of as having lower emissions than heavy industry, the service sector is a vital part of the global economy and has seen recent growth in many regions. The services sector includes a wide range of activities, including logistics, transportation, information technology, and finance, all of which have carbon footprints. For instance, a significant portion of GHG emissions is caused by transportation services, including air travel. Additionally, new sources of emissions include the energy used by data centers and the operation of digital services. Additionally, it is abundantly obvious from the graph above that mining and agricultural industries still do not use I4.0 technologies in their operations. The majority of studies on the subject have used experimental approaches, as seen in Fig. 5. Experimental approaches outnumber all other methods combined with a rate of 56 % (38 papers). As a result, our SLR may be integrated with a wealth of empirical data. There were 68 papers from 33 distinct journals in the SLR (Table 5). The wide range of journals demonstrates the multidisciplinary character of I4.0 technologies in NZSC, which have been used in technology, transportation, operations, energy, healthcare, security, finance, management, academics, and more. Table 5 makes clear that Applied Energy and the Journal of Cleaner Production are the two journals with the most articles published at the intersection of I4.0 technologies and NZSC.

4. Research findings and analysis

This section examines the nature and historical development of the thematic findings from the publications included in the current systematic review. The findings include descriptions of all the identified technologies as well as benefits for NZSC performance.

4.1. Thematic findings

The analysis of the chosen samples was launched. The literature on I4.0 technologies and NZSC performance is screened in the ensuing section. The key technologies of I4.0 have been identified through an extensive investigation. Issues connected to I4.0 and NZSC were found through a literature review. During the analysis of the literature, several I4.0 technology keywords were developed. Table 6 includes a list of the 14 essential technologies that constitute I4.0.

The findings on I4.0 technologies are provided in the subsections that follow.

4.1.1. Artificial intelligence

Artificial intelligence is defined as computer intelligence that can replicate, approximate, automate, and eventually outperform human reasoning [128,129]. Due to its ability to provide reasoning, learning, and acting, AI is crucial to I4.0 and SCs [130]. The consensus is that AI helps to reduce carbon emissions [131]. First, technological advancement may encourage economic growth, alterations to the energy structure, and modernization of the industrial structure, all of which can effectively reduce carbon emissions [132]. AI technology may be used to solve complex problems using large amounts of data from various sources, increasing productivity and lowering the CO2 emissions level of gross domestic product (GDP) [133]. Second, cutting-edge technology such as AI creates

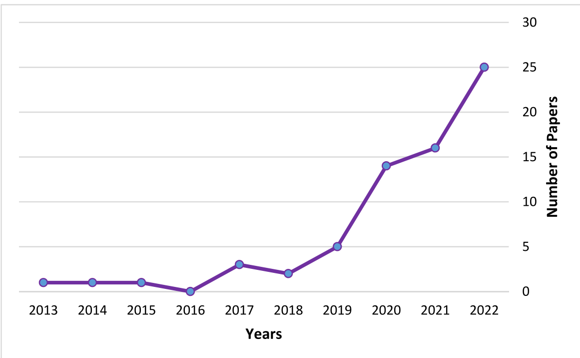

Fig. 2. Trends in a historical publication by year.

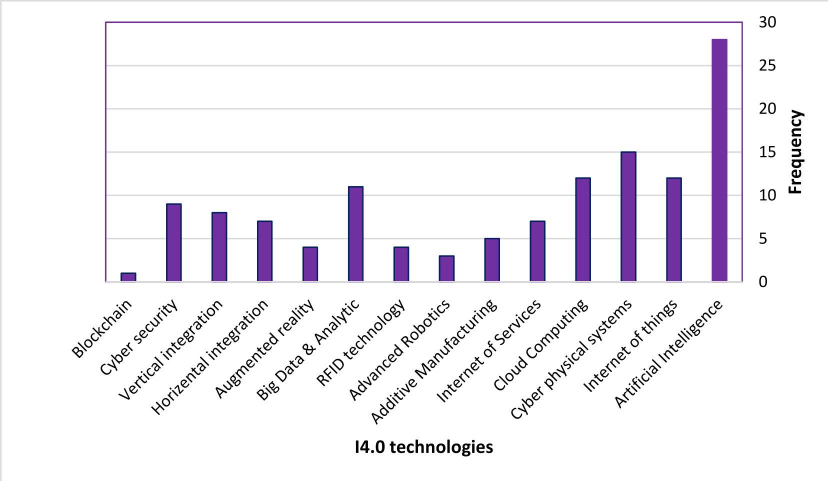

Fig. 3. Industry 4.0 technologies used in the selected papers.

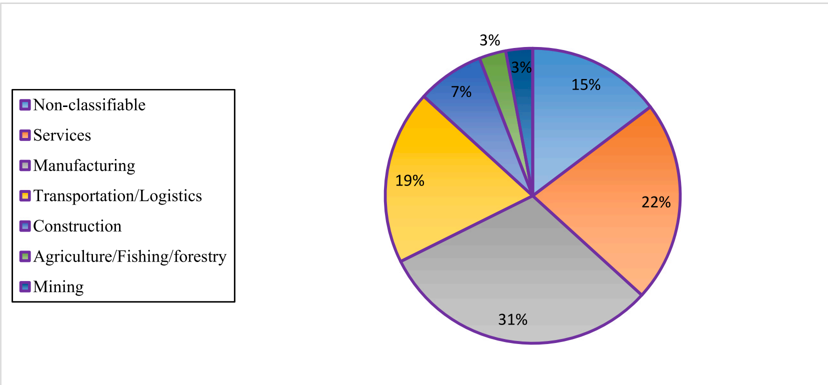

Fig. 4. Industry classification.

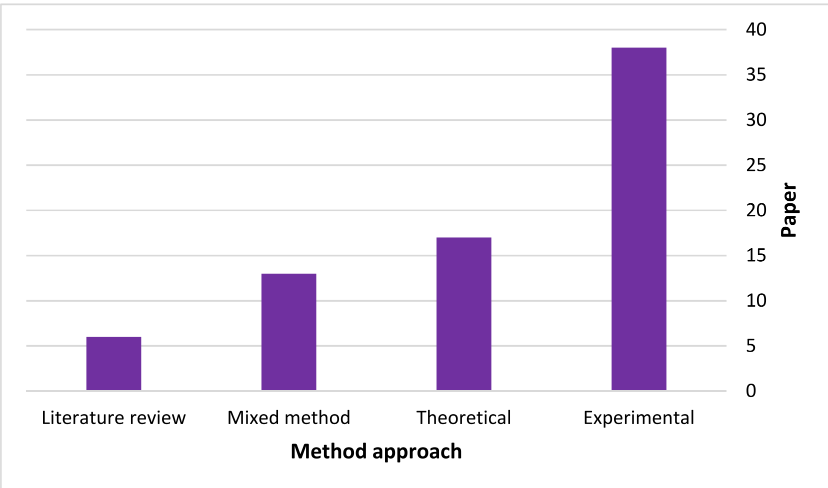

Fig. 5. Distribution of selected articles by methodology.

Table 5
Classification by journals.

Sources	Articles	% of Total
APPLIED ENERGY	11	16 %
JOURNAL OF CLEANER PRODUCTION	7	10 %
ENERGIES	5	7 %
ENERGY	5	7 %
RENEWABLE AND SUSTAINABLE ENERGY REVIEWS	4	6 %
ENERGY POLICY	3	4 %
RENEWABLE ENERGY	3	4 %
RESOURCES, CONSERVATION AND RECYCLING	3	4 %
ENERGY AND ENVIRONMENTAL SCIENCE	2	3 %
ENERGY CONVERSION AND MANAGEMENT	2	3 %
BUILDING RESEARCH AND INFORMATION	1	1 %
CASE STUDIES IN CONSTRUCTION MATERIALS	1	1 %
CLEAN TECHNOLOGIES AND ENVIRONMENTAL POLICY	1	1 %
CLEANER ENGINEERING AND TECHNOLOGY	1	1 %
DEVELOPMENTS IN THE BUILT ENVIRONMENT	1	1 %
ELECTRICITY JOURNAL	1	1 %
ENERGY STRATEGY REVIEWS	1	1 %
FOREIGN TRADE REVIEW	1	1 %
FRONTIERS IN ENERGY RESEARCH	1	1 %
IEEE ENGINEERING MANAGEMENT REVIEW	1	1 %
IEEE/CAA JOURNAL OF AUTOMATICA SINICA	1	1 %
INTERNATIONAL JOURNAL OF ENERGY RESEARCH	1	1 %
INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL	1	1 %
INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	1	1 %
ISCIENCE	1	1 %
JOURNAL OF ALLOYS AND COMPOUNDS	1	1 %
JOURNAL OF MODERN POWER SYSTEMS AND CLEAN ENERGY	1	1 %
NATIONAL INSTITUTE ECONOMIC REVIEW	1	1 %
PLOS ONE	1	1 %
RESOURCES	1	1 %
SMART ENERGY	1	1 %
SUPPLY CHAIN FORUM	1	1 %
WATER RESEARCH	1	1 %
Total	68	100 %

Table 6
Crucial I4.0 enabling technologies regarding NZSC.

Technology	References
Artificial Intelligence	[61–88]
Internet of things	[62,65,89–98]
Cyber-physical systems	[62,72,75,91,97,99–108]
Cloud Computing	[38,64,65,76,86,92,106,109–113]
Internet of Services	[65,67,83,90,96,113,114]
Additive Manufacturing	[62,99,115–117]
Advanced Robotics	[62,115,117]
RFID technology	[62,66,85,91]
Big Data & Analytics	[62,64,66,67,69,82,88,90,92,118,119]
Augmented reality	[62,66,116,120]
Horizontal integration	[62,69,84,115,121–123]
Vertical integration	[62,78,91,107,115,119,120,124]
Cyber security	[62,90,92,98,110,112,123,125,126]
Blockchain	[127]

information and knowledge spillover, which makes carbon-neutral technologies possible [134]. Third, AI makes it possible to predict and detect corporate pollution with greater accuracy, which helps to build a strong market for carbon emissions trading and reduce CO2 emissions [135]. Table 7 lists all of the claimed benefits of AI.

4.1.2. Internet of things

The Internet of Things is a grid of various material things that have digital components such as actuators and sensors embedded in them. To gather and exchange data, these components are interconnected [145]. Moreover, the network enables communication between systems, services, and devices, enabling the sharing of data [146]. According to Ref. [147], the Internet of Things is the outcome of numerous technical advancements enhancing one another and bridging the gap between the real and virtual worlds. The IoT network infrastructure connects actual items and virtual systems, enabling more precise, intelligent and efficient operation

Table 7
Artificial intelligence benefits.

Perceived Benefits	Source
Reduce Carbon Emissions	[136]
Optimize industry structure	[137]
Enhance information infrastructure	[138]
Enhance Green Technology innovation	[139]
Improve energy conservation and efficiency	[140]
Promote cleaner manufacturing processes	[141]
Foster the growth of an innovation ecosystem	[142]
Encourage dematerialization of economic activity	[143]
Reduce pollution emissions and resource losses	[144]
Promote the reallocation of production factors	[143]

performance [148]. The IoT has numerous benefits for businesses. Table 8 lists the alleged benefits of the IoT as mentioned in the literature.

4.1.3. Cyber-physical systems

Several networked agents, such as sensors, control processing units, actuators, and communication devices, make up the CPS [162]. Embedded systems provide communication and information flow between multiple components as physical items and software become more entwined in the CPS, which facilitates greater collaboration between the material objects and their related computational components or services [163]. As shown in Table 9, several broad benefits of using CPS technologies in the NZSC are highlighted by the present literature.

4.1.4. Cloud computing

The concept of "cloud computing" refers to the provision of computing services through the internet using assets that are both scalable and visible [179]. The four deployment models that make up CC are private, public, hybrid, and social clouds [180,181]. The private cloud is developed by the specific company and may be built using assets and equipment that already exist in the company's local information station or on a novel distinct architecture [180]. In both situations, the private cloud is owned and managed by the company itself. Instead, businesses that require greater security and reduced risk can use a private cloud [181]. A public cloud is created for open use by everyone. This is offered by a third-party cloud provider and is manageable by businesses and their partners [180]. Table 10 lists the CC benefits that have been deemed to be useful in the literature.

4.1.5. Internet of Services

The Internet of Service (IoS), as a core component of the larger I4.0 paradigm, digitalizes and connects service-oriented SC operations, enabling a change toward increased effectiveness and environmental responsibility [191]. IoS can be used to optimize resource allocation, maintenance, and other service-related processes with a strong emphasis on sustainability by SC stakeholders [192]. The real-time data analytics and AI features that IoS includes can enhance decision-making and enable proactive waste management, carbon emissions tracking, and energy management [193]. Furthermore, IoS supports collaborative business models and the sharing economy, enabling practical resource and asset utilization throughout the SC network [179].

4.1.6. Additive manufacturing

The majority of the research claims that AM technology provides benefits over conventional production. The usage of AM, according to Ref. [194], can decrease the amount of wasteful material. While only approximately 40 % of the debris produced by conventional subtraction techniques may be recycled, AM enables recycling rates of 95 % to 98 %. Furthermore, according to Ref. [195], using AM working following the pull concept allows for the production of customized goods with shorter lead times, a

Table 8
Internet of things benefits.

Perceived Benefits	Source
Optimize decision-making and processes	[149]
Reduce energy consumption	[150,151]
Facilitate preemptive maintenance	[152]
Balance demand with generation	[153]
Distribute energy efficiently	[154,155]
Reduce transmission losses in T&D	[155]
Deploy a flexible and an agile system	[156]
Reduce wasteful production	[157]
Detect malfunctioning components	[158]
Reduce the tear and wear of assets	[159]
Increase product delivery speed	[160]
Reduce costs	[161]

Table 9
Cyber-physical systems benefits.

Perceived Benefits	Source
Promote low-carbon energy provision	[164,165]
Reduce costs	[166]
Improve Utilization of energy infrastructure	[167,168]
Facilitate energy storage	[169,170]
Analyse and predict performance efficiency	[171]
Reduce waste and work in lean manufacturing	[172,173]
Advanced fault detection	[174]
Allow for real-time information sharing	[175]
Enhance the value chains	[176]
Optimize delivery responsiveness	[177]
Increase transparency and traceability	[178]

Table 10
Perceived benefits of cloud computing.

Benefits	Source
Reduce energy consumption	[182]
Improve flexibility and scalability	[183]
Optimize logistics	[184]
Reduce waste	[185]
Reduce Inventory	[186]
Improve system performance	[187]
Reduce GHG emissions	[188]
Planning and forecasting	[189]
Decentralized production	[190]

decrease in raw material inventory volumes, the elimination of finished product inventory, and more effective capacity utilization [196]. also make the case that suppliers and customers can work together to design and produce precisely what the customer needs with short lead times and minimal material usage, resulting in a more environmentally friendly method of producing mass-customized goods through AM.

4.1.7. Advanced robotics

With the advent of the next waves of low-cost, sophisticated robots, automation within industries will be improved. In many industrial applications, advanced robotics is the machinery utilized for automation. By incorporating software and sensor capabilities, the production line will become smarter and communicate better both within and outside the facility [197]. In the I4.0 context, advanced robots are developing further. This is accomplished by enhancing system entities' ability to communicate, which improves the production system by enhancing its capacity to respond to robot malfunctions, fluctuating demand, etc. According to Ref. [198], some general advantages of the use of robots include the maintenance of clean energy infrastructure, lower labour costs, higher quality, more flexibility, shorter cycle times, and higher throughput rates.

4.1.8. RFID technology

While RFID and IoT are critical components of the I4.0 ecosystem, they serve different purposes and have specific characteristics that call for distinct examination. RFID technology is primarily concerned with accurately identifying, monitoring, and collecting data on specific assets or items using radio frequencies [199]. IoT, conversely, refers to a broader framework of interconnected gadgets, sensors, and systems created for data sharing, analysis, and judgment in various applications [200]. By maintaining a different conceptual distinction, researchers can explore the precise capabilities and implications of RFID within the context of SC operations, such as inventory management, quality control, and traceability. Logistics, warehouses, work in progress, finished items, and raw materials may be tracked with RFID technology [201]. Through real-time monitoring of material flows, RFID offers complete inventory and process transparency [199]. RFID has also been utilized to track various objects at significant retailers, manufacturing facilities, distribution centers, and stages of disposal and recycling.

4.1.9. Big data analytics

Big data analytics has a significant impact on the performance of the NZSC by providing the tools and knowledge required to improve sustainability practices throughout the ecosystem of the SC [202]. Advanced analytics techniques can be used to tap into the vast and varied data generated within supply chains, including details on inventory, production, and energy usage [203]. These techniques make it possible to find inefficiencies, waste, and opportunities for optimization that can significantly cut resource use and carbon emissions [204]. Supply chain stakeholders can reduce their impact on the environment, maximize energy use, and streamline logistics processes by analysing historical and current data. BDA also enables predictive modelling and scenario analysis, enabling businesses to foresee and address environmental challenges such as resource shortages or disruptions brought on by climate change

[202,203].

4.1.10. Augmented reality

AR technologies offer a variety of applications that can improve sustainability in supply chains by superimposing digital information such as images, data, and simulations onto the actual physical environment [205]. AR also enhances the traceability and transparency of the SC. It enables real-time tracking of goods, supplies, and shipments, improving SC visibility [206]. This transparency is essential for monitoring and reducing waste, streamlining routes to save fuel, and ensuring that materials are ethically sourced [205]. Furthermore, AR can support initiatives for sustainable packaging by providing consumers with thorough information about product origins, sustainability certifications, and recycling instructions via interactive labels or product packaging [205]. Furthermore, AR enhances inventory control and warehouse layouts and promotes energy efficiency [207]. It makes it possible for intelligent, data-driven decisions to be made, which reduces energy use and waste in SC operations [208].

4.1.11. Horizontal and vertical integration

Horizontal and vertical integration, as critical components of I4.0, are unequivocally rooted in the integration and adoption of cutting-edge technologies within modern industrial processes [209]. Horizontal integration, wherein various functional units within an organization communicate and collaborate seamlessly through the IoT, CPS, and CC, exemplifies the digital convergence that underpins I4.0 [210]. On the other hand, vertical integration extends this integration across the entire value chain, linking suppliers, manufacturers, distributors, and customers in real time, enabled by technologies such as BC, AI, and BDA [211]. The synergy between these I4.0 technologies allows for the efficient flow of information, resources, and processes, leading to improved decision-making, reduced operational costs, and enhanced overall productivity, providing compelling empirical evidence of the close relationship between I4.0 technologies and horizontal and vertical integration in the modern industrial landscape [209,212,213].

4.1.12. Cybersecurity

The emergence and evolution of I4.0 technologies have brought about a profound transformation in cybersecurity [214]. This transformation is evident in the increasing interconnectivity of industrial systems, driven by technologies such as the IoT, CC, and CPS, which form the foundation of I4.0 [215]. With these technologies, manufacturing and critical infrastructure sectors have become more vulnerable to cyber threats, necessitating a paradigm shift in cybersecurity practices [130]. I4.0 technologies have expanded the attack surface and facilitated the automation and remote monitoring of industrial processes, thereby introducing new vectors for cyberattacks [216]. The convergence of information technology (IT) and operational technology (OT) within I4.0 necessitates a holistic and adaptive cybersecurity approach, wherein traditional cybersecurity practices are supplemented with real-time threat detection,

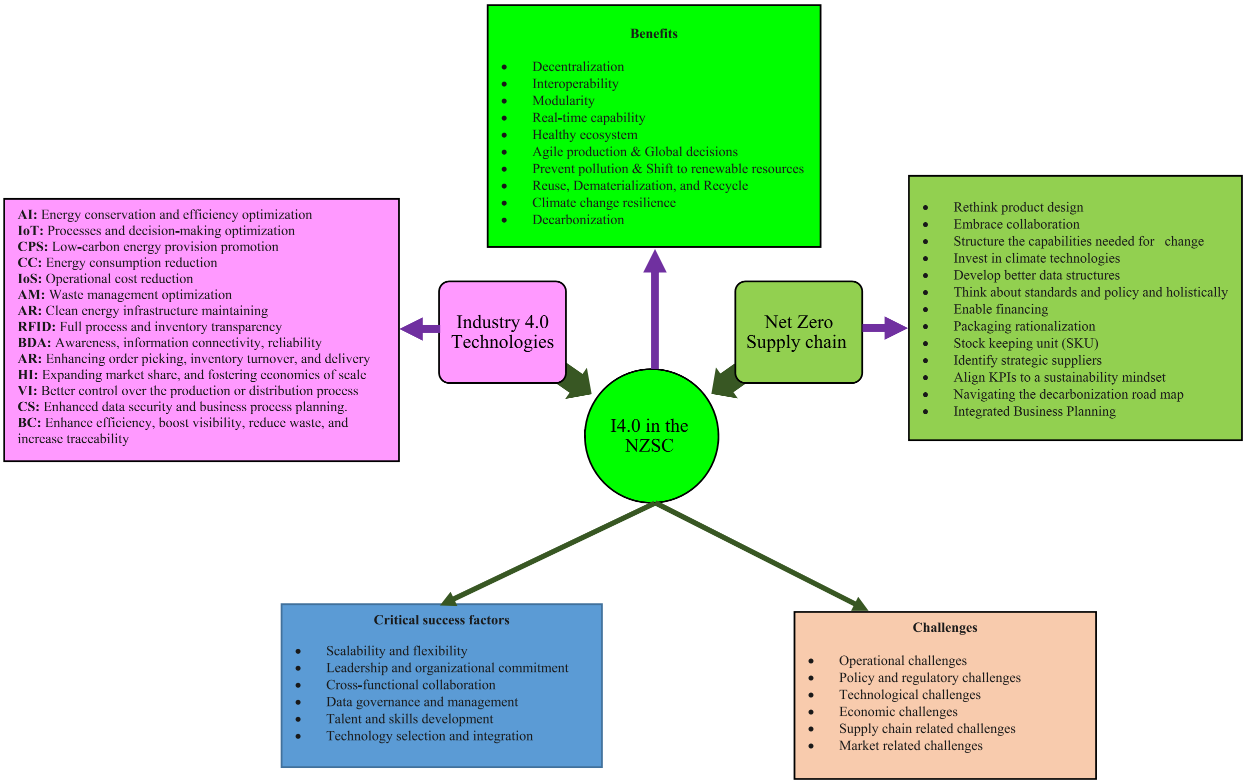

Fig. 6. Industry 4.0-based net zero supply chain performance framework.

anomaly detection, and machine learning algorithms [214].

4.1.13. Blockchain

Distributed ledgers known as blockchains can store data indefinitely (such as transactions and decisions) [217]. Blockchain data sets are reliable because they cannot be altered or deleted without the approval of the majority of participants. Blockchain technologies can also assist with the assessment of revenue sharing while studying benefit uncertainty. Blockchain technologies could also make it easier to use data and help with updating supply and demand data. They also improve SC transparency [218] and product traceability [219]. Moreover, blockchain technology can make it easier to use data for better air logistics activities such as scheduling, improved demand and supply forecasting, and improved revenue management [218].

5. Synthesis of findings and framework development

To comprehend the evolving trends in this field and identify pertinent concerns that need to be addressed in future research, this section summarizes the findings from the systematic review. A thorough literature review led to the creation of the following framework. The first RQ is addressed in the proposed I4.0 and NZSC performance framework, which is applicable to supply efficiency operations as a supplementary instrument for businesses that want to implement I4.0 technologies but are unsure of the possible advantages that the various technologies could have for its NZSC performance. The framework shown in Fig. 6 provides a summary of I4.0 technologies that can be applied to enhance NZSC performance.

Most of the earlier work, given the field's infancy, focuses on decarbonization [220] before shifting its attention to an empirical analysis of the effects of carbon and GHG emissions [221]. The articles included in this review can be broadly divided into four themes. These include (i) decarbonization of the supply chain, (ii) challenges important to NZSC when utilizing I4.0 technologies, (iii) key success factors of I4.0 technologies for NZSC performance, and (iv) benefits of I4.0 technologies for NZSC performance. Themes connected to decarbonization in the SC largely concern carbon emissions and auditing control. The number of studies on this topic has recently dramatically expanded, although it is still a very new and underdeveloped topic. The second theme emphasizes a number of challenges NZSC faces while utilizing I4.0 technologies, including those linked to policy, technology, economy, and markets (Table 11). The third theme encompasses the key success factors of I4.0 technologies for NZSC performance (Table 12). The benefits of I4.0 technologies for NZSC performance are covered by the fourth theme (Table 13). Examples of how specific I4.0 technologies connect to the numerous benefits are provided.

5.1. Reduced carbon & GHG emissions

According to the literature, carbon and GHG emissions can be decreased by using AI, CPS, CC, IoS, AM, AR, BDA, and horizontal and vertical integration. Here, using AI to facilitate the transition to new energy sources is an example. Solar energy forecasting can assist in locating possible hotspots for increased solar energy consumption, which would reduce GHG emissions [238]. CPS can lessen energy intensity, alter the energy structure, and promote the diffusion of green technologies [239].

5.2. Optimized industry structure

According to the literature, industry structure can be optimized with the use of AI, IoT, CPS, AR, RFID, horizontal integration, and vertical integration. These tools provide access to the real-time data and business insights required to make better, quicker decisions about the company's operations, ultimately increasing the effectiveness and profitability of the entire enterprise [240]. They also assist in managing and optimizing all manufacturing processes and SC components.

Table 11
Challenges associated with NZSC implementation.

Challenges	Description	Source
Operational challenges	Data relating to carbon emissions not being disclosed	[222]
	Inadequate infrastructure	[223]
	Not all industrial sectors are equally supportive of the net zero aim.	[224]
Regulatory and policy challenges	Government restrictions pertaining to the net-zero goal are not rigorous enough.	[11]
	Ineffective and slow global policies	[224]
Technological challenges	Technical infrastructure deficit	[225]
	Insufficient technical expertise	[226]
	Widespread absence of low-carbon technology	[33]
Economic challenges	Excessive expenses incurred in implementing the net zero policy Ineffective net-zero budget	[106,227]
Supply chain related challenges	Inability to regulate carbon emissions produced by businesses outside of the operations of the businesses	[228]
	Measurement of environmental impact and performance across the SC is challenging	[229]
Market related challenges	Limited public awareness of net-zero	[230]

Table 12
Key success factors associated with NZSC implementation.

Key success factors	Description	Source
Scalability and flexibility	Ensure the sustainability practices and technologies selected are scalable and flexible to accommodate future expansion and shifting market conditions.	[231]
Leadership and organizational commitment	Strong leadership commitment and support are essential at all organizational levels. This includes being prepared to invest in infrastructure, talent, and technology to fuel the transformation.	[232]
Cross-functional collaboration	Encourage collaboration and communication among various groups, such as operations, SC, IT, and sustainability. A broad approach to integration can be facilitated by cross-functional teams.	[233]
Data governance and management	Establish robust data governance practices to ensure data accuracy, quality, security, and privacy. Effective data management is essential for leveraging Industry 4.0 technologies.	[234]
Talent and skills development	Invest in staff development and training to operate and maintain Industry 4.0 systems. Encourage a culture of innovation and lifelong learning.	[235]
Technology selection and integration	Consider the specific requirements and difficulties of the supply chain when selecting and integrating the ideal combination of Industry 4.0 technologies. Ensure seamless system interoperability.	[236]
Sustainability Assessment	Make a thorough analysis of the supply chain's present environmental impact and pinpoint areas for improvement. Establish precise net-zero goals and benchmarks.	[237]

Table 13
Literature findings.

Potential Benefits	Artificial Intelligence	Internet of things	Cyber physical systems	Cloud Computing	Internet of Services	Additive Manufacturing	Advanced Robotics	RFID technology	Big Data & Analytics	Augmented reality	Horizontal integration	Vertical integration	Cyber security
Reduced Carbon & GHG Emissions	X		X	X	X	X	X		X		X	X	
Optimized Industry Structure	X	X	X				X	X			X	X	
Enhanced Green Technology Innovation	X		X	X	X		X			X			
Improved energy conservation and efficiency	X				X	X	X		X				
Promoted cleaner manufacturing processes		X	X			X	X			X	X	X	
Fostered the growth of an innovation ecosystem		X	X		X				X				X
Encouraged dematerialization of SC activities	X			X				X	X	X			
Reduced resource losses and pollution emissions		X	X		X	X	X						
Promoted the reallocation of production factors	X	X	X								X	X	
Optimized decision making and processes		X			X			X	X				
Reduced energy consumption	X		X			X	X		X				
Distributed energy efficiently	X		X	X	X								
Deployed flexible and an agile system		X	X	X	X	X				X			
Reduced wasteful production	X	X	X	X		X	X				X	X	
Improved product delivery speed	X										X	X	X
Reduced costs	X		X	X	X	X			X	X	X	X	
Increased the integration between the virtual & real world			X	X	X				X				
Real-time integration of customer needs	X		X	X					X			X	
Traceability & Visibility		X	X	X	X			X	X		X	X	X
Enhanced robustness of linkages in the SC			X	X	X				X				
Enhanced the value chains	X	X							X				
Improved flexibility and scalability	X	X		X	X	X			X				

5.3. Enhanced green technology innovation

According to the literature, green technology innovation can be improved by using AI, CPS, CC, IoS, and AR. Here, the use of AI, CC, and IoS can serve as an illustration of how these technologies can assist in improving the performance of green technology, safeguarding the environment, and conserving natural resources [241].

5.4. Improved energy conservation and efficiency

The literature suggests that AI, IoS, AR, and BDA can increase energy efficiency and conservation. As an illustration, IoS can be employed to increase resource sharing between cars through improved sensing, networking, data processing, and communication capabilities by monitoring and tracking each vehicle's location and forecasting the position of the vehicle in the future [242]. A framework for smart manufacturing is presented by Ref. [243] and incorporates networks for communication between conveyors, machines, or automated guided vehicles (AGVs), the cloud and smart products.

5.5. Promoted cleaner manufacturing processes

IoT, CPS, AM, AR, and horizontal and vertical integration have the potential to support cleaner manufacturing processes, according to the literature. For instance, CPS technology enables the elimination of hazardous and toxic raw materials, decreasing the amount and toxicity of waste and emissions at the source during manufacturing operations [244]. Another illustration is the Internet of Things, which, when applied to manufacturing procedures, may foster innovation and increase economic viability while also enabling systems to become cleaner and use fewer resources [245].

5.6. Fostered the growth of an innovation ecosystem

IoT, CPS, IoS, BDA, and CS are technologies that have been recognized as supporting the expansion of an innovation ecosystem. IoT has made it possible to significantly improve a company's innovation and productivity performance. It also enables businesses to streamline and automate operations, which increases their efficiency and boosts staff productivity. To imagine, develop, establish, improve, and maintain smart systems in fields that result in the improvement of communities, industries, and individuals [246]. CPSs can be utilized with BDA to have a technological impact in a wide variety of businesses and organizations [247].

5.7. Encouraged dematerialization of SC activities

In the literature, it was discovered that AI, CC, BDA, RFID, and AR promote the dematerialization of SC activities. Manufacturers can, for instance, increase resource efficiency by minimizing product mass or material types by adopting CC [248]. Using AI in dematerialized supply chains is another example of how it can reduce the amount of materials needed to fulfil the tasks of those systems.

5.8. Reduced resource losses and pollution emissions

The literature has shown that IoT, CPS, IoS, AM, and AR can reduce resource waste and pollutant emissions. As an illustration, consider how AM lowers material waste by just adding material to a work item and not removing it as the name implies. CPSs can create and implement enhanced processes to reduce inputs, such as water, raw materials, and nonrenewable minerals, while reducing waste and improving resource efficiency [249].

5.9. Promoted reallocation of production factors

Horizontal and vertical integration, IoT, CPS, AI, and IoT have been mentioned in the literature as having the potential to encourage the reallocation of production elements. IoT, for instance, can be used to integrate information directly into the workplace, assisting producers by easing their cognitive load and enhancing the effectiveness of various activities [250]. Without the use of a specific simulator or trainer, an operator can obtain instruction on a virtual machine using CPS [251]. AI can be used by manufacturers to locate new information, spot trends that can help them enhance procedures, and pinpoint production-related variables [252].

5.10. Optimized decision making and processes

IoT, IoS, RFID, and BDA are the technologies that have been mentioned in the literature as having the potential to improve decision-making and processes. By facilitating the accessibility, sharing, and monitoring of real-time data, these technologies can enhance decision-making [253]. When real-time data are available, problems can be identified as they arise, and actions may be addressed immediately [254].

5.11. Reduced energy consumption

CPS, AI, AM, AR, and BDA are technologies that have been recognized in the literature as reducing energy consumption. Through the optimization of value chains, a CPS can help reduce energy usage by enhancing the resilience and robustness of industrial links [244]. Moreover, AI can be utilized with sensors to measure each machine's energy usage and subsequently improve in the subsequent stage [255].

5.12. Distributed energy efficiently

The literature suggests that IoS, CPS, AI, and CC can all contribute to effective energy distribution. By utilizing manufacturing software solutions and making them more available to all stakeholders to reduce energy use, AI can enhance order personalization [255]. By stopping the loss of electricity and heat in structures and industrial processes, as well as by switching to energy-efficient appliances and lighting, a CPS can lower the amount of energy utilized [244].

5.13. Deployed flexible and agile system

According to the literature, agility and flexibility are impacted by IoT, CPS, CC, IoS, AR, and AM. For instance, because AM can create virtually any product that is designed in a CAD file, it provides boosted production flexibility [198]. Due to its location-independence feature, which gives the SC agility and flexibility, CC can also increase flexibility [189].

5.14. Reduced wasteful production

The literature has shown that the use of AI, IoT, CPS, AM, AR, vertical and horizontal integration, and other technologies can lessen production waste. CPS can enhance zero defect manufacturing (ZDM), digital quality management, and predictive maintenance, all of which boost production quality while lowering waste [249]. Businesses can build smart factories with real-time manufacturing tracking and waste reduction using IoT and wireless sensors [256].

5.15. Improved product delivery speed

According to the literature, product delivery speed can be improved using CS, AI, and vertical and horizontal integration. For instance, decentralized production is made possible by AI technology, which brings businesses and their clients closer together. This is especially helpful when producing tools or spare parts because the transportation lead time can be greatly reduced [257].

5.16. Reduced costs

According to the literature, SC costs can be decreased by using AI, CPS, IoS, AM, BDA, AR, CS, and horizontal and vertical integration. As an illustration [258], consider how CPS can lower production costs by enhancing engineering change execution, product design, manufacturing equipment performance, and process and operations variability. IoT uses ongoing analysis and monitoring to lower maintenance costs and increase reliability. Manufacturers can use historical data analysis and predictive analytics to schedule predictive maintenance, which will lower the cost of maintenance thanks to BDA [259].

5.17. Increased connection between the virtual and real worlds

The virtual and real worlds can be more seamlessly integrated thanks to CPS, CC, IoS, and BDA. SC can benefit from the assistance of CC with virtual teamwork, experience-based learning, and process and product design [260]. The visualization capabilities made possible by BDA-enhanced designs enable architects, product engineers, and designers to quickly switch between several concepts and assess them at the moment [261]. Employees can engage with coworkers using virtual avatars or work together around a common visualization using CPS [258].

5.18. Real-time integration of customer needs

The literature suggests that the use of AI, CPS, CC, BDA, and vertical integration can enhance the assimilation of client needs in real time. AI can enhance customer interactions and enable real-time integration of client needs [149,262]. Customer engagement and satisfaction can be improved using BDA if the management of customer relationship data is included [259].

5.19. Traceability & visibility

When the SC's visibility and traceability are enhanced, it becomes possible to identify and eliminate additional stages while also boosting the effectiveness of SC procedures. The literature suggests that CPS, IoT, CC, IoS, RFID, CS, BDA, horizontal, and vertical integration may enhance traceability and visibility. Embedded sensors gather relevant information about the manufacturing process, enabling accurate visibility all along the SC, which is considered a quality of all technologies [263]. IoT enables real-time resource tracking through the SC utilizing sensor equipment, which will ensure process visibility [264].

5.20. Enhanced robustness of linkages in the SC

IoS, CC, CPS, and BDA have the ability to increase the strength of links in the SC, according to the literature. For instance, CPS supports the creation of self-aware, connected devices that may exchange data about their location, storage conditions, and usage levels [265]. These smart gadgets' shared data can be used to enhance everything from R&D and logistics to customer service and product quality. Manufacturers can detect and forecast production changes by using IoS and the analysis of sensor data. Another illustration is BDA, which gathers data from embedded sensors in machines and analyses it to continuously raise the caliber of items going forward [259].

5.21. Enhanced the value chains

The literature suggests that BDA, IoT, AI, and BDA can improve value chains. IoT can enhance customer-facing activities that add the most value and assess ways to raise the value of less valued activities. Agile manufacturing technologies, data engineering, and data science are among the areas in which BDA can help to train a workforce. It also boosts innovation in areas such as advanced and analytics production automation [265].

5.22. Improved flexibility and scalability

According to the literature, flexibility and scalability are affected by AI, IoT, CC, IoS, BDA, and AM. For instance, because AM can create virtually any product that is conceived in a CAD file, it provides boost manufacturing flexibility [198]. Due to its location independence feature, which gives the SC agility and flexibility, CC can also boost scalability [188].

An increasing number of studies have also been conducted to investigate and analyse a range of aspects that affect net zero as well as the challenges that SCs face when attempting to achieve a net-zero target [11,32,229]. The results showed that the NZSC aim is positively impacted by digitalization, resource management and sustainability. I4.0 technologies are a part of digitalization, while sustainability includes a set of circular economy techniques, such as circular human resource applications, circular SC practices, and circular economy design standards. Resource management is primarily concerned with effective resource management and the use of renewable energy sources. However, it is evident from studies on NZSC that these theories have not been applied to describe the phenomena surrounding net zero, including transitional theories, information system theories, strategic management theories, and behavioral theories.

6. Discussion and future research agenda

6.1. Discussion of the findings

The various I4.0 technologies used in NZSC and their potential for bringing about change in this field have been covered in this paper. Even though the studies previously mentioned highlight the potential benefits of I4.0 technologies in enhancing NZSC performance (Table 13), it is crucial to remember that these technologies are not a magic bullet for achieving net-zero goals. Depending on variables such as the industry context, technological maturity, and integration level [266,267], the impact of I4.0 technologies on SC sustainability can vary greatly. For instance, some industries may benefit the environment more than others by adopting these technologies, and the degree to which businesses use these technologies to cut emissions and resource consumption can vary greatly.

The potential for I4.0 technologies to act as enablers of more sustainable SC practices is a recurring theme in the literature. These innovations provide SC participants with previously unheard-of opportunities for real-time data collection and analysis [266],

Table 14
Thematic gaps and potential future research questions.

Major theme	Gap identified	Source	Future research questions
Benefits of core I4.0 technologies for NZSC performance	1. Benefits from combining several I4.0 technologies and their interdependence	[237]	RQ1: Do these new technologies add to or replace the benefits that currently exist? How? Why?
	2. Need to integrate I4.0 technologies with NZSC practices	[226]	RQ2: How does the adoption of the net-zero goal result from SC digitalization?
	3. A thorough examination of the benefits and new application fields of some I4.0 technologies currently used in NZSC, such as IoT, AR, and CPS.	[56]	RQ3: How might the NZSC profit from the integration of many core technologies?
Challenges of core I4.0 technologies for NZSC performance	1. Analysis of business initiatives and tactics to tackle issues	[229]	RQ1: How might other current or brand-new upcoming technologies (or a mixture of technologies) handle the problems that have been identified?
	2. Detailed study of the challenges that some I4.0 technologies, such as CC, AR, IoT, AI, CS, BC, and IoS, have about NZSC	[273]	RQ2: What difficulties arise with the application of AR, CC, IoT, AI, CS, BC, and IoS?
	3. Assessing the effects of various issues and their interdependencies	[263]	RQ3: What steps can businesses take to reduce the effects of these challenges?
Key success factors of core I4.0 technologies for NZSC performance	1. Effect of context on key I4.0 technology success factors	[237]	RQ1: How might the performance of the NZSC be imagined and implemented in light of technologies like IoS, AI, AR, and robotics?
	2. Interdependence of I4.0 technology success factors	[235]	RQ2: When two or more I4.0 technologies are combined, how do key success factors change?
	3. Key success factors for combining several I4.0 technologies	[233]	RQ3: How do different circumstances affect the key success factors of I4.0 technologies?
Challenges, benefits, and success factors of I4.0 technologies on NZSC performance	1. Insights from various disciplines on how I4.0 technologies affect NZSC performance	[58]	RQ1: How can the effects of I4.0 technologies be studied from a multidisciplinary perspective about NZSC performance?
	2. Influence of the NZSC setting on the challenges, benefits, and key success factors of I4.0 technologies	[25]	RQ2: How can such contextual disparities be resolved when examining challenges, benefits, and key factors of I4.0's success?
	3. Interactions between the most typical challenges, benefits, and success factors	[274]	RQ3: What are the relationships among the most prevalent challenges, benefits, and success factors of I4.0 technologies?

enabling them to monitor and optimize resource use, cut waste, and lower GHG emissions. Implementing intelligent and connected systems can also improve transparency and traceability, supporting circular economy principles and responsible sourcing [268]. However, it is crucial to recognize the complex issues and nuanced challenges that this integration raises. These challenges include concerns about the environmental footprint of manufacturing advanced technology components and the energy demands of data centers, as well as the necessity for substantial financial investments and the need to address ethical issues related to data privacy and security [269,270].

Furthermore, the research indicates that while I4.0 technologies can significantly enhance the performance of NZECs, their efficient integration and deployment call for a thorough knowledge of the larger sustainability context and dedication to addressing both the opportunities and challenges they present. More research is required to navigate this complex nexus of technology and sustainability successfully.

6.2. *Scope future research agenda*

This section aims to serve future researchers with a variety of research avenues that could be pursued in light of the study's findings. According to our study of the available literature, interest in the potential effects of I4.0 technologies on NZSCs increased rapidly between 2013 and 2023 and has since maintained a high level. Due to this, over three times as many papers on this subject were published between 2019 and 2022 as had previously been. This development serves as evidence of the topic's importance in terms of both the economy and organizations. Therefore, acquiring a solid understanding and a body of information over time is crucial. As a result of our analysis, it is clear that future studies would benefit from concentrating on the challenges, benefits, key success factors, and fundamental I4.0 technologies for NZSC performance. A thorough future research agenda is provided in Table 14 for the use of researchers working in the NZSC, I4.0, and related topics.

The study's findings show that manufacturing, transportation, logistics, and construction make up the majority of the research conducted in these fields. However, studies in fields including agriculture, fishing, forestry, and mining are scarce. Future research in I4.0 and NZSC may cover these topics in further detail. Our SLR also shows that, generally, the benefits of I4.0 technologies for the NZSC have been discussed more thoroughly than their challenges and key success factors. Focusing too little on their challenges and key success factors is hazardous and harmful. For example, it deprives businesses of informed advice that is based on solid facts and offers assistance on how to utilize I4.0 technologies. Another issue is that unrealistic expectations might arise from overemphasizing positive aspects. Businesses may abandon their transition to I4.0 and lose the benefits if technologies fail to swiftly live up to the unreasonable expectations of managers. When managers lack instructions on how to use their technologies, they are more likely to fall short of expectations. Studying the benefits of I4.0 technologies will nevertheless be essential as technology advances, new technologies appear, and fresh applications for existing technologies are investigated. Thus, the benefits of I4.0 summarized in our SLR and previously conducted research are by no means all-inclusive.

Furthermore, our SLR demonstrates that the degree to which the various technologies at the heart of I4.0 have been previously researched varies. While some fundamental technologies, such as AI and CPS, are regularly debated, others have received less attention (e.g., BC, ARs, and RFID technology). Future studies on the interaction of technologies and how the benefits, challenges, and key success factors can alter when combining two or more I4.0 technologies are very promising. New features and capabilities are developing as many technologies continue to advance (such as "Industry 5.0"; [271]).

The current studies lack a thorough examination of how businesses and nations have worked to achieve the NZSC, the procedures and practices that need to be restructured, and the risk management techniques adopted by businesses. The financial crisis is also crucial in changing the architecture from fossil fuels to alternative renewable resources as the planet warms by 1.5–2 °C. Future research should be done to help decision-makers develop a net-zero approach that targets different geographic areas. We also examine the actions taken by other nations and their potential effects on the NZSC. Finally, we found that more than half of the chosen articles had used experimental methods. It is possible to perform additional theoretical and mixed-methods research to fully utilize the capabilities of the technologies at the heart of I4.0 because they are currently undergoing ongoing development. To evaluate and validate the constructs, quantitative research methodologies must nevertheless be used. For instance, methods such as analytical hierarchy processing and interpretive structural modelling may be suitable for examining the connections among challenges, benefits, and success factors. The key to successful decarbonization is adopting I4.0 technologies and an interorganizational approach [272].

A thorough modification and optimization of operational parameters is required when moving from a laboratory-scale study to a pilot-scale study, which is larger and more similar to real-world industrial conditions. This is necessary to ensure the validity and scalability of the findings. The scalability of the I4.0 technologies and interventions investigated in the lab environment must first be determined. To determine how these technologies can be effectively integrated into more extensive SC systems, feasibility studies and pilot testing may be needed. To accommodate the increased scale, operational factors such as equipment requirements, data collection techniques, and process automation should be scaled proportionately. Moreover, to meet the needs of pilot-scale operations, resource management considerations, such as energy and raw material usage, should also be reviewed and optimized. Furthermore, the complexities and potential bottlenecks in more extensive networks must be considered, and modifications must be made to address these challenges. Likewise, to guarantee the consistent performance of I4.0 technologies at the pilot scale, it is also necessary to test and improve the robustness of the systems, data analytics algorithms, and quality control measures. Researchers, engineers, and industry partners must work together to successfully adapt and optimize operational conditions during this transitional process. This will enable the successful implementation of I4.0 technologies in more extensive, real-world SC scenarios.

7. Implications

Fig. 7 illustrates how the I4.0 technology-based NZSC performance framework has significant implications for triple helix actors (academics, industry, and governments).

7.1. Theoretical implications

This study makes four contributions to the literature on NZSC and I4.0. By concentrating on the I4.0 technologies in the NZSC field, the study first highlights the state of the literature as it stands today. Second, the study shows that digitalization has a beneficial impact on NZSC performance. Therefore, the results can help academics better grasp the strategic role these aspects play in achieving the net-zero target. Third, by offering a structured framework for further discussion of the potential challenges, benefits, and success factors of particular I4.0 technologies, this study assists in the adoption of I4.0 technologies in NZSC. The framework we create promotes a comprehensive approach to NZSC. The paper also identifies specific topics for further study and future research questions (Table 14).

The current SLR offers interdisciplinary insights while bridging gaps between disciplines. It combines perspectives from various disciplines, including engineering, SC management, sustainability research, and technological innovation. This interdisciplinary approach fosters collaboration across academic and industry boundaries while also enhancing the richness and depth of our understanding. Furthermore, our review systematically identifies knowledge gaps in the field today. These gaps focus on areas that need more research and act as a road map for future studies. As a result, this study provides SC professionals with useful advice that will enable them to use I4.0 technologies to successfully and sustainably create an NZSC. This aids in the conversion of theoretical knowledge into practical applications.

The added value of our SLR to the body of knowledge is due to its original synthesis and analysis of an interdisciplinary field that is rapidly developing. Our contribution is meticulously collecting and scrutinizing the most current and vital research at the nexus of I4.0 and sustainable supply chains. By doing this, we offer a thorough and contemporary overview of the state of knowledge in this field, highlighting essential trends, gaps, and emerging themes. Furthermore, our work is vital for addressing urgent global issues such as achieving net-zero emissions in supply chains. It provides a valuable resource for academics, professionals, and decision-makers who want to comprehend the dynamic relationship between I4.0 technologies and SC sustainability. Providing a clear overview of the current literature enables stakeholders to make well-informed decisions and advance research in this critical area. In this way, our SLR contributes to the ongoing discussion about sustainable SC management in the era of I4.0 by serving as a fundamental reference point for upcoming theoretical and empirical studies.

7.2. Practical implications

Digitalization managers, technology officers, SC managers, and related practitioners who are spearheading net zero initiatives or digitalized SC will benefit from the structured literature review presented in this study in developing a thorough knowledge of the strategic significance of net zero in various ways. First, the suggested framework might assist these managers in gaining a more comprehensive understanding of the technologies at the heart of I4.0 and the consequences of those technologies in terms of potential challenges, benefits, and success factors. The 14 key technologies in particular give managers a wide range of potential solutions to meet the objectives of their particular NZSC. This framework could be used to evaluate the advantages, opportunities, and dangers of a focused company, prepare the related operational procedures and coordinate the relevant investment efforts as businesses fight to

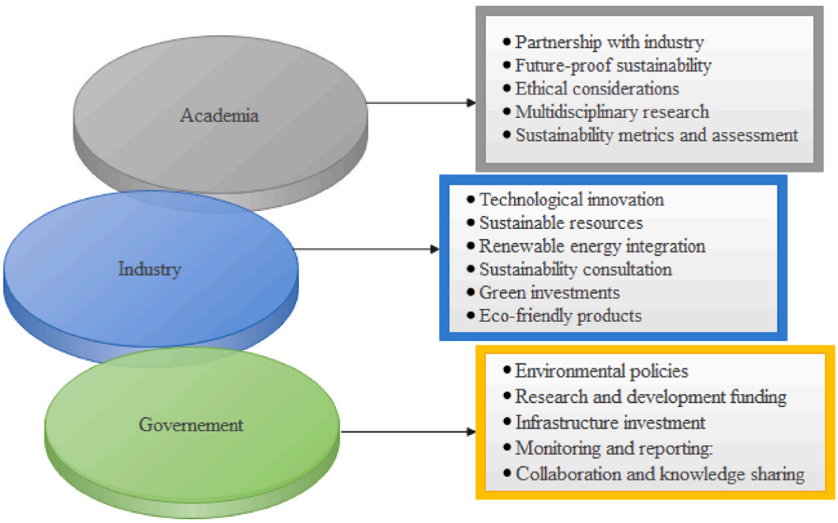

Fig. 7. Triple helix framework for I4.0-based NZSC implications.

create advanced digital and NZSCs. Second, the research will help practitioners reach net-zero goals by implementing strategies including resource management, the circular economy, and digitization. Moreover, managers might talk about the shortcomings of the company's current legacy systems and potential solutions using net zero strategies and I4.0 technologies using the proposed framework. Third, the dearth of studies utilizing qualitative and behavioral data as well as the sparse use of cutting-edge analytical methods such as machine learning techniques and neural networks refer to the need for practitioners to examine various facets of decarbonization practices and understand the psychological aspects of net-zero goals. Finally, I4.0 net zero supply chains (also known as "NZSC 4.0″) may inherently be a part of and have a large impact on many recent trends, including the circular economy, digital decarbonization, sustainability, and the sharing economy (e.g., Refs. [56,58]). The findings of our study may be used by researchers in these fields to design and plan a sustainable digital transformation of the NZSC.

Furthermore, in the context of achieving NZSC, the research presented in this study has important implications for process engineering design and practice. Our research examines how I4.0 technologies can be integrated into SC management, and the results give process engineers a scientific basis on which to rethink and improve their processes. The endeavor's core component is the application of cutting-edge sensors and data analytics, which allows engineers to collect real-time data on resource use, emissions, and energy consumption [270]. This engineering information is essential for improving the creation and application of environmentally friendly and energy-saving processes. Furthermore, I4.0's core component of smart logistics and autonomous systems engineering enables efficient and environmentally friendly transportation and warehousing, lowering the supply chain's carbon footprint [269].

In addition, this SLR offers substantial economic benefits for applications in industry. The first benefit is that this review gives businesses a summarized and current understanding of the financial benefits connected to the incorporation of I4.0 solutions into SC operations. Furthermore, the review provides valuable information to businesses to make well-informed investment decisions by providing insights into cost-reduction strategies, improved resource efficiency, and increased operational productivity. Industries can use these findings to optimize resource allocation, streamline operations, and ultimately increase bottom-line profitability. In essence, the economic gains from this SLR go beyond academia, providing real advantages to economic sectors looking to increase economic sustainability while advancing more general environmental goals.

Likewise, our thorough review paper emphasizes the critical contribution of technological advancements to the transformation of the field of sustainable SC management. We identify several significant technological advancements within the conceptual framework that are pertinent to the pursuit of NZSC. These developments cover a wide range of products, from the widespread use of the IoT and sensor technology for real-time monitoring and data-driven decision-making to the incorporation of AI and CPS for predictive analytics and optimized resource allocation. Our review also highlights the importance of BDA in utilizing massive amounts of SC data for improved efficiency and transparency. Furthermore, integrating blockchain technology into supply chains is emerging as a crucial enabler of trust, traceability, and sustainability. By revolutionizing operational procedures, improving resource utilization, and encouraging greater environmental responsibility across industries, these technological innovations help reduce resource consumption, emissions, and waste and provide a pathway to achieve NZSC.

Furthermore, the findings derived from this SLR present significant opportunities for technologically oriented applications with high commercialization potential. I4.0 technology integration, as discussed in this review, has the potential to transform supply chain management and lead to net-zero emissions. The synthesized knowledge can be used by commercial enterprises engaged in developing and deploying I4.0 solutions to improve their products. For instance, technology companies can tailor their products and services to address the particular needs of organizations aiming to transition to NZSC by understanding the specific challenges and success factors identified in the literature. This review can also be used as a starting point by businesses looking to create cutting-edge IoT gadgets, analytics tools, or software programs to improve SC sustainability. Furthermore, businesses can be helped by the knowledge of the shifting regulatory environment and sustainability standards to ensure compliance and integrate eco-friendly practices into their technologies.

Furthermore, this study reveals enormous potential for promoting a circular economy and mitigating the effects of global climate change. This review can shed light on how I4.0 innovations such as the IoT, AI, and BDA are being used to improve supply chains' sustainability and efficiency by synthesizing existing research results. Thanks to the insights gained from this review, policymakers, businesses, and practitioners can learn about best practices and new trends in using these technologies. Therefore, the rapid adoption of I4.0 solutions within supply chains can result in lower GHG emissions through improved resource utilization, transportation efficiencies, and energy management. The review can also encourage practices that reduce waste generation, promote product reuse, and ultimately contribute to a more sustainable and resource-efficient global economy by highlighting the significance of circular economy principles in SC operations.

In essence, this in-depth examination of the literature contributes significantly to the SDGs of the United Nations. It offers important new information about the trends and difficulties in implementing NZSC related to adopting I4.0 technologies. First, it demonstrates how I4.0 technologies can support sustainable industrialization and innovation, which aligns with several SDGs, including SDG 9 (Industry, Innovation, and Infrastructure). Our review also considers SDG 12 (Responsible Consumption and Production), focusing on how these technologies can improve responsible production while lowering waste and maximizing resource use in supply chains. Furthermore, it supports SDG 13 (Climate Action) by investigating how I4.0 technologies can reduce emissions and promote energy-efficient operations. Furthermore, our review indirectly contributes to the achievement of SDG 17 (Partnerships for the Goals) by encouraging research collaboration and knowledge exchange among policymakers, industry stakeholders, and other stakeholders.

Our review reveals several crucial conclusions regarding trends and challenges within the SDG paradigm. One notable trend is the increasing compatibility of I4.0 technologies with sustainability objectives. Businesses are becoming more committed to the values embodied in the SDGs, and they see these technologies as enablers of responsible production and consumption [263]. However, difficulties still exist, especially regarding data security and privacy, as the proliferation of data-driven solutions raises ethical and legal questions. Regulation and policy frameworks are changing to promote sustainability while addressing potential risks brought on by new technologies. Likewise, our SLR offers insights for future research and policy formulation in pursuing sustainability in NZSC by aligning with multiple SDGs and illuminating trends and challenges within the SDG paradigm.

7.3. Policy implications

The integration of I4.0 technologies into supply chain management holds significant policy implications for achieving NZSC performance. Firstly, policymakers need to recognize the potential of these advanced technologies in enhancing supply chain efficiency, transparency, and sustainability. Government incentives and supportive policies can encourage industries to invest in digitalization, automation, and data analytics, which are fundamental components of I4.0. Secondly, regulatory frameworks should be updated to address data security and privacy concerns associated with the increased use of IoT devices and digital platforms. Thirdly, fostering collaboration between governments, industry stakeholders, and academic institutions is crucial in promoting research and development efforts aimed at reducing the environmental footprint of supply chains. Policy measures that incentivize carbon-neutral practices, such as renewable energy adoption, efficient transportation systems, and circular economy principles, can align with the NZSC performance goals. Finally, the strategic alignment of policy initiatives with I4.0 technologies can accelerate progress towards more sustainable and environmentally responsible supply chains.

8. Conclusion

Through a thorough assessment of the literature, this study explores and combines the challenges, benefits, and success factors of 14 technologies that define I4.0 in relation to NZSC performance. The study includes 68 articles from more than 30 journals and discusses the core technological elements of I4.0, including AI, IoT, CPS, CC, IoS, ARs, RFID technology, BDA, AR, vertical integration, horizontal integration, CS, and BC. As an NZSC is emerging, this paper sheds light on the I4.0 technologies affecting NZSC performance. It was evident from prior literature evaluations that there were few studies on the effect of I4.0 on NZSC performance. Moreover, it was clear that there were no reviews of the literature on I4.0 and NZSC performance; thus, this work adds an SLR to that body of knowledge. The proposed framework outlines the effects of various I4.0 technologies on NZSC performance and is one of the first attempts to add to the theory of I4.0, the interrelationships of technologies, and the enhancement of NZSC performance.

To maintain the integrity and credibility of our research, we encountered several notable bottlenecks while conducting our review paper that required careful mitigation strategies. The lack of primary research studies explicitly addressing the point of intersection between I4.0 technologies and the NZSC was a significant limitation. To mitigate this limitation, we adopted a practical and inclusive approach to source materials, incorporating a more comprehensive range of studies relating to I4.0 technologies and SC sustainability. Even though this strategy increased the body of available literature, we were meticulous in our evaluation and outlined each study's relevance and applicability to our research goals. This allowed us to present a thorough perspective while ensuring the caliber and relevance of the sources used. Another limitation was the inherent diversity in research methodologies and terminologies used across the selected studies. This diversity introduced the risk of incomparability and complexity in finding synthesis. To address this issue, we used a methodical categorization and thematic analysis approach, enabling us to extract and harmonize key insights from studies with various methodologies.

By combining and synthesizing existing research to push the boundaries of knowledge, this SLR represents a significant advancement in sustainable SC management and I4.0. This study provides a contemporary perspective on the complex relationship between I4.0 technologies and NZSC, going beyond what was previously known by integrating new research and trends. A multidisciplinary approach is also used in our review, which incorporates insights from economics, technology studies, environmental science, and industrial engineering. Along with enhancing domain-specific knowledge, this interdisciplinary approach can stimulate the cross-fertilization of insights among different academic disciplines, fostering innovation in these areas. Furthermore, our data synthesis, gap analysis, and development of a comprehensive framework enable a deeper understanding of the topic, laying a solid foundation for further study in this area and perhaps sparking creative solutions that breakdown traditional silos.

As a result, this SLR has much potential to have significant local, national, and global research impacts. On a global scale, the in-depth knowledge gained from this review can significantly advance our understanding of the relationship between sustainability and technology, fostering international knowledge of best practices and challenges. The findings made here have the potential to assist national policymakers in formulating regulations and policies that support sustainable SC practices. This review is also positioned to provide industries with crucial information that will motivate strategic choices supporting net-zero goals. Finally, at the local level, the context-specific insights from this review have the potential to spur cooperation among regional stakeholders, propel educational initiatives, and shape research agendas that address the particular dynamics of local SC ecosystems. This SLR's research effects are wide-ranging and poised to spur significant change in academia, business, and communities, ultimately assisting in establishing sustainable and net-zero supply chains globally.

This study has some limitations, but these limitations can help future research move forward. First, this review only considered articles and review papers, ultimately decreasing the total number of papers under review. As a result, researchers may, in the future, consider more diverse papers. Second, a single qualitative study cannot map the entire role of I4.0 technologies in achieving NZSC. Third, the pace of technological advancement in this field means that studies included in the review may not fully capture the most up-to-date applications or implications of these technologies in supply chains. Moreover, sustainability goals and regulations are continually evolving, affecting the relevance and applicability of older studies.

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Asmae El jaouhari: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jabir Arif:** Supervision, Resources, Project administration, Investigation. **Ashutosh Samadhiya:** Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Anil Kumar:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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