Journal of Cleaner Production 418 (2023) 138111

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Introducing a framework toward sustainability goals in a supply chain 4.0 ecosystem

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ARTICLE INFO

Handling Editor: Dr. Govindan Kannan

Keywords:
Industry 4.0 implementation
SCOR model
Supply chain 4.0
Sustainability performance
Sustainable development goals

ABSTRACT

The business and research community are called upon to take concrete actions to achieve the Sustainable Development Goals (SDGs). We state that Industry 4.0 technologies are the innovative capability that should be supported to move supply chains from their linear model, known for its high energy and resource consumption, to a circular model where technology replaces intermediaries and drives operations towards sustainability and efficiency. The study reflects the impact of integrating Industry 4.0 technologies on each of the processes in the Supply Chain Operations Reference Model (SCOR) to construct the supply chain 4.0 and links the resulting capabilities of this transformation to the potential achievements of the Sustainable Development Goals (SDGs). This paper draws on recent studies and secondary data sources to provide a framework that could help academics and practitioners reduce tensions related to the maturity level of Industry 4.0 technologies and foster concrete implementations to achieve sustainability goals.

1. Introduction

The digital transformation of supply chains continues while attracting huge interest from academicians, practitioners, and institutions to discover its potential benefits on sustainability performance.

The approaching 2030 deadline for achieving the 17 Sustainable Development Goals (SDGs) (Table 1 near the end of the paragraph) and the increase in sustainability issues have emphasized the importance of rethinking the development of supply chain processes and business models and investing in sustainable technologies to achieve the sustainability goals.

Industry 4.0 is the fourth industrial revolution that was first introduced by German officials in 2011 (Madsen, 2019), to encompass advanced technologies like the Internet of Things (IoT), Blockchain (BC), artificial intelligence (AI), machine learning (ML), cloud computing (CC), 3D printing, and cyber-physical system (CPS) (Cortes-Murcia et al., 2022; Ferrantino and Koten, 2019).

Following this, supply chain 4.0 has begun to gain momentum as the new design network powered using Industry 4.0 advanced technologies. It extends the functionality of a digital supply chain to the fusion of the physical and virtual worlds through the adoption of smart objects and advanced Industry 4.0 technologies (Khan et al., 2023).

Supply Chain 4.0 is a novel paradigm that involves new industry models, where human beings, machines, processes, products, and technologies are interconnected and communicate with each other in real-time. This integration enables increased process efficiency, which in turn leads to improved economic, environmental, and social sustainability (Cañas et al., 2020).

While the concept of Supply Chain 4.0 was not widely recognized during the adoption of the 2030 sustainable development goals (SDGs), the growing number of urgent sustainability requirements set by the United Nations (UN) has led to increasing interest regarding this new paradigm, which opens up a great field of research.

Existing research tends to focus on discovering Industry 4.0 technology applications in specific industries (Tsolakis et al., 2023), identifying new sustainability practices (Chauhan et al., 2023), or exploring SDG synergies (Pradhan et al., 2017). The gap remains in identifying the resulting SDGs from the supply chain 4.0 paradigm (Karmaker et al., 2023), where Industry 4.0 technologies play a significant role in elevating supply chain processes. Furthermore, tensions are still raised regarding the maturity level of Industry 4.0 technologies in terms of their interoperability and integration within intra- and inter-organizational contexts (Kamble et al., 2020a; Nascimento et al., 2019).

Thus, there is a pressing need for research that provides decision-

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https://doi.org/10.1016/j.jclepro.2023.138111
Received 12 December 2022; Received in revised form 10 March 2023; Accepted 14 July 2023
Available online 20 July 2023
0959-6526/

List of abbreviations

AI	Artificial intelligence
AM	Additive manufacturing
BC	Blockchain
CC	Cloud computing
CPS	Cyber-physical system
GHG	Greenhouse gas
I4.0	Industry 4.0
IAV	Intelligent autonomous vehicles
IoT	Internet of Things
ML	Machine learning
RFID	Radio Frequency Identification
SC 4.0	Supply chain 4.0
SC	Supply chain
SCOR	Supply chain operations reference
SDGs	Sustainable development goals
SSC4.0	Sustainable supply chain 4.0
UN	United Nations

Table 1
The UN sustainable development goals (UN, 2015)

SDG 1 – No poverty
SDG 2 – Zero Hunger
SDG 3 – Good health and well-being
SDG 4 – Quality education
SDG 5 – Gender equality
SDG 6 – Clean water and sanitation
SDG 7 – Affordable and clean energy
SDG 8 – Decent work and economic growth
SDG 9 – Industry, innovation, and infrastructure
SDG 10 – Reduced inequalities
SDG 11 – Sustainable cities and communities
SDG 12 – Responsible consumption and production
SDG 13 – Climate action
SDG 14 – Life below water
SDG 15 – Life on land
SDG 16 – Peace, justice, and strong institutions
SDG 17 – Partnerships for the goals

making and application frameworks to understand how sustainable performance can be achieved through the integration of Industry 4.0 technologies into supply chain processes, specifically focused on the SDGs (Dwivedi et al., 2023). This gap in the literature presents an opportunity for academics and practitioners to develop practical solutions to achieve sustainability and contribute to the SDGs through the adoption of Industry 4.0 technologies in supply chain processes.

It is important that research focuses on finding new ways to reframe supply chain processes to fit the sustainability agenda. Therefore, our first contribution is to develop a new conceptual framework that represents how Industry 4.0 technologies can dynamically leverage new capabilities to SCOR-based supply chain processes to improve sustainability initiatives and achieve the goals of the United Nation's agenda.

Second, the proposed framework can be applied to different industries to offer insights to companies and institutions on how optimization of supply chain processes would result in contributions to the sustainability goals.

Finally, the study joins the discussion of supply chain 4.0 in relation to sustainability goals and reflects on how transitioning to a supply chain 4.0 would enable new management practices to best utilize resources, reduce costs, and generate sustainability values.

This paper relies on reviews of the scientific literature on the sustainable supply chain 4.0 and other secondary data sources. It is structured as follows: Section 2 introduces the positioning of the paper in the literature by offering insights from previous literature to justify the study's contribution and reflect on the methodology. Section 3 discusses the transformation to a sustainable supply chain 4.0, followed by Section 4 which describes the supply chain 4.0 capabilities in the SCOR model. Section 5 discusses the benefits of sustainable supply chain 4.0 capabilities to achieve sustainability goals. The proposed framework is described in Section 6. Finally, Section 7 summarizes the main results and highlights limitations and implications.

2. Background and positioning

In recent years, there has been a surge of interest in exploring the potential of Industry 4.0 technologies for achieving supply chain sustainability.

The internet of things (IoT), artificial intelligence (AI), 3D printing and Blockchain are among the advanced technologies that have been identified as having significant potential to enable the development of smart, resilient, and sustainable digital industrial processes (Karmaker et al., 2023).

By promoting sustainable production practices, exploring innovative waste reduction techniques, improving connectivity, and bringing greater visibility and transparency to supply chains, these advanced technologies can play a critical role in achieving corporate supply chain sustainability goals (Fatimah et al., 2020; Karmaker et al., 2023). Mature companies are breaking new ground in this context to pursue change towards sustainability (De Villiers et al., 2021). Bag et al. (2021) state that Industry 4.0 enablement contributes to decreasing total industrial waste and total industrial wastewater discharge.

Authors discuss this topic from different angles. Some studies focus on identifying the potentials of Industry 4.0 technologies for supply chain management and triple bottom line sustainability (Bag et al., 2021), and reflect on the direct influence of these technologies on sustainable supply chain transformation (Schilling and Seuring, 2023), while others consider the trade-off between their costs and returned values (Birkel and Müller, 2021).

Sustainability is a critical consideration throughout the product life cycle, from ideation in the planning process to delivery to end-users and eventual return (Schilling and Seuring, 2023). Digital strategies are being implemented to transform operations and strategies by leveraging digital technologies to drive green innovation activities across research and development, manufacturing, warehousing, transportation, and recycling (Xu et al., 2023).

To support this, researchers have proposed frameworks for Sustainable Supply Chain Management (SSCM) in the Industry 4.0 era. For example, Toth-Peter et al. (2023) proposed a conceptual framework to shift from traditional business to circular models using Industry 4.0 to achieve sustainability goals. Yang et al. (2021) presented a framework to help firms understand the purpose and potential impact of technology adoption in supply chain processes and how transformation could affect the supply chain to achieve sustainability benefits.

Other literature fragments explored the impact of technology on the SDGs (Fig. 1 near the end of the paragraph) (Agrawal et al., 2022b; Tsolakis et al., 2021). For instance, Chandan et al. (2023) investigated the potential of Blockchain technology to reduce environmental impact in the food supply chain to achieve the SDGs. Additionally, Del Río Castro et al. (2021) provided a general overview and guidance on the SDGs and their nexus with digitalization.

Despite the considerable knowledge in the literature, the implications of supply chain 4.0 transformation for sustainable development goals are still understudied. This field remains open to research and investigation, and the achievement of concrete results towards sustainability goals may be hindered by a restricted focus on supply chain processes, which are subject to technological disruptions (Srhir et al., 2023).

Technology selection must be aligned with business needs and

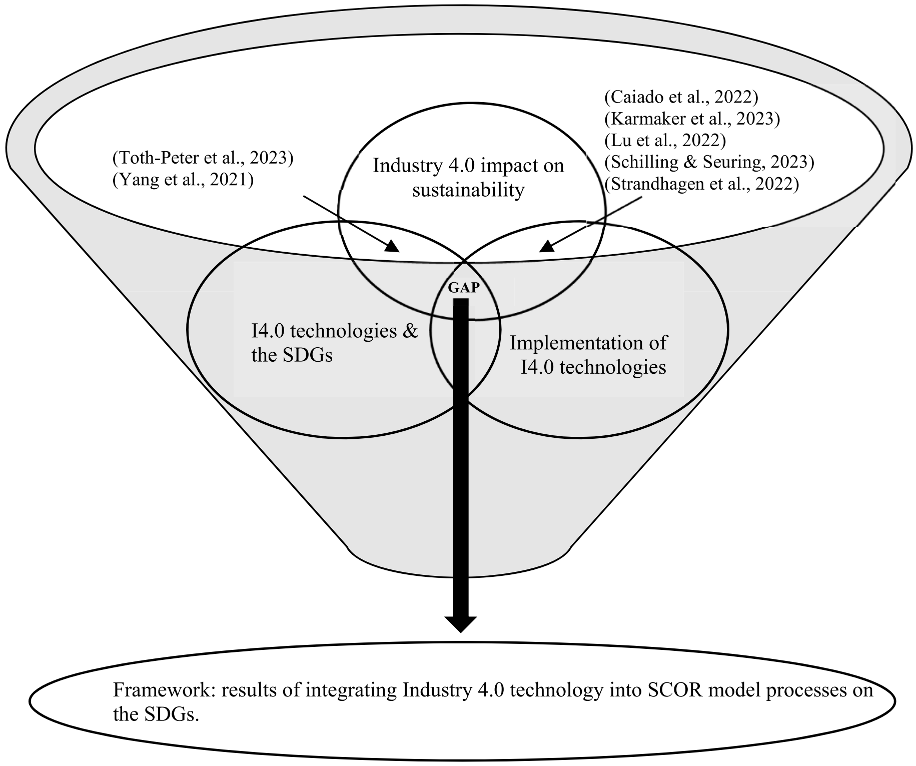

Fig. 1. Research gap.

objectives and must be tailored to the business environment (Zangiacomi et al., 2020). Furthermore, only a few industrial implementations have been identified regarding the implementation of these technologies and some projects are still in pilot phase (Strandhagen et al., 2022). In this regard, frameworks are needed to guide the implementation of these digital tools and make their relevance to sustainability more evident (Lu et al., 2022; Strandhagen et al., 2022).

To respond to this, our study aims to build a conceptual framework that acts in three main axes: (i) The transformation from sustainable supply chain to sustainable supply chain 4.0, (ii) the capabilities that emerge from the transformation in the SCOR model processes, and (iii) the link between the benefits of technology integration to the achievement of sustainability goals.

The present study relies on a comprehensive literature review, encompassing recent publications and research studies related to the subject matter. Additionally, the study also analyzed secondary data sources, including companies' reports and press reports, to gather insights into the practical applications and benefits of Industry 4.0 technologies for the SDGs. By utilizing both primary and secondary sources, the study aims to provide a holistic framework that can help inform policymakers, business leaders, and other stakeholders on the potential of Industry 4.0 technologies to foster sustainable development.

3. Sustainable supply chain 4.0

This section addresses the first objective of the study, which is to provide insights into the transformation of supply chains. It is structured into three parts. It discusses sustainable supply chains in today's fast-moving business environment. It explores the key components and pillars of supply chain 4.0, which drives the transformation of modern supply chains, and concludes with a state-of-art of sustainable supply chain 4.0.

3.1. Sustainable supply chain (SSC)

Sustainable supply chain management (SSCM) has emerged as an essential aspect of the supply chain, with the goal of integrating sustainability concerns, practices, and goals into core supply chain processes such as planning, sourcing, making, delivery, storage, and return (Srhir et al., 2023). Sustainability became the success factor of businesses, as social economic and environmental dimensions are essential to meet the strategic goals of all stakeholders in the value chain (Yavuz et al., 2023).

Sustainable supply chains are based on maintaining performance on three levels. Economic sustainability, such as reducing inaccuracies, costs, waste, and delays, while improving quality compliance and process management (Sislian and Jaegler, 2022).

The social dimension is represented in some literatures by indicators such as job opportunities, extended producer responsibility (Moreno-Camacho et al., 2022), equality, quality of work, health, well-being, and social capital (Fatimah et al., 2020).

The rise in environmental concerns made research very active regarding this pillar. Multiple initiatives have been undertaken to reduce these concerns. Xu et al. (2023) introduced eco-innovation as a new concept to pursue environmental solutions such as reducing the use of harmful raw materials, reducing pollution and carbon emissions. It relies on the ability of companies to reshape product design, processes, and structures for environmental sustainability.

In addition, Toth-Peter et al. (2023), outlined the importance of practices and technologies that improves reverse logistics, which closes the loop of supply chain, reduces waste in the environment while improving resource efficiency (Agrawal et al., 2022b).

Companies are adopting sustainable practices to achieve sustainability, maintaining collaboration among stakeholders, and sharing information to optimize operational performance and reduce costs. In addition, regulatory pressure from governments to comply with environmental and social standards has also increased (Sharma et al., 2023).

The literature addresses sustainability in relation to the sustainable development goals (SDGs); these goals have been addressed by various sustainability-oriented supply chain strategies and practices (Agrawal et al., 2022a). According to Tsolakis et al. (2021), the UN agenda provides a chance for industries to revamp their businesses. The sustainable development goals reinforce sustainability in supply chains (Chandan et al., 2023), which means that alterations to the upstream and downstream processes of the supply chain are necessary to achieve these goals. Additionally, synchronizing sustainability efforts throughout the entire value chain is crucial (Modgil et al., 2020).

3.2. Supply chain 4.0 (SC4.0)

The term "Industry 4.0″ is gaining momentum in the academic world. It refers to a bundle of smart technologies whose integration leads to supply chain 4.0 transformation. The cluster of these technologies differs from one author to another. Among them, the most known are Internet of Things (IoT); Additive Manufacturing (AM); Artificial Intelligence (AI); Big Data Analytics (BA); Physical Objects (PO); Intelligent Autonomous Vehicles (IAV) and Blockchain (BC) (Srhir et al., 2023). Additionally, Shao et al. (2021) identify Cloud computing (CC) and Machine Learning (ML). These cutting-edge technologies work autonomously or in conjunction to drive supply chains towards process excellence and the attainment of sustainability goals (Caiado et al., 2022; Kopyto et al., 2020). They capture the massive data flowing from one physical system to another, enabling process integration and efficient, accurate decision making (Lu et al., 2022; Shao et al., 2021).

Supply chains 4.0 are powered by these technologies to make a global impact. They hold significant capabilities to improve productivity (Tortorella et al., 2019), economic sustainability (Azevedo et al., 2021), and quality and efficiency in global business (Ramanathan et al., 2017). Moreover, as supply chain 4.0 integrates stakeholders and supports collaboration, it influences strategic business alliances within industries (Benzidia et al., 2021), as well as income allocation across countries (Ferrantino and Koten, 2019). For instance, they offer great potential for information visibility and secure storage of data (Di Vaio and Varriale, 2020; Kouhizadeh et al., 2020), which allow for the calculation of metrics with implications for government operations, for example, the SCOPE 3 emissions metric for tax enforcement.

In fact, in supply chain 4.0, process management is smart (Moeuf et al., 2018), including automated warehousing and staging, and smart manufacturing which provide increased accuracy, visibility and auditing of data, reducing production process downtime, wastage, errors and worker safety risks (Dantas et al., 2021).

3.3. Sustainable supply chain 4.0 (SSC4.0)

Sustainable supply chain 4.0 requires appropriate technology integration and sustainability initiatives by involving targeted stakeholders (Silvestre and Ţîrcă, 2019). This new context has required technology contributions to help redefine business models and to reduce organizational boundaries (Weking et al., 2020), to effectively manage upstream and downstream challenges to maintain added value in the chain and address the sustainability challenge (Thakur and Mangla, 2019). Following that, at the company level, the connection between business partners, and the flow of data and the interconnection of physical objects and technologies makes processes smarter and more efficient (Dantas et al., 2021).

The application of Industry 4.0 technologies has revolutionized supply chain management by subjecting each process to one or more technologies that can improve sustainable efficiency. For instance, 3D printing, which is mostly used in the manufacturing process, has the potential to develop both new and retreated products. The tire industry is a good example of this (Shahpasand et al., 2023), as multiple giant tire manufacturers are relying on this technology to be using sustainable materials by 2050, thereby reducing the negative impact on the environment. Economically, implementing 3D printing increases the net profit of the supply chain and optimizes material flows (Chan et al., 2018).

Moreover, sustainable supply chains have been subject to extensive research that explores the potential of technologies such as the Internet of Things and Blockchain (Schilling and Seuring, 2023; Srhir et al., 2023). According to Khan et al. (2023), these technologies have the potential to create intelligent, robust, and sustainable systems by facilitating the flow of information and providing traceability (Kamble et al., 2020b). This integration not only fosters long-term partnerships with supply chain partners but also enhances process efficiency (Fatorachian and Kazemi, 2021; Yang et al., 2021).

4. Supply chain 4.0 capabilities in SCOR model processes

The SCOR model specifies six processes (plan-source- make-deliver-return-enable) that a supply chain must perform in order to deliver value to customers (SCC, 2017). This model was conceived by the Supply Chain Council in collaboration with leading manufacturing companies to uncover managerial practices to drive supply chain towards excellence and performance. It sets strategic parameters and objectives to maintain reliability, flexibility, agility, and cost effectiveness of operations (Dissanayake and Cross, 2018).

In its latest version, SCOR 12.0 considers some of the Industry 4.0 technologies such as, Internet of Things and Additive Manufacturing as emerging practices (SCC, 2017). Furthermore, the literature mentions that Industry 4.0 technologies transform supply chains by enabling new capabilities that disrupt their processes (Khanfar et al., 2021; Yang et al., 2021).

4.1. Planning process

The first step in supply chain management is the planning process in which companies aim to analyze demand and supply, to align them with sourcing, production, and distribution (Chehbi-Gamoura et al., 2020). Industry 4.0 integration offers the transparency of shared data, which facilitates planning by integrating all stakeholders into the supply chain planning process (Srhir et al., 2023).

The result of this integration is to accelerate cross-functional decision making, increase information visibility (Chandan et al., 2023), and optimize real-time collaboration with business partners (Khanfar et al., 2021), resulting in efficient use of resources and improved financial performance (Kazancoglu et al., 2022).

For instance, Industry 4.0 technologies enable the placement of customers at the center of the supply chain, to design the right products and plan efficiently to satisfy their demand (Yang et al., 2021). In addition, this integration allows the optimization of processes and the enforcement of demand forecasting (Shafique et al., 2019). According to Kumar et al. (2021), big data analytics enable lean planning, and support a sustainable network that is based on cost savings, waste and carbon emission reduction, governance, and social welfare (Awan et al., 2021).

4.2. Sourcing process

In the procurement process, managers aim to select the right suppliers for their business and value missions (Chehbi-Gamoura et al., 2020). Industry 4.0 integration makes this process smarter, boosts sustainability capabilities (Garcia-Muiña et al., 2019), and strengthens tier-supplier relationships (Chand et al., 2020). The traditional sourcing management is time-consuming and engenders a lot of costs (Yang et al., 2021).

Smart procurement is characterized by faster and efficient transactions thanks to real-time information sharing and transparency of data along the chain (Kazancoglu et al., 2022). This enablement could largely prevent time overruns due to miscommunication and strengthen sourcing activities, such as ordering, resource management, and forecasting (Kamble et al., 2020b; Tsolakis et al., 2021).

Sourcing seeks to strengthen the traceability of raw materials and maintain the registration of data on suppliers' certifications and product quality (Fatimah et al., 2020). For example, technology enables instant data recording and prevents fraudulent information from being validated (Liu et al., 2023), which facilitates the supplier selection process (Ghadimi et al., 2019), optimizes sourcing decisions, and strengthens responsible sourcing (Khan et al., 2023).

Industry 4.0 technologies such as data analytics and artificial intelligence enable win-win relationships with suppliers, resulting in better forecasting (Lin et al., 2020; Sharma and Joshi, 2020), efficient inventory and logistics organization, leading to economic benefits and better resource management (Kiel et al., 2017). However, this paradigm requires a high degree of data sharing capability, as well as transparency and security of data as it flows through supply chain partners (Liu et al., 2023).

4.3. *Making process*

Many companies have begun to explore the benefits of Industry 4.0 technologies on manufacturing processes. The integration of these technologies enhances production through automation optimized by data generated from other processes, making production lean and efficient in terms of costs and resources (Javaid et al., 2022; Müller et al., 2018).

Industry 4.0 integration results in synchronized operations, quality products, safe production, and employee safety (Liu et al., 2023). According to Holland et al. (2017), the bundle of additive manufacturing and Blockchain leads to better process auditing and improves product design characteristics by adhering to sustainability norms. Robotics and machine-to-machine connectivity led to sustainability benefits in terms of waste and emission reduction, resource mitigation (Yavuz et al., 2023), augmented workforce, and rapid identification of defective systems and machines (Dornelles et al., 2022), allowing for efficient order fulfillment and reduced impacts of downtimes both in terms of cost reduction and time management (Toth-Peter et al., 2023). Moreover, Industry 4.0 technologies, such as connected sensors, and IoT, enable manufacturers to satisfy their customers and generate more capital (Ghadimi et al., 2019; Müller et al., 2018).

4.4. *Deliver process*

The number of wrong orders, idle times, and damaged goods can be reduced by data transparency throughout the supply chain (Qiu et al., 2015). Supply chain 4.0 is characterized by efficient planning and synchronized operations through real-time data flow, which reduces logistics costs and waste in logistics processes (Ferrantino and Koten, 2019).

The use of technologies such as artificial intelligence and Internet of Things enables efficient routing, to find cost-effective emission thresholds based on customers within a route, vehicle efficiency, distance to customers, and density of the point of delivery area. On the other hand, autonomous vehicles have been widely investigated to improve the efficiency of the delivery process in terms of sustainability (Figliozzi, 2020).

Many studies consider autonomous vehicles to be a potential solution for reducing fuel consumption and emissions (Bechtsis et al., 2018; Figliozzi, 2020). They have the capability to autonomously interoperate with the external environment with a goal of promoting rational economic costs and societal advantages such as enhanced human safety and accessibility (Srhir et al., 2023). For instance, Slowik and Sharpe (2018) focus on the long-haul transportation and heavy freight vehicles and find that the benefits of autonomous trucking could be significant in terms of fuel consumption and emissions, resulting in relevant sustainability performance outcomes. This technology can also reduce the consistency of the driver shortage problem (Wang et al., 2022).

Supply chain 4.0 has customers integrated into process operations working together with the entire network (Nabila et al., 2022). This alignment enables transportation optimization (Govindan et al., 2018; Nguyen et al., 2018), cost reduction through consolidation and last-mile management (Yang et al., 2021), and ensures good return on capital (Caiado et al., 2022).

4.5. *Return process*

Industry 4.0 supports the flow and activities associated with reverse logistics and closed-loop chain management (Toth-Peter et al., 2023). This process entails designing and monitoring operations to ensure value creation throughout a product's lifecycle (Dev et al., 2020). Lacking a focus on reverse logistics management drives companies to lose capital and value against the competition.

Some studies have focused on this process and suggest the integration of Industry 4.0 technologies as a solution to maintain and improve it (Dwivedi et al., 2023; Toth-Peter et al., 2023). For instance, Internet of Things, Big Data analytics, and RFID tags enhance the reverse logistics operations as they enable product tracking, data collection and information processing (Garrido-Hidalgo et al., 2019; Kamble et al., 2020b).

Garrido-Hidalgo et al. (2019) follow on this and argue that the integration of Industry 4.0 supports the closed-loop supply chain and the reverse logistics. The use of Information and Communication Technologies (ICT) mitigates energy and resource consumption, facilitates remanufacturing, and allows product recovery (Dev et al., 2020).

As part of the Industry 4.0 paradigm, the data collected throughout the return processes can benefit product handling and warehouse management (Kamble et al., 2020a). The paradigm supports the management of return for maintenance repair & operations (MRO) and recovered products (Korchagin et al., 2022).

Zhong et al. (2015) construct a RFID-based framework to reflect the importance of real-time data in the manufacturing shop floor and warehouse logistics. Managing reverse logistics has an important role in ensuring the sustainability of operations. It leverages market values while reducing environmental issues. Efficiently tracking high return areas with Industry 4.0 technologies quickly mitigates returns, thereby reducing their impact on the environment (Dwivedi et al., 2023).

4.6. *Enable process*

Enable processes drive supply chains toward reliability and efficiency. It includes supply chain management operations related to business rules, facility performance, data management, supplier relationships and risk management to drive continuous improvement (SCC, 2017).

Industry 4.0 technologies support this process by providing the data and tools required to synchronize all processes and support their execution and governance (Manupati et al., 2020). The literature still lacks research on the impact of Industry 4.0 technologies on this specific process. Nevertheless, supply chain 4.0 has balancers that align and bring transparency and visibility to transactions among different operations such as finance, product and portfolio management, product design, customer satisfaction, etc. (Awan et al., 2021; Ferrantino and Koten, 2019; Mak and Max Shen, 2021), which allows for alignment and makes their management more effective, hence more likely to achieve sustainability goals (Fernández-Portillo et al., 2019; Kiron and Unruh, 2018).

5. Sustainable supply chain 4.0 capabilities in the achievement of sustainability goals: conceptual framework

The previous sections provide a comprehensive overview of the transformation to a supply chain 4.0, this section answers the objective of the study and constructs a framework that designs the achievement of sustainability goals through the construct of supply chain 4.0 powered by the integration of Industry 4.0 technologies into SCOR model processes.

This study responds to the demand in the literature. Ghadimi et al. (2019) state that the literature needs actions to support organizations to embrace sustainable supply chain management based on industry 4.0 technologies. In addition, in today's industry, innovations in strategies and technologies are rapidly evolving (Caiado et al., 2022), compelling companies to test new frameworks to develop new solutions for the sustainability challenge, especially to achieve the 17 Sustainable Development Goals. Therefore, the study provides a new framework (Fig. 2 near the end of the paragraph) that recommends integrating sustainability into the core of business operations, redesigning processes, and ensuring alignment and collaboration with stakeholders to make faster progress toward the SDGs. It addresses three main axes that support the achievement of the goals, (1) the integration of Industry 4.0 technologies, (2) the impact of this integration on the SCOR model process in terms of sustainability benefits, (3) the scope of the UN Agenda 2030.

The United Nations 2030 Agenda (UN, 2015) provides a framework designed for communities to manage and lead sustainability practices. It is based on 17 Sustainable Development Goals (SDGs), with subgoals in which the social, economic, and ecological pillars are considered as complementary and interdependent parts. Despite this, some thinking continues to segregate the goals under the three pillars (Dantas et al., 2021).

The literature has seen an increase in commitment to studying the achievement of these goals after many institutions declared a state of emergency (UN, 2015). However, it still lacks practical implications and innovative frameworks that incorporate emerging technologies to leverage new opportunities (França et al., 2020).

To achieve the SDGs, companies must change the way they do business. Innovative technologies are the emerging solution with promising attributes to achieve production and consumption savings (Garcia-Muiña et al., 2019; Pham et al., 2019). However, their integration must be accompanied by organizational and systematic changes to reach all processes in the supply chain (Xu et al., 2023).

As mentioned earlier, Industry 4.0 technologies hold the power to capture and record data throughout the supply chain processes. The huge data generated can help measure the impact of business operations on a particular SDG (Modgil et al., 2020).

It provides visibility to regulate working hours, ensure good working conditions, and communicate the implementation of sustainability initiatives (Govindan et al., 2016). This may contribute to SDG (6) water conservation, (12) energy consumption, and (8) decent work and economic development.

The visibility enabled strengthens performance measurement and provides an incentive for companies to further reduce costs (Unerman et al., 2018), to focus investments on achieving more sustainability goals. Becker et al. (2020) state that Industry 4.0 technologies provide high visibility of data and transactions that support process management and sustain a driving force for accurate measurement, reporting, and quantification of GHG inventory. The latter goes further and includes SCOPE 3 emissions (Johnsson et al., 2020), life cycle assessment, and quality assessment (Chen et al., 2021), resulting in the achievement of various SDGs such as (3) Good health and well-being, (12) Responsible consumption and production, (13) Climate action, (14) Life under water, and (15) Life on land. Fu et al. (2018) uncover how the bundle of IoT mitigates carbon emissions in the clothing production lifecycle, which results in sustainability goals.

In the context of Industry 4.0, the implementation of sustainable supply chain practices can improve organizational performance by minimizing waste, enhancing operational efficiency, and boosting profitability of businesses (Khan et al., 2023).

The Commission on Business and Sustainable Development suggests rethinking business strategy entirely in the direction of the SDGs. This perspective must be supported by collaboration with peers to make

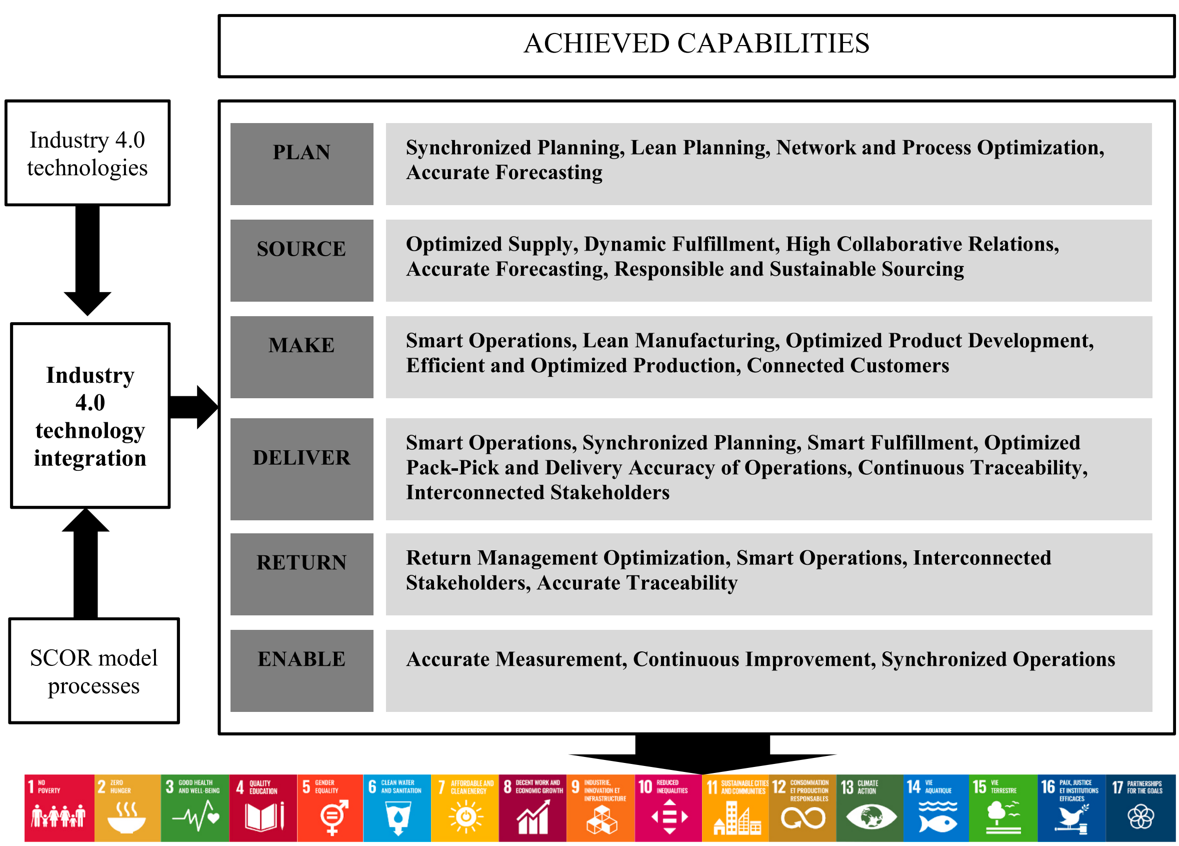

Fig. 2. Framework of Industry 4.0 integration to drive SCOR processes towards the 17 SDGs.

faster progress towards achieving the SDGs (WBCSD, 2020). In line with this, Industry 4.0 technologies drive traceability, decentralization, interconnection of processes and increased trust between stakeholders which drive supply chains towards innovation to build resilience and promote an inclusive and sustainable infrastructure (SDG9) (Cruz Sanchez et al., 2020; Hidayatno et al., 2019).

Certain industries are covered repeatedly in the literature to study the effect of Industry 4.0 on achieving the SDGs (De Villiers et al., 2021; Johnsson et al., 2020; Tsolakis et al., 2021). In the construction industry, Karlsson et al. (2020) show that the application of technologies enables sustainable practices that reduce emissions from road construction, including SCOPE (1-2-3) emissions. They include the application of biomass energy for transportation; the electrification of transports and industrial processes; and the deployment of Carbon Capture and Storage technology (CCS). These capabilities embody innovation in the industry (SDG 9), besides hybridization and electrification of operations positively impact air pollution, thereby fostering sustainable cities and communities (SDG 11) (Johnsson et al., 2020). In the agricultural and food industry, the literature refers mainly to traceability (Behnke and Janssen, 2020; Chen et al., 2021). For instance, in the fishing sector, Blockchain technology and IoT report unregulated fishing activities which preserves the marine ecosystem (SDG 14) (Whiting, 2020), track illegal and labour rights abuses (SDG 8) (Lindley and Techera, 2017), and provide safe products to customers (SDG 12–3) (Nong, 2019).

Traceability in supply chains ensures ethical consumption, and control of production in terms of the use of synthetic fertilizers, which contributes to SDG (15) (De Villiers et al., 2021). Therefore, traceability becomes an important attribute for companies that engage with the SDGs. In the luxury industry, Blockchain technology is being explored as the main driver of raw material and finished product traceability (Choi, 2019). In addition, it offers the ability to create digital certificates that serve as anti-counterfeiting evidence (VeChain, 2019). These capabilities can be considered in response to SDG (12) (De Villiers et al., 2021).

Significant investments are being made in developing countries to achieve the desired SDGs. Automated payment systems with crypto currencies are useful in this sense and help eliminate the need for intermediaries, increasing the security and speed of financial transactions (Kamble et al., 2020b). This capability can also encourage the development of relationships with local suppliers, without the need for NGOs (Saurabh and Dey, 2021). Therefore, technology innovations can address social, economic, and environmental issues upstream and downstream (Paliwal et al., 2020).

6. Conclusion

With 2030 fast approaching, it is important for the business community to understand the potential of Industry 4.0 technologies to drive innovation towards the 17 Sustainable Development Goals (SDGs). For research, the UN's emergency call means stimulating extensive, engaged, and transdisciplinary studies to suggest practical frameworks for meeting the agenda's goals. However, the challenge revolves around the ability of companies to adopt these technologies in terms of investment and ability to change their organizational structures and processes.

The studies focus on Industry 4.0 technologies and consider their capabilities as drivers of sustainability goals. Moreover, it reflects on the important foundations for developing sustainability capabilities that strengthen the functioning of supply chain processes. Subsequently, it set out to link supply chain 4.0 capabilities to the SCOR model processes to achieve sustainability goals.

The study builds on literature to develop a conceptual framework (Fig. 2 in part 5), we draw from themes in the literature to extract the sustainability capabilities and link them with SCOR model processes. The knowledge from previous studies show that emerging technologies offer a high level of data interoperability even at the trivial process level, which can help reduce deficiencies resulting from mixed data sources and supply chain capabilities, and restructure operations in processes.

The proposed paradigm can be tested in different units and contexts as it covers all processes and a different set of technologies. Its objective is to uncover challenges, opportunities, and threats to align business, society, and environment thanks to the adoption of Industry 4.0 technologies. The results can uncover the contribution of Industry 4.0 technologies to achieving the 17 SDGs.

6.1. Implication for research

Recent research has emphasized the importance of integrating Industry 4.0 technology into supply chains to achieve the 17 SDGs (Bonilla et al., 2018; Caiado et al., 2022). These are two areas of great concern to business, government, and the natural environment. The literature has suggested that Industry 4.0 is likely willing to drive sustainable development goals but still raise questions of its drivers and application.

First, responding to the call for more developed research in this context (Agrawal et al., 2022a), we present a conceptual framework. This framework aims to contribute to the literature by providing a detailed and practical picture of Industry 4.0 technology capabilities, their impact on SCOR model processes, and the achievement of sustainability goals. This conceptual framework advances the research and proposes that the positive impact of Industry 4.0 technologies on sustainability goals is induced by proper technology integration at the inter- and intra-organizational level, and by a concrete shift in supply chain processes towards technology-induced sustainability capabilities. Second, to our knowledge, no study had empirically validated the impact of integrating Industry 4.0 technologies on supply chain processes on achieving the goals of the UN agenda. Third, the developed framework is intended to be refined and empirically tested, creating new research opportunities.

6.2. Implications for managerial practices

The study provides a framework for decision makers to view the importance of Industry 4.0 technology integration on Sustainable Development Goals (SDGs).

This framework can be valuable for sustainability-focused business leaders who aim to uncover the potential of Industry 4.0 technologies. It could help them in their strategies, to integrate the right technology for each process in the supply chain to unlock sustainability initiatives that could lead them to achieve their sustainability goals. The major challenge for companies lies in the first part of the framework, which concerns technology integration. How companies engage with technology and the strategic decision to choose the right technology for each process are critical to uncovering sustainability capabilities and linking them to sustainability goals. The study offers a clear picture to view the iteration.

The application of the framework in different companies and industries can advance the general knowledge on the importance of Industry 4.0 technologies in addressing the sustainability challenge. In addition, the proposed framework serves as a support for policy makers responsible for developing policies and guidelines. It can provide them with a perspective on the importance of directing investments towards smarter development and sustainability-driven business processes.

6.3. Limitations

Our study should be considered in view of some limitations that can be further elaborated.

On one hand, the literature offers studies on the Sustainable Development Goals (SDGs) focused on specific industries or products. This makes it difficult to select articles that establish the link to supply chain processes in a very general approach.

Despite this, the proposed framework intended to be as general as possible to be implemented in any industrial sector. In this line, indeed, the paper proposes a conceptual framework that connects two different axes regarding Industry 4.0 capabilities on supply chain processes and their link to the Sustainable Development Goals (SDGs).

Since this framework is based on the analysis of literature, real-life applications can be useful to test it on particular industries or supply chains through empirical approaches. Finally, as studies in this context are rapidly evolving, new publications, applications, and evaluation of the state of the SDG need to be constantly analyzed for possible inclusion and adaptation of the proposed framework.

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.

Data availability

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

Acknowledgements

The work of the third author was carried out under research grant INGPHD-30-2020 from Universidad de La Sabana, Colombia.

References

Agrawal, R., Majumdar, A., Majumdar, K., Raut, R.D., Narkhede, B.E., 2022a. Attaining sustainable development goals (SDGs) through supply chain practices and business strategies: a systematic review with bibliometric and network analyses. Bus. Strat. Environ. https://doi.org/10.1002/bse.3057.
Agrawal, R., Wankhede, V.A., Kumar, A., Luthra, S., Huisingh, D., 2022b. Progress and trends in integrating Industry 4.0 within Circular Economy: a comprehensive literature review and future research propositions. Bus. Strat. Environ. 31 (1), 559–579. https://doi.org/10.1002/bse.2910.
Awan, U., Sroufe, R., Shahbaz, M., 2021. Industry 4.0 and the circular economy: a literature review and recommendations for future research. Bus. Strat. Environ. 30 (4), 2038–2060. https://doi.org/10.1002/bse.2731.
Azevedo, S.G., Pimentel, C.M.O., Alves, A.C., Matias, J.C.O., 2021. Support of advanced technologies in supply chain processes and sustainability impact. Appl. Sci. 11 (7) https://doi.org/10.3390/app11073026.
Bag, S., Wood, L.C., Telukdarie, A., Venkatesh, V.G., 2021. Application of Industry 4.0 tools to empower circular economy and achieving sustainability in supply chain operations. Prod. Plann. Control. https://doi.org/10.1080/09537287.2021.1980902.
Bechtsis, D., Tsolakis, N., Vlachos, D., Srai, J.S., 2018. Intelligent Autonomous Vehicles in digital supply chains: a framework for integrating innovations towards sustainable value networks. J. Clean. Prod. 181, 60–71. https://doi.org/10.1016/j.jclepro.2018.01.173.
Becker, S., Bouzdine-Chameeva, T., Jaegler, A., 2020. The carbon neutrality principle: a case study in the French spirits sector. J. Clean. Prod. 274, 122739 https://doi.org/10.1016/j.jclepro.2020.122739.
Behnke, K., Janssen, M.F.W.H.A., 2020. Boundary conditions for traceability in food supply chains using blockchain technology. Int. J. Inf. Manag. 52 https://doi.org/10.1016/j.ijinfomgt.2019.05.025.
Benzidia, S., Makaoui, N., Subramanian, N., 2021. Impact of ambidexterity of blockchain technology and social factors on new product development: a supply chain and Industry 4.0 perspective. Technol. Forecast. Soc. Change 169. https://doi.org/10.1016/j.techfore.2021.120819.
Birkel, H., Müller, J.M., 2021. Potentials of industry 4.0 for supply chain management within the triple bottom line of sustainability – a systematic literature review. In: Journal of Cleaner Production, vol. 289. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.125612.
Bonilla, S.H., Silva, H.R.O., da Silva, M.T., Gonçalves, R.F., Sacomano, J.B., 2018. Industry 4.0 and sustainability implications: a scenario-based analysis of the impacts and challenges. Sustainability 10 (10). https://doi.org/10.3390/su10103740.
Caiado, R.G.G., Scavarda, L.F., Azevedo, B.D., Nascimento, D.L.M., Quelhas, O.L.G., 2022. Challenges and benefits of sustainable industry 4.0 for operations and supply chain management—a framework headed toward the 2030 agenda. Sustainability 14 (2). https://doi.org/10.3390/su14020830.
Cañas, H., Mula, J., Campuzano-Bolarín, F., 2020. A general outline of a sustainable supply chain 4.0. Sustainability 12 (19), 1–17. https://doi.org/10.3390/su12197978. MDPI.
Chan, H.K., Griffin, J., Lim, J.J., Zeng, F., Chiu, A.S.F., 2018. The impact of 3D Printing Technology on the supply chain: manufacturing and legal perspectives. Int. J. Prod. Econ. 205, 156–162. https://doi.org/10.1016/j.ijpe.2018.09.009.
Chand, P., Thakkar, J.J., Ghosh, K.K., 2020. Analysis of supply chain sustainability with supply chain complexity, inter-relationship study using delphi and interpretive structural modeling for Indian mining and earthmoving machinery industry. Resour. Pol. 68, 101726 https://doi.org/10.1016/j.resourpol.2020.101726.
Chandan, A., John, M., Potdar, V., 2023. Achieving UN SDGs in food supply chain using blockchain technology. Sustainability 15 (3), 2109. https://doi.org/10.3390/su15032109.
Chauhan, S., Singh, R., Gehlot, A., Akram, S.V., Twala, B., Priyadarshi, N., 2023. Digitalization of supply chain management with industry 4.0 enabling technologies: a sustainable perspective. Processes 11 (1). https://doi.org/10.3390/pr11010096.
Chehbi-Gamoura, S., Derrouiche, R., Damand, D., Barth, M., 2020. Insights from big Data Analytics in supply chain management: an all-inclusive literature review using the SCOR model. Prod. Plann. Control 31 (5), 355–382. https://doi.org/10.1080/09537287.2019.1639839.
Chen, S., Liu, X., Yan, J., Hu, G., Shi, Y., 2021. Processes, benefits, and challenges for adoption of blockchain technologies in food supply chains: a thematic analysis. Inf. Syst. E Bus. Manag. 19 (3), 909–935. https://doi.org/10.1007/s10257-020-00467-3.
Choi, T.-M., 2019. Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains. Transport. Res. E Logist. Transport. Rev. 128, 17–29. https://doi.org/10.1016/j.tre.2019.05.011.
Cortes-Murcia, D.L., Guerrero, W.J., Montoya-Torres, J.R., 2022. Supply chain management, game-changing technologies, and physical internet: a systematic meta-review of literature. In: IEEE Access, vol. 10. Institute of Electrical and Electronics Engineers Inc, pp. 61721–61743. https://doi.org/10.1109/ACCESS.2022.3181154.
Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., Pearce, J.M., 2020. Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy. J. Clean. Prod. 264, 121602 https://doi.org/10.1016/j.jclepro.2020.121602.
Dantas, T.E.T., de-Souza, E.D., Destro, I.R., Hammes, G., Rodriguez, C.M.T., Soares, S.R., 2021. How the combination of circular economy and industry 4.0 can contribute towards achieving the sustainable development goals. Sustain. Prod. Consum. 26, 213–227. https://doi.org/10.1016/j.spc.2020.10.005. Elsevier B.V.
De Villiers, C., Kuruppu, S., Dissanayake, D., 2021. A (new) role for business – promoting the United Nations' Sustainable Development Goals through the internet-of-things and blockchain technology. J. Bus. Res. 131, 598–609. https://doi.org/10.1016/j.jbusres.2020.11.066.
Del Río Castro, G., González Fernández, M.C., Uruburu Colsa, Á., 2021. Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): a holistic review. In: Journal of Cleaner Production, vol. 280. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.122204.
Dev, N.K., Shankar, R., Qaiser, F.H., 2020. Industry 4.0 and circular economy: operational excellence for sustainable reverse supply chain performance. Resour. Conserv. Recycl. 153 https://doi.org/10.1016/j.resconrec.2019.104583.
Di Vaio, A., Varriale, L., 2020. Blockchain technology in supply chain management for sustainable performance: evidence from the airport industry. Int. J. Inf. Manag. 52 https://doi.org/10.1016/j.ijinfomgt.2019.09.010.
Dissanayake, C.K., Cross, J.A., 2018. Systematic mechanism for identifying the relative impact of supply chain performance areas on the overall supply chain performance using SCOR model and SEM. Int. J. Prod. Econ. 201, 102–115. https://doi.org/10.1016/j.ijpe.2018.04.027.
Dornelles, J.A., Ayala, N.F., Frank, A.G., 2022. Smart Working in Industry 4.0: how digital technologies enhance manufacturing workers' activities. Comput. Ind. Eng. 163 https://doi.org/10.1016/j.cie.2021.107804.
Dwivedi, A., Agrawal, D., Jha, A., Mathiyazhagan, K., 2023. Studying the interactions among Industry 5.0 and circular supply chain: towards attaining sustainable development. Comput. Ind. Eng. 176 https://doi.org/10.1016/j.cie.2022.108927.
Fatimah, Y.A., Govindan, K., Murniningsih, R., Setiawan, A., 2020. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: a case study of Indonesia. J. Clean. Prod. 269 https://doi.org/10.1016/j.jclepro.2020.122263.
Fatorachian, H., Kazemi, H., 2021. Impact of Industry 4.0 on supply chain performance. Prod. Plann. Control 32 (1), 63–81. https://doi.org/10.1080/09537287.2020.1712487.
Fernández-Portillo, A., Almodóvar-González, M., Coca-Pérez, J.L., Jiménez-Naranjo, H. V., 2019. Is sustainable economic development possible thanks to the deployment of ICT? Sustainability 11 (22). https://doi.org/10.3390/su11226307.
Ferrantino, M.J., Koten, E.E, 2019. Understanding Supply Chain 4.0 and its Potential Impact on Global Value Chains, Global value chain development report, p. 103.
Figliozzi, M.A., 2020. Carbon Emissions Reductions in Last Mile and Grocery Deliveries Utilizing Autonomous Vehicles, vol. 2. Transportation Research Part D. https://pdxscholar.library.pdx.edu/cengin_fac.
França, A.S.L., Amato Neto, J., Gonçalves, R.F., Almeida, C.M.V.B., 2020. Proposing the use of blockchain to improve the solid waste management in small municipalities. In: Journal of Cleaner Production, vol. 244. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.118529.
Fu, B., Shu, Z., Liu, X., 2018. Blockchain enhanced emission trading framework in fashion apparel manufacturing industry. Sustainability 10 (4). https://doi.org/10.3390/su10041105.
Garcia-Muiña, F.E., González-Sánchez, R., Ferrari, A.M., Volpi, L., Pini, M., Siligardi, C., Settembre-Blundo, D., 2019. Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design. Soc. Sci. 8 (8) https://doi.org/10.3390/socsci8080241.
Garrido-Hidalgo, C., Olivares, T., Ramirez, F.J., Roda-Sanchez, L., 2019. An end-to-end internet of things solution for reverse supply chain management in industry 4.0. Comput. Ind. 112 https://doi.org/10.1016/j.compind.2019.103127.
Ghadimi, P., Wang, C., Lim, M.K., Heavey, C., 2019. Intelligent sustainable supplier selection using multi-agent technology: theory and application for Industry 4.0

supply chains. Comput. Ind. Eng. 127, 588–600. https://doi.org/10.1016/j.cie.2018.10.050.

Govindan, K., Cheng, T.C.E., Mishra, N., Shukla, N., 2018. Big data analytics and application for logistics and supply chain management. Transport. Res. E Logist. Transport. Rev. 114, 343–349. https://doi.org/10.1016/j.tre.2018.03.011. Elsevier Ltd.

Govindan, K., Jha, P.C., Garg, K., 2016. Product recovery optimization in closed-loop supply chain to improve sustainability in manufacturing. Int. J. Prod. Res. 54 (5), 1463–1486. https://doi.org/10.1080/00207543.2015.1083625.

Hidayatno, A., Destyanto, A.R., Hulu, C.A., 2019. Industry 4.0 technology implementation impact to industrial sustainable energy in Indonesia: a model conceptualization. Energy Proc. 156, 227–233. https://doi.org/10.1016/j.egypro.2018.11.133.

Holland, M., Nigischer, C., Stjepandic, J., 2017. Copyright protection in additive manufacturing with blockchain approach. Advances in Transdisciplinary Engineering 5, 914–921. https://doi.org/10.3233/978-1-61499-779-5-914.

Javaid, M., Haleem, A., Singh, R.P., Suman, R., Gonzalez, E.S., 2022. Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. Sustainable Operations and Computers 3, 203–217. https://doi.org/10.1016/j.susoc.2022.01.008.

Johnsson, F., Karlsson, I., Rootzén, J., Ahlbäck, A., Gustavsson, M., 2020. The framing of a sustainable development goals assessment in decarbonizing the construction industry – avoiding "Greenwashing.". Renew. Sustain. Energy Rev. 131 https://doi.org/10.1016/j.rser.2020.110029.

Kamble, S.S., Gunasekaran, A., Gawankar, S.A., 2020a. Achieving sustainable performance in a data-driven agriculture supply chain: a review for research and applications. Int. J. Prod. Econ. 219, 179–194. https://doi.org/10.1016/j.ijpe.2019.05.022. Elsevier B.V.

Kamble, S.S., Gunasekaran, A., Sharma, R., 2020b. Modeling the blockchain enabled traceability in agriculture supply chain. Int. J. Inf. Manag. 52 https://doi.org/10.1016/j.ijinfomgt.2019.05.023.

Karlsson, I., Rootzén, J., Johnsson, F., 2020. Reaching net-zero carbon emissions in construction supply chains – analysis of a Swedish road construction project. Renew. Sustain. Energy Rev. 120 https://doi.org/10.1016/j.rser.2019.109651.

Karmaker, C.L., Bari, A.B.M.M., Anam, M.Z., Ahmed, T., Ali, S.M., de Jesus Pacheco, D. A., Moktadir, M.A., 2023. Industry 5.0 challenges for post-pandemic supply chain sustainability in an emerging economy. Int. J. Prod. Econ. 258 https://doi.org/10.1016/j.ijpe.2023.108806.

Kazancoglu, I., Ozbiltekin-Pala, M., Mangla, S.K., Kumar, A., Kazancoglu, Y., 2022. Using emerging technologies to improve the sustainability and resilience of supply chains in a fuzzy environment in the context of COVID-19. Ann. Oper. Res. https://doi.org/10.1007/s10479-022-04775-4.

Khan, S.A.R., Tabish, M., Zhang, Y., 2023. Embracement of industry 4.0 and sustainable supply chain practices under the shadow of practice-based view theory: ensuring environmental sustainability in corporate sector. J. Clean. Prod., 136609 https://doi.org/10.1016/j.jclepro.2023.136609.

Khanfar, A.A.A., Iranmanesh, M., Ghobakhloo, M., Senali, M.G., Fathi, M., 2021. Applications of blockchain technology in sustainable manufacturing and supply chain management: a systematic review. Sustainability 13 (14). https://doi.org/10.3390/su13147870. MDPI AG.

Kiel, D., M, J., A, C., V, K.-I., 2017. Sustainable industrial value creation: benefits and challenges of industry 4.0. Int. J. Innovat. Manag. 21.

Kiron, D., Unruh, G., 2018. Sloan Review MIT. The Convergence of Digitalization and Sustainability.

Kopyto, M., Lechler, S., von der Gracht, H.A., Hartmann, E., 2020. Potentials of blockchain technology in supply chain management: long-term judgments of an international expert panel. Technol. Forecast. Soc. Change 161. https://doi.org/10.1016/j.techfore.2020.120330.

Korchagin, A., Deniskin, Y., Pocebneva, I., Vasilyeva, O., 2022. Lean Maintenance 4.0: implementation for aviation industry. Transport. Res. Procedia 63, 1521–1533. https://doi.org/10.1016/j.trpro.2022.06.164.

Kouhizadeh, M., Zhu, Q., Sarkis, J., 2020. Blockchain and the circular economy: potential tensions and critical reflections from practice. Prod. Plann. Control 31 (11–12), 950–966. https://doi.org/10.1080/09537287.2019.1695925.

Kumar, S., Raut, R.D., Nayal, K., Kraus, S., Yadav, V.S., Narkhede, B.E., 2021. To identify industry 4.0 and circular economy adoption barriers in the agriculture supply chain by using ISM-ANP. J. Clean. Prod. 293, 126023.

Lin, Y.C., Yeh, C.C., Chen, W.H., Liu, W.C., Wang, J.J., 2020. The use of big data for sustainable development in motor production line issues. Sustainability 12 (13). https://doi.org/10.3390/su12135323.

Lindley, J., Techera, E.J., 2017. Overcoming complexity in illegal, unregulated and unreported fishing to achieve effective regulatory pluralism. Mar. Pol. 81, 71–79. https://doi.org/10.1016/j.marpol.2017.03.010.

Liu, L., Song, W., Liu, Y., 2023. Leveraging digital capabilities toward a circular economy: reinforcing sustainable supply chain management with Industry 4.0 technologies. Comput. Ind. Eng. 178, 109113 https://doi.org/10.1016/j.cie.2023.109113.

Lu, H., Zhao, G., Liu, S., 2022. Integrating circular economy and Industry 4.0 for sustainable supply chain management: a dynamic capability view. Prod. Plann. Control. https://doi.org/10.1080/09537287.2022.2063198.

Madsen, D.Ø., 2019. The emergence and rise of industry 4.0 viewed through the lens of management fashion theory. Adm. Sci. 9 (3) https://doi.org/10.3390/admsci9030071.

Mak, H.Y., Max Shen, Z.J., 2021. When triple-A supply chains meet digitalization: the case of JD.com's C2M model. Prod. Oper. Manag. 30 (3), 656–665. https://doi.org/10.1111/poms.13307.

Manupati, V.K., Schoenherr, T., Ramkumar, M., Wagner, S.M., Pabba, S.K., Inder Raj Singh, R., 2020. A blockchain-based approach for a multi-echelon sustainable supply chain. Int. J. Prod. Res. 58 (7), 2222–2241. https://doi.org/10.1080/00207543.2019.1683248.

Modgil, S., Gupta, S., Bhushan, B., 2020. Building a living economy through modern information decision support systems and UN sustainable development goals. Prod. Plann. Control 31 (11–12), 967–987. https://doi.org/10.1080/09537287.2019.1695916.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., Barbaray, R., 2018. The industrial management of SMEs in the era of Industry 4.0. Int. J. Prod. Res. 56 (3), 1118–1136. https://doi.org/10.1080/00207543.2017.1372647.

Moreno-Camacho, C.A., Montoya-Torres, J.R., Jaegler, A., 2022. Sustainable supply chain network design: a study of the Colombian dairy sector. Ann. Oper. Res. https://doi.org/10.1007/s10479-021-04463-9.

Müller, J.M., Kiel, D., Voigt, K.I., 2018. What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. Sustainability 10 (1). https://doi.org/10.3390/su10010247.

Nabila, A.W., Er, M., Chen, J.C., Chen, T.L., 2022. The impact analysis of information technology alignment for information sharing and supply chain integration on customer responsiveness. Procedia Comput. Sci. 197, 718–726. https://doi.org/10.1016/j.procs.2021.12.193.

Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Rocha-Lona, L., Tortorella, G., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: a business model proposal. J. Manuf. Technol. Manag. 30 (3), 607–627.

Nguyen, T., Zhou, L., Spiegler, V., Ieromonachou, P., Lin, Y., 2018. Big data analytics in supply chain management: a state-of-the-art literature review. Comput. Oper. Res. 98, 254–264. https://doi.org/10.1016/j.cor.2017.07.004.

Nong, D., 2019. Potential economic impacts of global wild catch fishery decline in Southeast Asia and South America. Econ. Anal. Pol. 62, 213–226. https://doi.org/10.1016/j.eap.2019.04.004.

Paliwal, V., Chandra, S., Sharma, S., 2020. Blockchain technology for sustainable supply chain management: a systematic literature review and a classification framework. Sustainability 12 (18). https://doi.org/10.3390/su12187638. MDPI.

Pham, T.T., Kuo, T.C., Tseng, M.L., Tan, R.R., Tan, K., Ika, D.S., Lin, C.J., 2019. Industry 4.0 to accelerate the circular economy: a case study of electric scooter sharing. Sustainability 11 (23). https://doi.org/10.3390/su11236661.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., Kropp, J.P., 2017. A systematic study of sustainable development goal (SDG) interactions. Earth's Future 5 (11), 1169–1179. https://doi.org/10.1002/2017EF000632.

Qiu, X., Luo, H., Xu, G., Zhong, R., Huang, G.Q., 2015. Physical assets and service sharing for IoT-enabled supply hub in industrial park (SHIP). Int. J. Prod. Econ. 159, 4–15. https://doi.org/10.1016/j.ijpe.2014.09.001.

Ramanathan, R., Philpott, E., Duan, Y., Cao, G., 2017. Adoption of business analytics and impact on performance: a qualitative study in retail. Prod. Plann. Control 28 (11–12), 985–998. https://doi.org/10.1080/09537287.2017.1336800.

Saurabh, S., Dey, K., 2021. Blockchain technology adoption, architecture, and sustainable agri-food supply chains. J. Clean. Prod. 284 https://doi.org/10.1016/j.jclepro.2020.124731.

SCC, 2017. APICS Supply Chain Operations Reference Model SCOR Version 12.0.

Schilling, L., Seuring, S., 2023. Linking the digital and sustainable transformation with supply chain practices. In: International Journal of Production Research. Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2023.2173502.

Shafique, M.N., Khurshid, M.M., Rahman, H., Khanna, A., Gupta, D., 2019. The role of big data predictive analytics and radio frequency identification in the pharmaceutical industry. IEEE Access 7, 9013–9021. https://doi.org/10.1109/ACCESS.2018.2890551.

Shahpasand, R., Talebian, A., Mishra, S., Sabya), 2023. Investigating environmental and economic impacts of the 3D printing technology on supply chains: the case of tire production. J. Clean. Prod. 390, 135917 https://doi.org/10.1016/j.jclepro.2023.135917.

Shao, X.F., Liu, W., Li, Y., Chaudhry, H.R., Yue, X.G., 2021. Multistage implementation framework for smart supply chain management under industry 4.0. Technol. Forecast. Soc. Change 162. https://doi.org/10.1016/j.techfore.2020.120354.

Sharma, M., Joshi, S., 2020. Digital supplier selection reinforcing supply chain quality management systems to enhance firm's performance. TQM Journal. https://doi.org/10.1108/TQM-07-2020-0160.

Sharma, M., Luthra, S., Joshi, S., Kumar, A., Jain, A., 2023. Green logistics driven circular practices adoption in industry 4.0 Era: a moderating effect of institution pressure and supply chain flexibility. J. Clean. Prod. 383 https://doi.org/10.1016/j.jclepro.2022.135284.

Silvestre, B.S., Ţîrcă, D.M., 2019. Innovations for sustainable development: moving toward a sustainable future. J. Clean. Prod. 208, 325–332. https://doi.org/10.1016/j.jclepro.2018.09.244. Elsevier Ltd.

Sislian, L., Jaegler, A., 2022. Linkage of blockchain to enterprise resource planning systems for improving sustainable performance. Bus. Strat. Environ. 31 (3), 737–750.

Slowik, P., Sharpe, B., 2018. Automation in the Long Haul: Challenges and Opportunities of Autonomous Heavy-Duty Trucking in the United States.

Srhir, S., Jaegler, A., Montoya-Torres, J.R., 2023. Uncovering industry 4.0 technology attributes in sustainable supply chain 4.0: a systematic literature review. Bus. Strat. Environ. https://doi.org/10.1002/bse.3358.

Strandhagen, J.W., Buer, S.V., Semini, M., Alfnes, E., Strandhagen, J.O., 2022. Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain. Prod. Plann. Control 33 (9–10), 995–1010. https://doi.org/10.1080/09537287.2020.1837940.

Thakur, V., Mangla, S.K., 2019. Change management for sustainability: evaluating the role of human, operational and technological factors in leading Indian firms in home appliances sector. J. Clean. Prod. 213, 847–862. https://doi.org/10.1016/j.jclepro.2018.12.201.

Tortorella, G.L., Giglio, R., van Dun, D.H., 2019. Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement. Int. J. Oper. Prod. Manag. 39 (6/7/8), 860–886. https://doi.org/10.1108/IJOPM-01-2019-0005.

Toth-Peter, A., Torres de Oliveira, R., Mathews, S., Barner, L., Figueira, S., 2023. Industry 4.0 as an enabler in transitioning to circular business models: a systematic literature review. J. Clean. Prod. 393 https://doi.org/10.1016/j.jclepro.2023.136284.

Tsolakis, N., Goldsmith, A.T., Aivazidou, E., Kumar, M., 2023. Microalgae-based circular supply chain configurations using Industry 4.0 technologies for pharmaceuticals. J. Clean. Prod. 395 https://doi.org/10.1016/j.jclepro.2023.136397.

Tsolakis, N., Niedenzu, D., Simonetto, M., Dora, M., Kumar, M., 2021. Supply network design to address United Nations Sustainable Development Goals: a case study of blockchain implementation in Thai fish industry. J. Bus. Res. 131, 495–519. https://doi.org/10.1016/j.jbusres.2020.08.003.

UN, 2015. The 17 Goals- Sustainable Development.

Unerman, J., Bebbington, J., O'dwyer, B., 2018. Corporate reporting and accounting for externalities. Account. Bus. Res. 48 (5), 497–522. https://doi.org/10.1080/00014788.2018.1470155.

VeChain, 2019. VeChain Whitepaper 2.0: Creating Valuable TXs.

Wang, M., Wood, L.C., Wang, B., 2022. Transportation capacity shortage influence on logistics performance: evidence from the driver shortage. Heliyon 8 (5), e09423. https://doi.org/10.1016/j.heliyon.2022.e09423.

WBCSD, 2020. Business Principles for People-Centered Technology Transformation: Now Available in Japanese. June 19 *(Portuguese and Spanish*.

Weking, J., Stöcker, M., Kowalkiewicz, M., Böhm, M., Krcmar, H., 2020. Leveraging industry 4.0 – a business model pattern framework. Int. J. Prod. Econ. 225 https://doi.org/10.1016/j.ijpe.2019.107588.

Whiting, K., 2020. Blockchain Could Police the Fishing Industry - Here's How. February 12.

Xu, J., Yu, Y., Zhang, M., Zhang, J.Z., 2023. Impacts of digital transformation on eco-innovation and sustainable performance: evidence from Chinese manufacturing companies. J. Clean. Prod. 393 https://doi.org/10.1016/j.jclepro.2023.136278.

Yang, M., Fu, M., Zhang, Z., 2021. The adoption of digital technologies in supply chains: drivers, process and impact. Technol. Forecast. Soc. Change 169. https://doi.org/10.1016/j.techfore.2021.120795.

Yavuz, O., Uner, M.M., Okumus, F., Karatepe, O.M., 2023. Industry 4.0 technologies, sustainable operations practices and their impacts on sustainable performance. J. Clean. Prod. 387 https://doi.org/10.1016/j.jclepro.2023.135951.

Zangiacomi, A., Pessot, E., Fornasiero, R., Bertetti, M., Sacco, M., 2020. Moving towards digitalization: a multiple case study in manufacturing. Prod. Plann. Control 31 (2–3), 143–157. https://doi.org/10.1080/09537287.2019.1631468.

Zhong, R.Y., Huang, G.Q., Lan, S., Dai, Q.Y., Chen, X., Zhang, T., 2015. A big data approach for logistics trajectory discovery from RFID-enabled production data. Int. J. Prod. Econ. 165, 260–272. https://doi.org/10.1016/j.ijpe.2015.02.014.

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