The role of technology in supply chain decarbonisation: towards an integrated conceptual framework

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Abstract

Purpose – This study aims to systematically review the current academic literature on the role of technologies in low-carbon supply chain management (SCM), identify and analyse critical themes and propose an integrated conceptual model.

Design/methodology/approach – A systematic literature review of 48 papers published between 2010 and 2022 was conducted. A conceptual model was advanced.

Findings – Based on the analysis and synthesis of the reviewed papers, this review provides an initial attempt to integrate technology adoption and low-carbon SCM by developing a diffusion of innovation model of technology-enabled low-carbon SCM within the technology–organisation–environment (TOE) framework, in which drivers, enablers and barriers to technology adoption practices are identified. The environmental, economic and social outcomes of adoption practices are also identified.

Originality/value – This study provides a novel and comprehensive roadmap for future research on technology-enabled low-carbon SCM. Furthermore, policy, as well as managerial implications, is presented for policymakers and managers.

Keywords Low-carbon supply chain management, Decarbonisation, Technology innovation, Literature review

Paper type Literature review

1. Introduction

Greenhouse gas (GHG) emissions consisting mainly of carbon dioxide (CO_2) and other gases, such as methane (CH_4), are a significant cause of global warming and can derail human lives and economic conditions (Yao *et al.*, 2021). Supply chain management (SCM) is the design and management of the product, information and cash flows in the supply chain, which is the network of all entities engaged in producing and delivering a product or service to the final customers (Sanders, 2020). SCM activities contribute significantly to carbon emissions (Gholizadeh *et al.*, 2020; Palak *et al.*, 2014; Xing *et al.*, 2016). It has been reported that almost a quarter of global energy-related CO_2 emissions come from transportation because of SCM development and surging travel demand (Cantillo *et al.*, 2022; Palak *et al.*, 2014). Agricultural production, the origin of food supply chains, releases over 30% of global GHG emissions (Jensen and Govindan, 2014; Singh *et al.*, 2018). As the climate crisis intensifies, public awareness of global warming has escalated, adding to carbon pressures in global SCM (Palak *et al.*, 2014). Much attention has been given to carbon performance management (Zvezdov and Hack, 2016). Incorporating sustainability and low- or zero-carbon (LZC) energy solutions into SCM has been placed high on an organisation's agenda (Bach *et al.*, 2020; Lundie *et al.*, 2019). There are different terminologies for carbon reductions, including decarbonisation (decarbonisation), low carbon, zero carbon, net zero and so on (Wimbadi and Djalante, 2020). The term decarbonisation is acknowledged to explain the process of achieving a low-carbon economy (Barros *et al.*, 2014). Therefore, in this review, SCM decarbonisation is used to describe the process of pursuing an LZC SCM.

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The growing number of new advanced techniques signals a strategic shift for the Fourth Industrial Revolution (Industry 4.0). The integration of digital and physical technologies characterises Industry 4.0 technologies (Chen *et al.*, 2022a; Sundarakani *et al.*, 2021) and has been conceptualised with SCM research as "Supply Chain 4.0" (Frederico *et al.*, 2019). Decarbonisation technologies have also been developed (Bataille *et al.*, 2018). The adoption of technologies has become imperative in today's SCM, stepping up the pace towards a low-carbon future (Sundarakani *et al.*, 2021).

In the academic literature on SCM, adopting advanced technologies to reduce carbon emissions is an underrepresented field. Literature has indicated that low-carbon SCM is a critical area that needs further investigation. De Sousa Jabbour *et al.* (2019) discuss the decarbonisation of low-carbon products and logistics practices and point out the lack of unanimity in the reviewed research. The role of Industry 4.0 technologies in SCM has been investigated (Frederico *et al.*, 2019; Gebhardt *et al.*, 2021; Hettiarachchi *et al.*, 2022). However, they do not examine the role of decarbonisation technologies in SCM. Wangsa *et al.* (2022) consider both types of technologies, while a conceptual model and managerial implications remain absent.

To fill the gaps, this review aims to study the existing knowledge on using technology for low-carbon SCM and to explore the role of technologies in SCM decarbonisation and the consequences. A conceptual model is derived from the analysis. A number of future research directions and managerial implications for governments and enterprises are also provided. Therefore, this systematic literature review (SLR) seeks to answer the following research questions (*RQs*):

RQ1. What are the drivers, practices, enablers, barriers and consequences of technology-enabled low-carbon SCM?

RQ2. What role do technologies play in SCM decarbonisation?

RQ3. How can the practices and research in this discussion be taken forward?

The rest of the paper is organised as follows. Section 2 introduces the theories used in this paper. In Section 3, the review presents the research methodology and the descriptive analysis, and the themes extracted from the reviewed articles are explained. Section 4 presents the conceptual development and suggests future research and implications in Section 5. Finally, this paper concludes the study and discusses the limitations in Section 6. In summary, this paper systematically reviews current studies of the role of technologies in low-carbon SCM.

2. Theoretical background

2.1 Diffusion of innovation theory

To explain the reasons and actions for spreading new ideas and technologies, diffusion of innovation (DOI) research has been conducted since the 1940s (Prescott and Conger, 1995). In the DOI model, technological innovation characteristics, including complexity, compatibility, relative advantage, trialability and observability, can impact the attitude and adoption of innovation (Prescott and Conger, 1995; Rogers, 1962). As a process approach, DOI research considers innovation stages, including discovery, development (adoption), diffusion and impact (Dos Santos *et al.*, 2014). DOI processes have been developed and widely adopted in SCM research to study the diffusion of various technologies in SCM (Quetti *et al.*, 2012; Ranganathan *et al.*, 2004; Wu and Chuang, 2010). According to Hameed *et al.* (2012), the pre-adoption stage explains the need and knowledge for innovation, and the post-adoption stage identifies the acquisition and acceptance. This study presents the driving factors of technology-enabled SCM decarbonisation at the pre-adoption stage and adoption practices and impacts in the pro-adoption stage.

Although DOI theory has been widely used to study SCM technological innovation, it describes individual-level adoption and does not provide sufficient adoption explanation in organisational or environmental contexts (Chau and Tam, 1997; Xiao *et al.*, 2013). Therefore, it has been suggested that DOI theory can be combined with other frameworks for more comprehensive and robust results (Shree *et al.*, 2021; Xiao *et al.*, 2013).

2.2 Technology–organisation–environment framework

The technology–organisation–environment (TOE) framework can explain the factors for technology adoption in organisations by affirming the significance of technological, organisational and environmental contextual factors (Tornatzky *et al.*, 1990; Venkatesh and Bala, 2012). It focusses on an organisational-level analysis and has been successfully applied in technology adoption in SCM research (Chen *et al.*, 2015; Chittipaka *et al.*, 2022; Venkatesh and Bala, 2012). Among the three contexts, the technological factor includes the technologies relevant to the organisation; the organisational factor describes the attributes within the organisation; and the environmental aspect concerns the influence of the business environment, including impacts from authorities, competitors and other stakeholders (Chong and Ooi, 2008; Tornatzky *et al.*, 1990).

The combination of the DOI and TOE frameworks has been studied to investigate the adoption process, including the factors that lead to innovation adoption and the consequences (Dos Santos *et al.*, 2014; Shree *et al.*, 2021), and to discuss technology diffusion in SCM (Chan and Chong, 2013; Chong *et al.*, 2009; Nath *et al.*, 2022). The TOE framework and DOI theory both discuss internal and external technologies and organisational factors. Moreover, with the environmental context, the TOE framework can help DOI theory provide a better explanation of intrafirm innovation diffusion (Hsu *et al.*, 2006; Wu and Chen, 2014). Innovation attributes from the DOI theory have been added to TOE frameworks to include more comprehensive factors (Ghezzi *et al.*, 2013). Furthermore, the TOE framework can be included in the pre-adoption stage of a DOI model as the driving factors for innovation adoption (Cruz-Jesus *et al.*, 2019), followed by adoption and impacts (Xiao *et al.*, 2013).

In this study, we adopt the TOE framework in a DOI theory-based conceptual model to comprehensively study the adoption of technologies towards LZC SCM. From our reviewed articles, we found that there are driving factors inside and outside an organisation, which can lead to different outcomes, as suggested by DOI theory. Additionally, in line with the TOE framework, the drivers in the reviewed research come from various aspects, at the technical and individual level, and also from the external environment.

3. Research methodology

In this review, to study the current state of the relevant research, a SLR method is used based on the guidelines proposed by Kitchenham (2004). SLRs adopt a replicable, scientific and transparent process to minimise bias, which is different from the approach used in traditional narrative reviews (Tranfield *et al.*, 2003). By integrating and analysing the contributions of current studies on our topic, it is expected that a clearer and unprejudiced understanding of the role of technology in low-carbon SCM will be achieved.

In accordance with the SLR processes (Kitchenham *et al.*, 2009; Tranfield *et al.*, 2003), this review adopts the following steps: defining the research questions; searching and filtering the literature; conducting a quality assessment with inclusion and exclusion criteria; performing data collection and analysis; and presenting results. To ensure the objectivity and unbiased nature of this study to comply with the criteria of an SLR, the authors independently analysed and then discussed and consolidated the results to determine the article searching keywords, the inclusion and exclusion criteria and the coding scheme, drawing on the extraction process from the literature (Gold *et al.*, 2010; Talwar *et al.*, 2021; Tranfield *et al.*, 2003).

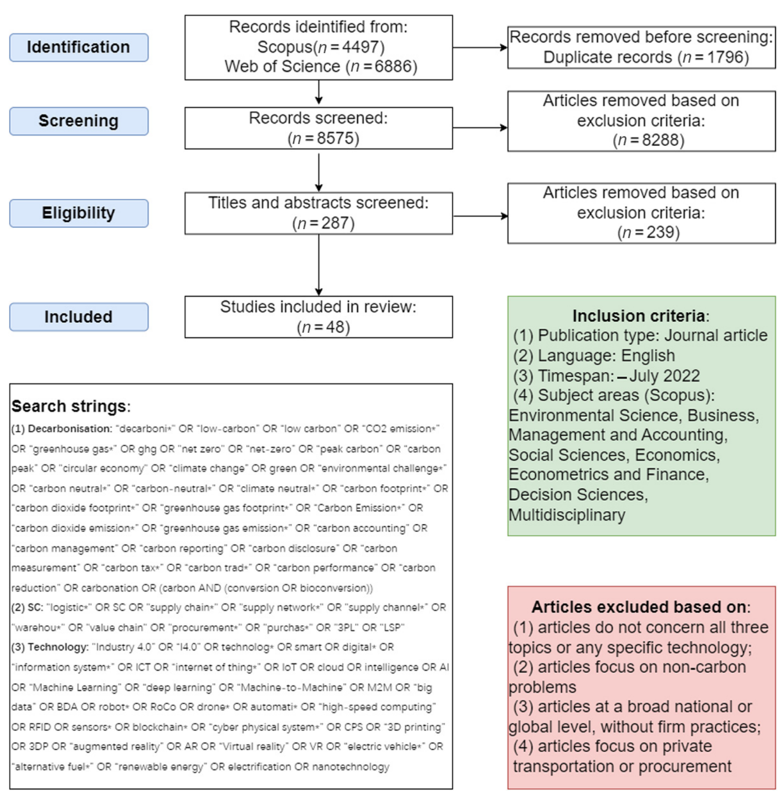
3.1 Literature selection strategy

Our reviewed papers were extracted from two electronic databases: *Scopus* and *Web of Science*. For a comprehensive set of search results, we developed three groups of keywords for the search strings that were used as input to the databases: "Decarbonisation" (Meyer, 2020; de Sousa Jabbour *et al.*, 2019), "Supply chain" (Gebhardt *et al.*, 2021; Jia *et al.*, 2018) and "Technology" (Frederico *et al.*, 2019; Oztemel and Gursev, 2020; Wangsa *et al.*, 2022), as we aimed to study the current academic research on the role of technology in low-carbon SCM. Each group was connected by "AND" to take the concurrent set, and each keyword was concatenated within each group by "OR" to take the intersection set. We conducted a search for all possible combinations. The complete set of keywords and search strings are illustrated in Figure 1.

In the first round of search, only published journal articles in English with titles, abstracts or keywords that matched all three of the above groups were addressed. Beyond these, the subject areas of *Environmental Science, Business, Management and Accounting, Social Sciences, Economics, Econometrics and Finance, Decision Sciences* and *Multidisciplinary* were chosen for the search in the *Scopus* database according to our research focus. The first stage of the mechanical search on November 21, 2022, yielded 4,497 and 6,886 probable articles, respectively. We then shortlisted 8,575 studies after deleting duplications.

Predefined inclusion and exclusion criteria can generate high-quality knowledge discovery and support further selection processes in this study (Ghadge *et al.*, 2020). The inclusion criteria selected only academic journals from *the Chartered Association of Business Schools* (2021)' *Academic Journal Guide* (*AJG 2021*). Papers from other sources and "grey literature" were excluded to ensure quality and relevance. Noting that we included articles that discuss the role of technology in

Figure 1 PRISMA flowchart for the SLR



low-carbon SCM, we excluded articles where any of SCM, carbon problem or technology was an unimportant element. Additionally, we only focus on articles that consider firm-level practices instead of those at a broad regional or global level. All the articles that aim at private transportation and the purchasing or pricing of specific products were excluded, as they are irrelevant to our research topic. The selection and coding phases were conducted by two authors separately. All doubtful articles were discussed within the group to reach a consensus.

In the second selection phase, we assessed the papers by reading the titles and abstracts of each paper, following the mentioned criteria. The sample was then reduced to 287 articles. The final round involved reading the full text of each shortlisted paper to ensure that it met the inclusion criteria. Finally, 48 articles were selected for this review. As identified in Figure 1, the selection steps are summarised using the *Preferred Reporting Items for Systematic reviews and Meta-Analysis* (PRISMA) flow diagram (Page *et al.*, 2021) as a systematic method to visualise the search process.

3.2 Descriptive analysis

This section aims to present the summary statistics of the 48 reviewed papers, including the number of publications by year, the journal distribution and the research methods. A timeline of research is also presented below.

Figure 2 shows the annual production of papers. The first reviewed articles were published in 2010. From 2010 to 2017, the production per year was slow. Then, the number of research articles on adopting technology for LZC SCM soared and marked its most significant increase in 2021, accounting for nearly 25% of the articles, which indicates the rising research interest in this research topic. Considering the timing of the final screening process, it is highly expected that more articles in this field will be published in late 2022.

As suggested in Table 1, our selected articles were in 15 Q1 journals. A total of 23 out of the 48 reviewed papers were published in the *Journal of Cleaner Production*, then the *International Journal of Production Economics, International Journal of Production Research* and *Technological Forecasting and Social Change* (3 papers), followed by *Supply Chain Management: An International Journal* (2 papers) and so on. Based on the *AJG, 2021*, 7 journals (32 papers) are rated as Level 2, and 8 (16 papers) are rated as Level 3. Regarding the research field, over 58% of the reviewed papers are from four *Sector Studies* journals. There are four journals in the fields of *Operations and Technology Management* and two in *Information Systems*, *Operations Research and Management Science*. The research areas of the remaining three journals are *Innovation*, *Social Sciences* and *Regional Studies, Planning and Environment*.

The research methodologies of the identified articles are also analysed in Figure 3. The dominance of the case study method (34 papers) can be observed, followed by modelling (22 papers), secondary data analysis (17 papers) and interviews (16 papers). Notably, the majority of the reviewed articles (38 out of 48) adopt two or more research methods.

Concerning the technology adopted, a research timeline is recorded in Figure 4. The first technology in our review research was the use of solar energy in 2010 (Vallentin and Viebahn, 2010). Other renewable energy technologies, including biomass and wind energy, have also been discussed; a good deal of focus is given to biomass energy. Industry 4.0 technologies have been widely adopted since 2015. Among the reviewed articles, blockchain technology (BCT) has attracted attention since 2020 (Manupati *et al.*, 2020).

4. Thematic analysis

4.1 Drivers

According to the selected papers, the drivers of technology adoption in low-carbon SCM come from inside and outside an organisation and are classified into three main categories aligned with the TOE framework: technology, organisation and environment (Tornatzky *et al.*, 1990). The following subsections discuss the drivers in detail.

4.1.1 Technological context

The relative advantage, compatibility and complexity of technologies can be the incentives for LZC SCM (Mastos *et al.*, 2020; Subramanian *et al.*, 2015). Our reviewed articles identify the importance of decarbonisation technologies and Industry

Figure 2 Distribution of papers per year

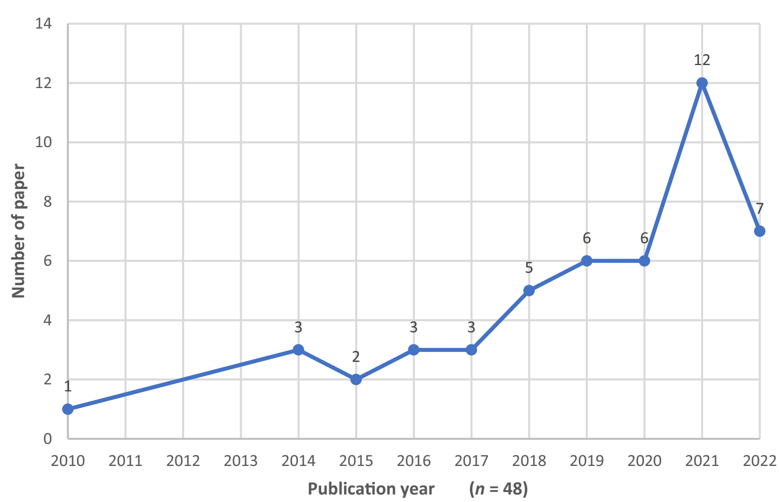


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Table 1 Distribution of papers across journals

Field	Journal Title	Number	AJG	Quartiles
SECTOR	*Journal of Cleaner Production*	23	3	Q1
OPS&TECH	*International Journal of Production Economics*	3	3	Q1
OPS&TECH	*International Journal of Production Research*	3	3	Q1
INNOV	*Technological Forecasting and Social Change*	3	3	Q1
OPS&TECH	*Supply Chain Management: An International Journal*	2	3	Q1
SOC SCI	*Business Strategy and the Environment*	2	3	Q1
SECTOR	*Energy Policy*	2	2	Q1
SECTOR	*Transportation Research Part E: Logistics and Transportation Review*	2	3	Q1
INFO MAN	*Industrial Management and Data Systems*	2	2	Q1
OPS&TECH	*IEEE Transactions on Engineering Management*	1	3	Q1
OR&MANSCI	*Omega (United Kingdom)*	1	3	Q1
REGIONAL STUDIES, PLANNING AND ENVIRONMENT	*Cambridge Journal of Regions, Economy and Society*	1	2	Q1
OR&MANSCI	*Computers and Operations Research*	1	3	Q1
SECTOR	*Transportation Research Part D-Transport and Environment*	1	3	Q1
INFO MAN	*Journal of Enterprise Information Management*	1	3	Q1

Figure 3 Distribution of research methods

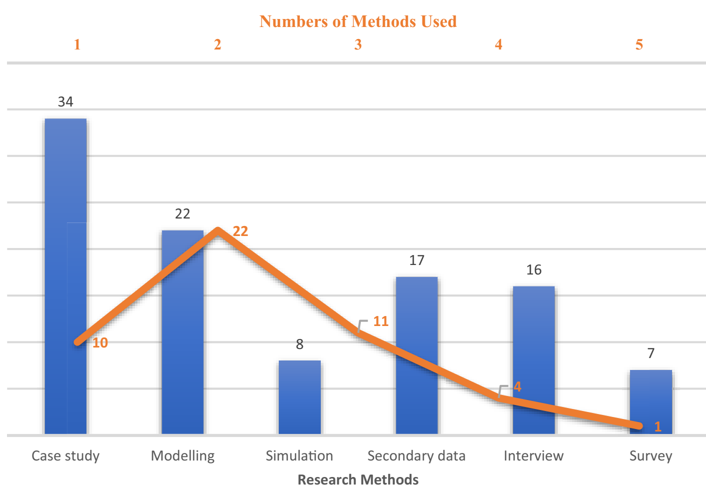
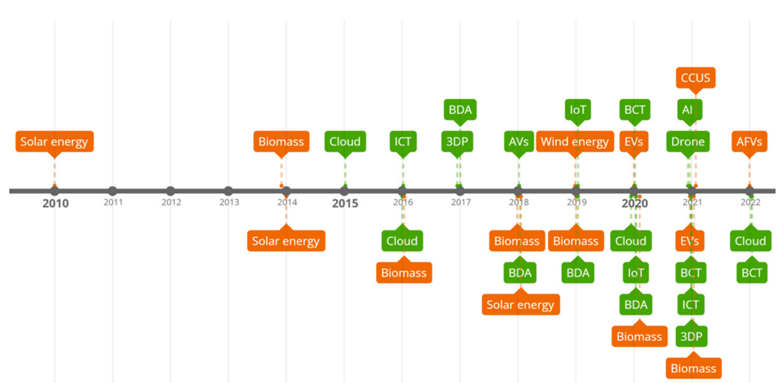


Figure 4 Research timeline



4.0 technologies. The former emits low or no levels of CO_2 emissions, while Industry 4.0 technologies, although designed for different purposes, can also be helpful for SCM decarbonisation.

Decarbonisation technologies, also known as LZC technologies, aim to reduce GHG emissions (Yao *et al.*, 2021). Alternative energy technologies have been developed to replace fossil fuels (Bento *et al.*, 2021; Cantillo *et al.*, 2022; Thomas and Mishra, 2022; de Vargas Mores *et al.*, 2018; Zahraee *et al.*, 2019). Among them, alternative fuel vehicle technologies, including electric, hybrid and compressed natural gas, are available on the market to support transportation with lower operating costs and GHG emissions (Bach *et al.*, 2020; Cantillo *et al.*, 2022; Sadiq Jajja *et al.*, 2021). Additionally, to tackle the environmental threats and make the most use of regional natural resources, many countries enable the use of renewable energy to support decarbonisation (Palak *et al.*, 2014; Tanaka *et al.*, 2018; Thomas and Mishra, 2022). Biomass, developed from plants, plant-derived substances and other organic matter, is also a renewable and versatile energy source; it has been regarded as a promising option (Jensen and Govindan, 2014; Zahraee *et al.*, 2019).

Carbon capture, utilisation and storage (CCUS) technology can substantially reduce net carbon emissions of power plants and industrial facilities. Each year, it can capture and permanently store nearly 40 Mt of CO_2 and prevent it from entering the atmosphere (Yao *et al.*, 2021).

In Industry 4.0, new technologies integrate the physical, digital and biological worlds and impact multiple disciplines (Schwab, 2017). Industry 4.0 is supported by information and communications technology (ICT). Big data analysis (BDA), also known as the analysis of a vast and complex set of data, can provide a better understanding and competitive advantages for SCM due to the unprecedented innumerable data generated in supply chain networks (Gholizadeh *et al.*, 2020; Sundarakani *et al.*, 2021; Zhao *et al.*, 2017). Besides its maturity in the cryptocurrency market, BCT, consisting of a series of interlinked cryptographic time-stamped immutable records of blocks, shows potential in enterprise integration with peer-to-peer networks, transparency, security and accurate information sharing (Diniz *et al.*, 2021; Manupati *et al.*, 2020; Sundarakani *et al.*, 2021; Zeng *et al.*, 2022). Cloud computing technology (CCT) integrates information technology resources, providing ICT service in its architecture and assisting in business resource alignment and information sharing in today's SCM (Huang *et al.*, 2021; Singh, 2015). Modern-day artificial intelligence (AI) is generally accepted as intelligence demonstrated by machines to tackle specific tasks and study new problems (Damoah *et al.*, 2021).

In addition to digital technologies, additive manufacturing (AM) technology (3D Printing) is a rapid prototyping technology that creates 3D objects with computer designs to minimise and recycle plastic waste (Li *et al.*, 2017; Thomas and Mishra, 2022). Radiofrequency identification (RFID), a form of wireless communication, can automatically identify and track tags of objects with electromagnetic fields and is widely used in logistics management (Liu *et al.*, 2019).

The combination of Industry 4.0 technologies has great potential. Supported by CCT, ICT technology and RFID, the Internet of Things (IoT) connects and exchanges data within physical objects through sensors, software and other technologies (Lim *et al.*, 2020; Liu *et al.*, 2019). Similarly, big data CCT can assist in capturing SCM carbon footprint information and supporting supplier selection (Singh *et al.*, 2018). BDA can also be developed with BCT to improve SCM (Sundarakani *et al.*, 2021). Meanwhile, AI applications accelerate drone technology development (Damoah *et al.*, 2021).

4.1.2 Environmental context

The environmental context includes the external drivers for technology adoption. This section identifies the driving factors, including the macroeconomic context, the regulatory environment and stakeholders.

As revealed in the review, the pressure from the international community is acknowledged as a main driver. With the concerns of global warming and climate change (Huang *et al.*, 2021), several international environmental protocols have been proposed, such as *the United Nations Framework Convention on Climate Change, the Paris Agreement, the Kyoto Protocol* and *COP26* (Bach *et al.*, 2020; Cantillo *et al.*, 2022; Diniz *et al.*, 2021; Tanaka *et al.*, 2018; Vallentin and Viebahn, 2010). Sustainable development has been an essential topic for governments worldwide (Damoah *et al.*, 2021; Ravigné and Da Costa, 2021). The United Nations unveiled the 2030 Agenda for Sustainable Development in 2015, which included 17 Sustainable Development Goals (SDGs) and 169 linked targets (UN, 2018). As a result, various countries have developed regulatory requirements to tackle climate change and meet SDGs (Lamba and Singh, 2019).

Regulatory requirements are another key determinant (Lim *et al.*, 2020; Manupati *et al.*, 2020; Sadiq Jajja *et al.*, 2021). In response to the SDGs, policymakers have launched laws and restrictions to achieve their climate commitments, such as emission and carbon footprint restrictions and penalties, and the use of renewable energy (Cantillo *et al.*, 2022; Khan *et al.*, 2021; Palak *et al.*, 2014; Vallentin and Viebahn, 2010; Zahraee *et al.*, 2019). Also, carbon offset allows firms to balance their own carbon footprints (Behnamfar *et al.*, 2022; Palak *et al.*, 2014). Carbon taxes, as a critical policy to levy taxes on carbon emissions (Manupati *et al.*, 2020; Ravigné and Da Costa, 2021; Thomas and Mishra, 2022), have been proposed and implemented in over 30 countries.

SCM stakeholders have also piled pressure on technology adoption with low-carbon cooperation opportunities or requirements (Diniz *et al.*, 2021; Hussain *et al.*, 2020; Melander and Pazirandeh, 2019; Xing *et al.*, 2016). Enterprises need advanced technologies to improve their performance against competitors (Gholizadeh *et al.*, 2020; Sundarakani *et al.*, 2021; Tawiah *et al.*, 2022). Investors care about firms' carbon performance when making investment decisions (Lundie *et al.*, 2019; Mastos *et al.*, 2020; Zvezdov and Hack, 2016). Customers are also becoming environmentally conscious and willing to make low-carbon purchases, influencing firms' adoption choices (Gružauskas *et al.*, 2018; Lamba and Singh, 2019; Sadiq Jajja *et al.*, 2021).

4.1.3 Organisational context

The organisational context covers organisational resources and characteristics that influence technology adoption (Ghezzi *et al.*, 2013; Hsu *et al.*, 2014). We concluded from the research that the scope of business operations and firm size are two key organisational factors.

Enterprises with a greater scope of business are more likely to invest in innovative technologies (Ghadge *et al.*, 2020; Khan *et al.*, 2021). In the logistics process, the low utilisation rate, increasing demand and the lack of dynamic information have resulted in higher costs, energy and resource consumption and loading rates, which may negatively impact firms' financial performance (Cantillo *et al.*, 2022; Liu *et al.*, 2019; Zeng *et al.*, 2022). Besides transportation costs, technologies may encourage the reduction of labour costs by automation (Chen *et al.*, 2022b; Gružauskas *et al.*, 2018). To ensure qualitative and environmental services and high fulfilment rates, companies may need to invest heavily in their inventory management and carbon footprint calculation (Kaur and Singh, 2018; Li *et al.*, 2017; Xing *et al.*, 2016). Firms may earn extra profits from governmental subsidies for using cleaner resources and carbon capture technology (Jensen and Govindan, 2014; Yao *et al.*, 2021). SCM members also need to consider carbon costs carefully under different carbon regulations (Gholizadeh *et al.*, 2020; Kaur and Singh, 2018; Palak *et al.*, 2014).

Selected articles also note that firm size is critical for technology adoption (Shen *et al.*, 2017). Increasing enterprise size can lead to task complexity, scale effects and dependence on advanced technologies (Gružauskas *et al.*, 2018; Kaur and Singh, 2018; Zvezdov and Hack, 2016). However, it has been reported that small- and medium-sized enterprises (SMEs) also need to improve service quality with advanced technologies, which can help them integrate with other supply chain members (Singh *et al.*, 2015; Zvezdov and Hack, 2016). Furthermore, these technologies provide more flexibility in making new attempts (Gružauskas *et al.*, 2018).

Table 2 shows the drivers for adopting technologies that enable carbon reduction in SCM in our reviewed papers.

4.2 Low-carbon supply chain management practices

Although Dovì *et al.* (2009) have pointed out that in industry, more attention is given to improving efficiency than to the integration of renewable sources, 19 of our reviewed articles have discussed LZC production with renewable resources or CCUS, 24 have focussed on enhancing carbon efficiency and 6 have considered both. In this section, we classify low-carbon SCM practices into two categories, LZC production and the improvement of carbon efficiency and discuss the role of technologies within them.

4.2.1 Low- or zero-carbon production

The use of renewable energy in SCM has developed on an unprecedented scale. Photovoltaic solar power generation systems and solar water heating systems have proved helpful for low-carbon production and climate change mitigation (Shen *et al.*, 2017; Tanaka *et al.*, 2018). Among natural gases, which account for a large proportion of the electricity market, bio-sourced gas is more environmentally than fossil fuels (Olson, 2014; Ravigné and Da Costa, 2021).

The reuse and recycling of resources in SCM are also necessary. Bioenergy is an attractive adjunct to food supply chains because companies can provide appropriate locations and food waste as resources (Jensen and Govindan, 2014). Combustion, gasification and anaerobic digestion can enable "waste to energy" (Hussain *et al.*, 2020). In the construction sector, concrete aggregates can be replaced by recycled concrete aggregates (Adaloudis and Bonnin Roca, 2021; Yu *et al.*, 2021). The heat energy recycling system can recycle wastewater to provide heat for cleaner production (Shen *et al.*, 2017).

There is also a growing acceptance of comprehensive low-carbon productions. For instance, solar and windmills can provide cleaner power for production with 3D Printing technology (Thomas and Mishra, 2022). Large companies look to purchase renewable energy to support their cloud platforms (Patchell and Hayter, 2021). By consolidating biorefineries, biomass suppliers can obtain low life cycle GHG emissions, increasing the potential of biomass resources (Zahraee *et al.*, 2019). Additionally, CCUS, the primary manufacturing process and other methods in the iron and steel industry can be conducted simultaneously for cleaner production (Yao *et al.*, 2021).

Table 2 Drivers

No.	Drivers	Details	References
1	*Technological context*		
1.1	Industry 4.0 technologies	Physical, digital and biological technologies in the fourth industrial revolution	Khan *et al.* (2021); Schwab, (2017)
1.2	Decarbonisation technologies	Technologies that help reduce and eliminate carbon emissions	Bento *et al.* (2021); Yao *et al.* (2021)
2	*Environmental context*		
2.1	Pressures from the international community	International awareness and protocols that call for actions and cooperation in the face of climate change and global warming	Damoah *et al.* (2021); Huang *et al.* (2021); Ravigné and Da Costa, (2021)
2.2	Regulatory requirements	The environmental standards, rules and laws proposed by the authorities force organisations to conduct low-carbon practices	Khan *et al.* (2021); Lim *et al.* (2020); Manupati *et al.* (2020)
2.3	Stakeholders' pressure	Low-carbon opportunities or requirements from supply chain stakeholders	Diniz *et al.* (2021); Hussain *et al.* (2020); Xing *et al.* (2016)
3	*Organisational context*		
3.1	Scope of business operations	Supply chain business activities that support organisation operations	Kaur and Singh, (2018); Khan *et al.* (2021); Singh *et al.* (2018)
3.2	Firm size	The business size of enterprises includes the number of employees, services and products provided	Kaur and Singh, (2018); Zvezdov and Hack, (2016)

4.2.2 Improvement of carbon efficiency
Technologies have also been applied to improve SCM carbon efficiency. ICT encourages the enterprise resource planning (ERP) system to capture and analyse multi-dimensional business activities, obtaining automated solutions for carbon footprint (Zvezdov and Hack, 2016). Similarly, cloud LCA platforms can optimise, measure and share carbon footprint data and help identify SCM's carbon hotspots (Singh *et al.*, 2015; Xing *et al.*, 2016). For precise and timely carbon footprint evaluation, technologies can integrate LCA methods dynamically, encouraging SCM members to perform environmentally (Xing *et al.*, 2016).

For improving efficiency, digital technologies such as BDA can also enable data sharing among supply chain elements to maximise the utilisation of transportation tools and reduce carbon emissions (Gholizadeh *et al.*, 2020). It can also be valuable through SCM data acquisition, supplier selection and quality control, even under carbon policies (Gholizadeh *et al.*, 2020; Lamba and Singh, 2019; Zhao *et al.*, 2017). BCT can also help the effective decision-making process and identify the low-efficiency nodes in SCM (Zeng *et al.*, 2022). The developed BCT has overcome most limitations of previous approaches and can continuously monitor carbon asset transactions and ensure compliance in SCM without additional support (Manupati *et al.*, 2020; Tawiah *et al.*, 2022). BCT can bring trust, efficiency and transparency to SCM members (Diniz *et al.*, 2021; Khan *et al.*, 2021). Physical technologies can also be helpful. An AM-based supply chain can reduce transportation costs and raw materials, resulting in shorter supply chain length, lower variable costs and total carbon emissions (Li *et al.*, 2017).

Carbon efficiency can also be achieved with the extensive use of technologies (Kaur and Singh, 2018; Lim *et al.*, 2020; Liu *et al.*, 2019; Singh *et al.*, 2018). Industry 4.0 technologies can support alternative resources in SCM (Yu *et al.*, 2021). Connecting producers and buyers, IoT can provide automated negotiations in the online ecosystem (Mastos *et al.*, 2020), whereas BDA, CCT and BCT have been comprehensively used to record information, improve and share carbon calculators and reduce costs (Singh *et al.*, 2018; Sundarakani *et al.*, 2021). For carbon-efficient logistics, IoT and CCT can be integrated to enhance the shared delivery mode (Lim *et al.*, 2020) and achieve optimal dynamic solutions with the help of ICT, RFID, BDA and other advanced technologies (Gružauskas *et al.*, 2018; Liu *et al.*, 2019).

In summary, both types of SCM practices bring more possibilities for SCM decarbonisation with the assistance of various emerging technologies. Table 3 lists the mentioned practices.

4.3 Barriers and challenges
Although SCM decarbonisation has been conducted with the help of technologies, the practices have revealed various problems. In this section, the barriers and challenges are identified from 40 reviewed papers.

4.3.1 Technical problems
Low-carbon practices may run into roadblocks due to technical issues (Bento *et al.*, 2021; Zvezdov and Hack, 2016) and the lack of technology strategy and knowledge (Gebhardt *et al.*, 2021; Khan *et al.*, 2021; Llopis-Albert *et al.*, 2021; Subramanian *et al.*, 2015; Velenturf, 2016). Inaccurate carbon footprint measurements occur with system boundary issues, allocation issues, supply chain variability and scalability (Zvezdov and Hack, 2016). Network failure can also be problematic, especially in emerging economies and rural areas, restricting the use of advanced technology and causing inconsistencies, delays and blind spots (Singh *et al.*, 2018; Sundarakani *et al.*, 2021). Meanwhile, the growing quantity of data can influence the complexity and computational efficiency of low-carbon SCM optimisation (Huang *et al.*, 2021; Lamba and Singh, 2019).

Worse, technologies are not always carbon-efficient (Lim *et al.*, 2020; Zahraee *et al.*, 2019). The mining process of BCT and the production process of lithium batteries require a large amount of space and energy (Sadiq Jajja *et al.*, 2021; Tawiah *et al.*, 2022). Embodied carbon generated in the adoption of technologies may be ignored. With a smaller carbon footprint, AM may lead to higher energy consumption (Li *et al.*, 2017). Similarly, producing renewable energy, the biomass industry still needs an overhaul in its production and transportation to reduce carbon emissions (Palak *et al.*, 2014; Zahraee *et al.*,

Table 3 Practices

No.	Practices	Details	References
1	*Low or zero carbon production*		
1.1	Renewable energy	Using renewable resources instead of fossil fuels for energy or material production	Jensen and Govindan, (2014); Olson, (2014); Zahraee *et al.* (2019)
1.2	Waste management	Recycling, reusing or remanufacturing of returned products or material waste for re-production	Adaloudis and Bonnin Roca, (2021); Hussain *et al.* (2020); Yu *et al.* (2021)
1.3	Integrated low-carbon production	Integrating low-carbon technologies with Industry 4.0 technologies or other SCM processes for fewer carbon emissions during production	Patchell and Hayter, (2021); Thomas and Mishra, (2022); Yao *et al.* (2021)
2	*Improving carbon efficiency*		
2.1	Improving accuracy	Improving the carbon data calculation with the help of advanced technologies for accurate and efficient SCM	Singh, (2015); Xing *et al.*, (2016), (2016)
2.2	Enabling data sharing	Enabling transparent, efficient and safe data sharing between SCM members and other stakeholders	Gholizadeh *et al.* (2020); Lamba and Singh, (2019); Zeng *et al.* (2022)
2.3	Integrated carbon efficiency improvement	Integrating various technologies to improve the overall carbon efficiency in the supply chain	Gružauskas *et al.* (2018); Lim *et al.* (2020); Mastos *et al.* (2020)

2019), whereas compressed natural gas may emit more GHGs than diesel in a trip (Ravigné and Da Costa, 2021).

4.3.2 High costs

Most of our reviewed papers agree that the high costs of innovative technologies are a crucial barrier to low-carbon SCM (Khan *et al.*, 2021; Tanaka *et al.*, 2018; de Vargas Mores *et al.*, 2018; Yao *et al.*, 2021; Zhao *et al.*, 2017).

Not all decarbonisation technologies are economically viable, mainly due to the high initial costs and uncertain return on investment (Jensen and Govindan, 2014; Liu *et al.*, 2019; Llopis-Albert *et al.*, 2021). The high fixed costs of AM have been reported as a critical reason for its questionable feasibility and applicability (Adaloudis and Bonnin Roca, 2021; Li *et al.*, 2017). The large-scale applications can be expensive for CCUS technology (Yao *et al.*, 2021). Additionally, only industries in developed economies or large firms can take on costly and sizeable low-carbon technology investments (Sadiq Jajja *et al.*, 2021; Singh *et al.*, 2018; Tawiah *et al.*, 2022). In addition, firms' costs can also be driven by biomass, scarce materials or energy price volatility (Jensen and Govindan, 2014; Tanaka *et al.*, 2018). Stakeholders are usually price-sensitive, and customers may not want to pay more for environmental products (Cantillo *et al.*, 2022; Olson, 2014; Yao *et al.*, 2021).

4.3.3 Lack of data

As advanced technologies such as BCT are at the early stage, researchers have found it hard to obtain enough data from firms (Subramanian *et al.*, 2015; Tawiah *et al.*, 2022), especially when the required supply chain data may come from multiple companies in different countries (Lundie *et al.*, 2019). Also, with the development of technologies, SCM and relevant regulations, up-to-date data are needed (Cantillo *et al.*, 2022). Worse still, it has been reported that some supply chain members, especially officials and SMEs, are reluctant to share their data and information due to fierce competition and the potential impact on profits (Diniz *et al.*, 2021; Liu *et al.*, 2019; Melander and Pazirandeh, 2019; Patchell and Hayter, 2021).

4.3.4 Privacy and ethical issues

Technology also raises privacy and security concerns (Lim *et al.*, 2020). Customers' data privacy and security, together with the safety of parcels, are recognised as obstacles to logistics (Lim *et al.*, 2020; Subramanian *et al.*, 2015). There are also concerns about the code-cracking potential of quantum computers, which may provoke long-term data safety risks through hackable encryption algorithms for public blockchains (Sundarakani *et al.*, 2021).

Furthermore, it can be challenging to ensure the equitability of low-carbon practices (Patchell and Hayter, 2021). The lack of mutual trust between supply chain members and concerns about intellectual property rights can generate high stakes in information sharing (Melander and Pazirandeh, 2019; Velenturf, 2016; Xing *et al.*, 2016).

4.4 Enablers

Unlike drivers that provide direct influences, enablers indirectly facilitate drivers and SCM implementation (Austin, 2000; Chen *et al.*, 2022c; Sancha *et al.*, 2015). Four enablers for SCM decarbonisation are introduced in this section.

4.4.1 Life cycle assessment research

The development of life cycle assessment (LCA) research can help with scientific and comprehensive environmental performance evaluation (Boschiero *et al.*, 2019). LCA, also known as life cycle analysis, is a method for assessing the environmental impacts of a product, process or service from cradle to grave (Singh *et al.*, 2015). The development of technologies can re-energise LCA by enabling easy and cost-effective data sharing among SCM partners (Xing *et al.*, 2016). In addition, the LCA costing method is commonly used to calculate ownership costs and can be integrated into the green innovation value chain study (Olson, 2014).

4.4.2 Optimisation research

The development of optimisation models can improve the performance of the technologies used (Huang *et al.*, 2021; Lim *et al.*, 2020; Thomas and Mishra, 2022; Zeng *et al.*, 2022; Zhao *et al.*, 2017). Mixed-integer program optimisation models have been applied to the low-carbon SCM (Gholizadeh *et al.*, 2020; Lamba and Singh, 2019). According to our reviewed papers, costs and GHG emissions are two primary objectives for optimisation research (Lamba and Singh, 2019; Lim *et al.*, 2020; Thomas and Mishra, 2022), followed by the efficiency of vehicles (Gholizadeh *et al.*, 2020), production waste (Thomas and Mishra, 2022) and so on. Multi-objective optimisation approaches have been studied to pursue multiple goals, such as lower emissions and costs (Gholizadeh *et al.*, 2020; Huang *et al.*, 2021; Lim *et al.*, 2020; Liu *et al.*, 2019; Zhao *et al.*, 2017).

To support decision-making, many studies have studied multi-echelon-integrated optimisation problems (Manupati *et al.*, 2020; Palak *et al.*, 2014; Thomas and Mishra, 2022; Zeng *et al.*, 2022) rather than considering only the buyer's perspective (Lamba and Singh, 2019). Under the blockchain environment, three-echelon supply chain integrated scheduling optimisation models with multiple participants have been proposed to maximise the supply chain's utility and tackle resource waste (Zeng *et al.*, 2022). The multi-stage optimisation algorithm is also widely used to ensure the robustness and authenticity of the models (Huang *et al.*, 2021; Lim *et al.*, 2020; Zeng *et al.*, 2022). A CCT-based three-stage management system has been proposed to optimise the decision-making of green SCM members (Huang *et al.*, 2021).

4.4.3 Technical development

The development of technologies improves successful LZC SCM applications (Hussain *et al.*, 2020; de Vargas Mores *et al.*, 2018; Zvezdov and Hack, 2016).

Industry 4.0 technologies have been advancing. BCT takes advantage of its irreversibility and trustworthiness and has been widely used and developed recently (Khan *et al.*, 2021; Tawiah *et al.*, 2022; Zeng *et al.*, 2022). The development of the consortium BCT facilitates data sharing among authorised SCM members (Manupati *et al.*, 2020; Sundarakani *et al.*, 2021); BCT can also trace and automatically monitor carbon asset data by smart contracts for SCM optimisation (Diniz *et al.*, 2021; Manupati *et al.*, 2020; Tawiah *et al.*, 2022). Meanwhile, BDA methods have been applied to traditional database management systems, Web and unstructured data analysis and feature data analysis to help with predictive analytics (Kaur and Singh, 2018; Sundarakani *et al.*, 2021). CCT has been developed to provide three service delivery models with the deployment models of public, private, community and hybrid clouds (Singh *et al.*, 2015; Xing *et al.*, 2016). Scientists have energised AM, and new AM techniques, such as elective laser sintering, enable effective configurations and production in SCM (Li *et al.*, 2017).

Decarbonisation technologies have also been developing continuously. CCUS is expected to commercialise in the power industry though it is still at a laboratory scale (Yao *et al.*, 2021). After years of research, the development and cost plummet of the photovoltaic system have enabled its diffusion to various countries (Tanaka *et al.*, 2018; Vallentin and Viebahn, 2010).

4.4.4 Governmental support

Governmental support can encourage technology adoption (Damoah *et al.*, 2021; Jensen and Govindan, 2014; Zahraee *et al.*, 2019; Zhao *et al.*, 2017). Incentive mechanisms, including subsidies, loan guarantees, tax preferences, certificates of renewable energy, public procurement, government-led applications and price regulations, can encourage enterprises to undertake more corporate social responsibilities (Adaloudis and Bonnin Roca, 2021; Bach *et al.*, 2020; Damoah *et al.*, 2021; Diniz *et al.*, 2021; Olson, 2014; Patchell and Hayter, 2021; de Vargas Mores *et al.*, 2018; Velenturf, 2016; Yao *et al.*, 2021; Zhao *et al.*, 2017). A number of governments incentivise the production of alternative energy, including the USA, Malaysia, Brazil, Denmark and Japan (Olson, 2014; Ravigné and Da Costa, 2021; Vallentin and Viebahn, 2010; Zahraee *et al.*, 2019), while less governmental support for low-carbon technologies in developing countries has been reported (Sadiq Jajja *et al.*, 2021). Table 4 summarises the challenges and enablers in SCM decarbonisation with technology.

4.5 Outcomes

In line with the triple bottom line of the sustainability framework in SCM research (Carter and Rogers, 2008; Zhu *et al.*, 2022), the reviewed papers show that technology-enabled SCM decarbonisation can generate environmental, economic and social outcomes. As shown in the Appendix, two papers discuss only economic performance, five concern environmental performance and none mention social performance alone, as it entered the discussion late (Beske-Janssen *et al.*, 2015). Most articles (34 out of 48) focus on environmental and economic outcomes, and seven research studies discuss all three aspects.

4.5.1 Environmental outcomes

It has been proved that low-carbon practices with technology can deliver positive environmental outcomes. Environmental performance can be measured by the carbon footprint. Environmental efficiency, calculated as the ratio of net income and total carbon emissions, can also evaluate firms' environmental performance. Producing no emissions, drones and electric vehicles significantly contribute to carbon reduction in the ozone layer (Damoah *et al.*, 2021). Digital technologies such as BDA and BCT can also reduce paper use and resource waste (Chen *et al.*, 2021; Tawiah *et al.*, 2022, 2022). Generating electricity with renewable energy and using cleaner energy in SCM can reduce the overall carbon footprint and alleviate the carbon pressure (Boschiero *et al.*, 2019; Mastos *et al.*, 2020). The final waste from using renewable resources can provide nutrient-rich compost for agriculture (Hussain *et al.*, 2020).

However, environmental challenges still exist. Electricity generation mechanisms relying on fossil fuels can unleash pollution, even though electric vehicles have zero emissions (Sadiq Jajja *et al.*, 2021). Also, the production of renewable energy sources may derail the environment, such as farmlands and wildlife habitats (Olson, 2014).

4.5.2 Economic outcomes

Low-carbon SCM practices with technology have been proven economical (Llopis-Albert *et al.*, 2021). Procurement and logistics costs can be reduced, including raw material costs, transportation costs, fuel consumption rates, ordering costs and inventory holding costs (Gružauskas *et al.*, 2018; Kaur and

Table 4 Barriers and enablers

No.		Details	References
1	*Barriers and challenges*		
1.1	Technical problems	Technical issues and shortages that bring inconvenience and energy waste in the practices	Bento *et al.* (2021); Sadiq Jajja *et al.* (2021); Zahraee *et al.* (2019)
1.2	High costs	The adoption of technologies can be halted because of high relevant costs and low profits expectation	Jensen and Govindan, (2014); Llopis-Albert *et al.* (2021); Tanaka *et al.* (2018)
1.3	Lack of data	The lack of adequate data can limit the outcomes of research and practices	Cantillo *et al.* (2022); Liu, (2019); Subramanian *et al.* (2015)
1.4	Privacy and ethical issues	The concerns of privacy, security and trust in the SCM practices can be problematic	Patchell and Hayter, (2021); Subramanian *et al.* (2015)
2	*Enablers*		
2.1	LCA research	Life cycle assessment research can improve carbon accuracy	Boschiero *et al.* (2019); Singh, (2015); Xing *et al.* (2016)
2.2	Optimisation research	Mathematical modelling of optimisation research help enhances the use of technologies and decision-making	Huang *et al.* (2021); Lim *et al.* (2020); Thomas and Mishra, (2022)
2.3	Technical development	Technology development overtimes gradually improve the application and economic performance of SCM practices	Khan *et al.* (2021); Tawiah *et al.* (2022); Zeng *et al.* (2022)
2.4	Governmental support	Support and incentives provided by governments increase the willingness and performance of organisations	Adaloudis and Bonnin Roca, (2021); Diniz *et al.* (2021); Olson, (2014)

Singh, 2018). Costs for intermediaries and paper-based offices can be minimised using BCT (Tawiah *et al.*, 2022). Thomas and Mishra (2022) found that 3D printing technology and renewable energy can yield greater profits for the SCM under the carbon cap policy. The efficiency of drones also eases the pressure from demand and reduces total waste, lowering the total costs (Damoah *et al.*, 2021). However, with technical development, the price of natural gas has fallen dramatically compared with the price of alternative energy, leading to a total financial deficit (Olson, 2014). Additionally, the costs for integrated designs are difficult to assess.

4.5.3 Social outcomes

Aligned with Do *et al.*'s (2021) conclusion of the leading indicators of social impact assessment, the reviewed articles show that health and safety, as well as job creation, can be achieved by adopting low-carbon technologies in SCM. Traffic burden can be reduced using IoT technology in logistics activities (Liu *et al.*, 2019). Furthermore, the technology project in the medical supply chain contributes to lifesaving. The adoption of medical drones in the health care SCM allows practitioners to deliver supplies to their patients in a few minutes (Damoah *et al.*, 2021).

Meanwhile, low-carbon SCM practices can preserve societal benefits by creating new job opportunities and a knowledge-sharing environment (Damoah *et al.*, 2021; Jensen and Govindan, 2014). Some stakeholders may not be aware of the importance of low-carbon activities but are guided to follow environmental competitors and learn about decarbonisation to obtain orders and help curb carbon emissions (Singh *et al.*, 2018). Furthermore, the transparency brought by technologies, together with unmodifiable data, can help governments track SCM processes and improve social integrity (Tawiah *et al.*, 2022)

Moreover, the question researchers are wrestling with is the interaction between performances. Good carbon-reduction performance may lead to a circularity index, but increasing the order quantity, together with high costs, can offset the environmental benefits (Olson, 2014; Thomas and Mishra, 2022) (Table 5).

5. Discussion

In this section, an integrated theoretical model of technology-enabled SCM decarbonisation based on the DOI theory and the TOE framework introduced (Section 2) is developed, integrating the key themes identified above. Based on the thematic analysis and conceptual model, the scope for future studies, policy and organisational implications are discussed in the following subsections.

5.1 Development of an integrated conceptual framework

The conceptual model aims to provide a more comprehensive understanding of the topic and explain the relationship between themes. As proposed by Hameed *et al.* (2012), the DOI model consists of two main processes: *pre-adoption* of technology and *post-adoption* (Cruz-Jesus *et al.*, 2019). Extending on this, we develop two steps: *Pre-Adoption* (TOE drivers) and *post-adoption* (adoption: technology-enabled low-carbon SCM practices and impacts/performances), to answer the research questions. The details of our conceptual framework are discussed in the following sections, as shown in Figure 5.

5.1.1 Pre-adoption stage

For the *pre-adoption* stage, based on the review and TOE framework, we code the drivers into technological, environmental and organisational contexts (Awa *et al.*, 2017; Tornatzky *et al.*, 1990). In the technological context, Industry 4.0 and decarbonisation technologies attract SCM members with key DOI factors: compatibility, complexity and relative advantage. The environmental context includes the external impacts from international awareness, regulatory environment and stakeholder pressure. At the organisational level, business scope and enterprise size play significant roles.

We also find that the growing attention from the international community is an alarm bell, calling on governments to reduce carbon emissions (Bach *et al.*, 2020;

Table 5 Outcomes

No.	Outcomes	Details	References
1	*Environmental outcomes*		
1.1	Carbon emission	Fewer carbon emissions can be achieved with the use of technologies in SCM	Damoah *et al.* (2021); Gružauskas *et al.* (2018)
1.2	Ecosystem	The implementation can impact the ecosystem such as wildlife habitats	Olson, (2014); Sadiq Jajja *et al.* (2021)
2	*Economic outcomes*		
2.1	Relevant costs	Costs for production, intermediaries and other SCM processes can be reduced	Kaur and Singh, (2018); Llopis-Albert *et al.* (2021)
2.2	Market profits	The technology used can influence firms' income and market status	Olson, (2014); Thomas and Mishra, (2022)
3	*Social outcomes*		
3.1	Health and safety	With the help of technology, services and products can be provided to people in need	Damoah *et al.* (2021); Liu, (2019)
3.2	Job creation	More jobs and education opportunities can be provided with the SCM development	Jensen and Govindan, (2014); Singh, (2015)
3.3	Social integrity	Governments can track the whole SCM process with unmodifiable data sources	Patchell and Hayter, (2021); Tawiah *et al.* (2022)

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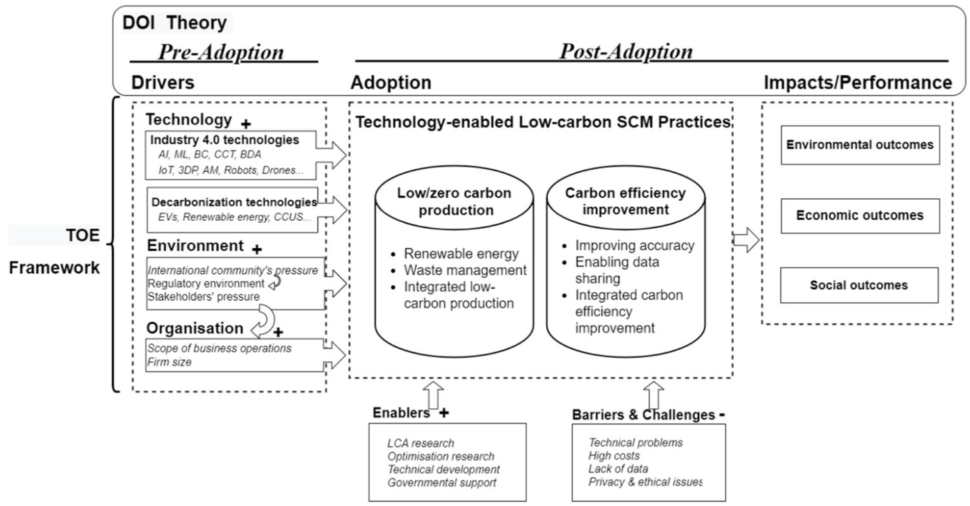
Figure 5 Conceptual framework



Lamba and Singh, 2019; Shen et al., 2017). Regulatory requirements can influence firms' potential financial prospects and business operations, forcing them to conduct low-carbon SCM activities (Palak et al., 2014; Thomas and Mishra, 2022). Therefore, we use arrows to indicate the relationships between drivers.

5.1.2 Post-adoption stage

The *post-adoption* stage is also aligned with the basic DOI model, consisting of technology adoption and relevant impacts, as introduced in Section 2. For a more comprehensive understanding, we consider the ex-post enablers and barriers during SCM technology adoption.

In the adoption process, technology-enabled low-carbon SCM practices are classified into two types: LZC production and carbon efficiency improvement. To decarbonise production, renewable energy and high-tech waste management have been developed (Melander and Pazirandeh, 2019). However, how to effectively reuse and recycle materials is still under research (Adaloudis and Bonnin Roca, 2021; Hussain et al., 2020). Furthermore, to achieve cleaner production, renewable energy can be used as the energy source for other technologies, such as 3D printing, CCT and CCUS (Patchell and Hayter, 2021; Thomas and Mishra, 2022; Yao et al., 2021). Technologies can also assist in improving SCM carbon efficiency. The carbon footprint can be accurately calculated using digital technologies (Singh et al., 2015; Xing et al., 2016; Zvezdov and Hack, 2016). For SCM data sharing, technologies such as BDA, BCT and AM can enable utilisation, traceability and transparency (Gholizadeh et al., 2020; Lamba and Singh, 2019; Li et al., 2017). Digital and physical technologies can be integrated to improve SCM carbon efficiency (Gružauskas et al., 2018; Liu et al., 2019; Sundarakani et al., 2021).

Considering challenges, technical issues and high costs are two key obstacles. For SMEs and SCM members in less developed areas, multiple technical limitations have been reported due to the lack of knowledge, resources and capital (Hussain et al., 2020; Xing et al., 2016). Meanwhile, the technological drawbacks and complexities cannot be ignored (Huang et al., 2021; Lamba and Singh, 2019). Data shortages and ethical issues are inevitable at the current stage and negatively impact practices (Lim et al., 2020; Patchell and Hayter, 2021).

However, during adoption, enablers have positive impacts on technology adoption. We identify LCA and optimisation research as two main enablers for SCM decarbonisation, as they provide extra support and can enhance SCM performance (Melander and Pazirandeh, 2019; Singh et al., 2015). Although creating technical issues, technological development generates more help for practices. Governments offer support in various ways. Two arrows are used to show that both barriers and enablers can influence SCM practices.

Outcomes can be achieved after implementing low-carbon SCM practices. In addition to economic impacts (Mokyr, 1990), we conclude the environmental and social impacts from the reviewed papers. Environmental performance is paramount, aligns with the research topic. Besides carbon reduction, it has been noted that technologies may damage the ecological environment (Olson, 2014). Most organisations adopt green SCM practices with technology only when they expect potential economic profits. However, not all of them can eventually reach their goals (Adaloudis and Bonnin Roca, 2021). Although with longer computing time, the analytical target cascading cloud-based model can enable organisations to achieve both: obtaining a total profit with lower CO_2 emissions compared to the centralised method, and providing more information to SCM members for a higher total profit (Huang et al., 2021). Finally, social outcomes demonstrate the worthiness of adoption practices, as they can bring material and spiritual benefits to citizens (Damoah et al., 2021; Patchell and Hayter, 2021).

5.2 Future research directions

We have investigated technology-enabled SCM decarbonisation in this literature review and identified several gaps. Thus, further efforts should be made to improve future research.

5.2.1 Multi-objective research

Although decarbonisation is the key objective for low-carbon SCM, due to the complexity of implementation and firms' motivation and conflicts, multiple objectives should be taken into account to ensure feasibility (Singh *et al.*, 2018). A large number of research works have considered a single objective in their optimisation methods, such as the minimisation of the carbon footprint (Singh *et al.*, 2015), the minimisation of total costs (Zeng *et al.*, 2022) or the maximisation of profits (Thomas and Mishra, 2022). However, with the complexity of SCM decarbonisation, it can be more scientific and viable to conduct multi-objective research in the future (Zeng *et al.*, 2022). Economic and environmental purposes should both be perceived (Gružauskas *et al.*, 2018; Manupati *et al.*, 2020), along with the concerns of other participants (Thomas and Mishra, 2022; Zhao *et al.*, 2017). For instance, future research can investigate multiple objectives, such as emissions, marketing decision-making, supplier selection and product family design, for different members in a multilevel SCM, by developing a multi-stage management system (Huang *et al.*, 2021). Such research can also be conducted in a delivery study by designing a multi-layer architecture that looks into routes, matches and emissions and delivery costs (Lim *et al.*, 2020).

5.2.2 Technology integration

The integration of technologies with low-carbon SCM practices can be a future research direction. Among our 48 reviewed studies, as listed in the Appendix, only 8 papers have discussed technology integration in SCM decarbonisation. Research on the effectiveness of technology integration in SCM decarbonisation can be conducted in the future to synthesise the advantages of different technologies. Integrating digital technologies can support decision-making and improve SCM decarbonisation (Sundarakani *et al.*, 2021). For instance, CCT can be adopted with BDA in the automotive SCM and the food SCM to provide effective and low-carbon tools at lower costs (Llopis-Albert *et al.*, 2021; Singh *et al.*, 2018). Additionally, the integration can enhance the adoption of renewable energy. With reliable tracking and validation systems, BCT can overcome the current drawbacks and re-energise the renewable energy market (Diniz *et al.*, 2021). To power cloud data centres, companies have negotiated long-term contracts for renewable energy (Patchell and Hayter, 2021).

5.2.3 Computational efficiency for supply chain management decarbonisation

Improving computational efficiency for large-sized or complex problems can be a critical challenge (Huang *et al.*, 2021). It has been reported that a parallel and distributed computing environment can significantly contribute to the computing efficiency of a low-carbon SCM system with multiple members (Huang *et al.*, 2021). In addition, to reduce the computation time for SCM decarbonisation practices, future studies can also use an extended range for the relaxation of their models (Gholizadeh *et al.*, 2020). Mixed integer linear programs can provide an optimal solution with less computational time. In addition, Kaur and Singh (2018) proposed a heuristic for BDA that can provide solutions close to the optimal results for low-carbon procurement and logistics, and they have called for more new heuristic approaches in the future.

5.2.4 Research with multiple data sources

According to our reviewed papers, technology-enabled SCM decarbonisation studies are dominated by case study research (34 papers) that can provide real-world case evidence, as shown in Figure 3. However, nearly half of them do not specify the source of data (from surveys, interviews, simulation or secondary data), and most of the rest only consider single-source data, which may not be effective and objective in solving complex real-world problems (Damoah *et al.*, 2021). Therefore, multiple data sources can be helpful for future research. A large amount of first and secondary information can be collected through various other sources, such as meetings, workshops, reports, public domain information, mass media information and expert views (Llopis-Albert *et al.*, 2021).

5.3 Policy implications

For the government, supporting technology adoption in SCM can be a win-win prospect (Melander and Pazirandeh, 2019; Velenturf, 2016). On the one hand, proactive governmental incentives can be helpful for a low-carbon SCM by covering part of the economic costs in the pilot stage to reduce the inherent risk and carbon emissions (Yao *et al.*, 2021; Yu *et al.*, 2021; Zhao *et al.*, 2017). Firms using cleaner energy can obtain financial benefits from national subsidies (Cantillo *et al.*, 2022; Jensen and Govindan, 2014). On the other hand, SCM technologies can alleviate national economic, environmental and social pressures in areas such as health care SCM, emissions registry of national GHG protocol and the energy market (Damoah *et al.*, 2021; Diniz *et al.*, 2021). Additionally, although it is questionable whether technology development may displace a number of jobs and squeeze workers' living standards, a range of personnel from field engineers to auxiliary staff are needed with low-carbon technologies in SCM. Employment and relevant training can empower employees and improve a country's economic and social sustainability (Damoah *et al.*, 2021). Cooperation between private firms and the public sector can enhance governmental and corporate performance (Damoah *et al.*, 2021) and support fair manipulation (Tawiah *et al.*, 2022).

However, the carbon policy should be taken seriously. SCM members may not change their minds about adopting low-carbon practices under small carbon tax rates, and the reliance on governmental subsidies may be problematic in the long term (Jensen and Govindan, 2014; Olson, 2014; Palak *et al.*, 2014). Worse still, some permanent green energy jobs require many subsidies and can destroy other jobs (Olson, 2014). Therefore, regulation and standardisation, experimentation and data sharing and workforce development all need to be emphasised (Adaloudis and Bonnin Roca, 2021). Policy-makers should formulate flexible, economically justified policies that encourage SCM members to adopt low-carbon technologies, develop competitiveness while limiting companies with outsized pollution (Olson, 2014; Sadiq Jajja *et al.*, 2021; Tawiah *et al.*, 2022; Velenturf, 2016) and take into account the whole life cycle carbon emissions (Ravigné and Da Costa, 2021). Supporting education on low-carbon technologies and research and development activities can benefit a country and other countries in need (Bach *et al.*, 2020; Bento *et al.*, 2021; Khan *et al.*, 2021; Lundie *et al.*, 2019; Vallentin and Viebahn, 2010). Additionally, governmental subsidies can be provided as support at the organisations' starting points and reduced at the technology maturity stage to ensure a fair market-oriented SCM environment (Yao *et al.*, 2021). With the decreasing carbon cap, increasing carbon tax or carbon prices and the introduction of new instruments or disclosure requirements, enterprises tend to minimise their carbon emissions (Lundie *et al.*, 2019; Palak *et al.*, 2014). Palak *et al.* (2014) also report that compared with carbon offset, a carbon cap-and-trade mechanism is more efficient because of the allowance of potential profits.

A country can consider a state-initiated development strategy to improve SCM decarbonisation. Less developed economies should prioritise upgrading technology and knowledge to stave off negative economic performance (Khan *et al.*, 2021). Alternative resource utilisation can be enhanced according to geographical distribution and the growing cycles of natural resources (Bach *et al.*, 2020; Jensen and Govindan, 2014; de Vargas Mores *et al.*, 2018). For instance, every year, approximately one-fifth of the total biomass in the USA can be used to pave the way for biofuel production (Palak *et al.*, 2014). The development of low-carbon technologies can ensure sufficient national resource supply to satisfy the growing demand, create more jobs and reduce the dependence on imports, such as a local biomethane industry (Ravigné and Da Costa, 2021). Incentives for renewable energy technologies in SCM can improve technology exports and build bilateral partnerships with other countries (Tanaka *et al.*, 2018; Vallentin and Viebahn, 2010).

5.4 Managerial implications

SCM members should take a long-term view in adopting low-carbon technologies (Gružauskas *et al.*, 2018). CCUS technology and low-carbon logistics implementation are all costly at the beginning but can generate profits for reinvestment in the later stages (Gružauskas *et al.*, 2018; Yao *et al.*, 2021). In addition, steelworks can also benefit long-term by purchasing raw materials with lower grades to reduce costs and capture more CO_2 for sale (Yao *et al.*, 2021).

With a limited budget, SMEs can adopt digital technologies, such as ERP systems, as a cost-effective choice (Zvezdov and Hack, 2016). In addition, they can easily obtain start-up CCT from third-party service providers and other online platforms without heavy investments in an IT infrastructure (Singh *et al.*, 2015; Xing *et al.*, 2016).

In addition to technologies, the choice of transport tools and packaging can also be carbon-efficient. Research has revealed that rail and ship freight transport have a less relevant carbon footprint than lorries (Boschiero *et al.*, 2019; Singh *et al.*, 2015). Palak *et al.* (2014) have reminded us that barge and rail emissions are smaller than trucks', while their total emissions for long hauls may be higher. Reusable packaging is an attractive option for reducing carbon emissions and cumulative energy demand (Boschiero *et al.*, 2019).

Research also calls for cooperation along the supply chain to achieve cost and carbon reductions for all SCM participants (Hussain *et al.*, 2020; Lundie *et al.*, 2019; de Vargas Mores *et al.*, 2018; Velenturf, 2016; Zheng *et al.*, 2021), in line with existing review research (Rossi *et al.*, 2013). Technology can energise and systematically manage low-carbon cross-enterprise collaboration (Lundie *et al.*, 2019; Melander and Pazirandeh, 2019; Xing *et al.*, 2016).

6. Conclusions

This paper seeks to provide a clear understanding of the role of technologies in SCM decarbonisation in the literature. We have identified critical themes by reviewing relevant SCM research and theories and proposed a conceptual model with drivers, practices, barriers, enablers and outcomes, building on TOE and DOI theories to answer the research questions.

Overall, our paper makes several contributions. First, it may be the first research to investigate technology-enabled SCM decarbonisation systematically. Second, by applying the DOI model in the overall framework and the TOE theory in the drivers for SCM technology adoption, this study considers the *pre-adoption* (drivers) and *post-adoption* (adoption, enablers, barriers, impacts) stages and their relationships to advance the understanding of the research topic. This review significantly enriches the SCM research and provides an integrated conceptual model for further study. Third, we suggest future directions for future SCM decarbonisation research and provide a comprehensive roadmap for managers and policy-makers to assess their decarbonisation strategies.

There are some limitations in this review. To ensure the quality of papers, our inclusion criteria only consider English journals in the *AJG 2021*, while studies published in other journals also provide important research value. Additionally, we target papers focussing on decarbonisation, which may result in missing some of the more comprehensive SCM research.

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Appendix

Table A1 Descriptive analysis of the reviewed 48 papers

No.	Authors	Technology	Year	Location	Method	Enablers	Outcomes	Practices	Objectives
1	Manupati, VK; Schoenherr, T; Ramkumar, M; Wagner, SM; Pabba, SK; Singh, RIR	Blockchain	2020		Case study, Modelling and simulation	TD	EN, EC	CE	This article developed a distributed ledger-based blockchain approach to monitor supply chain performance, optimise emission levels and operating costs in multi-headed supply chains under carbon tax policies to deliver optimal outcomes for supply chains
2	Lim, MK; Wang, JX; Wang, C; Tseng, ML	IoT, Cloud Computing, Shared vehicles	2020	China	Case study, Modelling		EN, EC	CE	This study considered a two-stage shared vehicle path problem in an IoT environment and develops a unified IoT-based architecture for this problem, finding that shared distribution has a positive effect on improving social vehicle resource utilisation and customer service
3	Gholizadeh H., Fazlollahtabar H., Khalilzadeh M.	Big data	2020	Iran	Modelling		EN, EC	CE	This paper investigated a comprehensive insight into a common logistics model for sustainable supply chains in the context of big data, proposing new fuzzy stochastic hybrid models to help companies make their operations more sustainable to achieve economic development goals
4	Thomas, A; Mishra, U	3DP, Renewable energy	2022		Modelling, Case study	OR	EN, EC	CE	This paper examined the plastics reform industry, maximizing profits by reducing costs, and circular supply chain modeling by implementing green technologies to reduce emissions, and 3 D printing technologies to minimize waste
5	Zeng, M; Sadeghzadeh, K; Xiong, T	Blockchain	2022	China	Modelling, Case study	TD	EN, EC	CE	Under the blockchain environment, this study proposed a three-echelon SC integrated scheduling model, considering the production capacity and multi-product with different delivery time factors to minimise the total cost in production and transportation
6	Li, Y; Jia, GZ; Cheng, Y; Hu, YC	3DP	2017		Modelling, Simulation	TD	EN, EC	CE	This paper compared a spare parts supply chain using 3DP additive manufacturing with a traditional supply chain to explore its impact on supply chain performance and to quantitatively examine the superiority of using AM in the spare parts supply chain
7	Liu S., Zhang Y., Liu Y., Wang L., Wang X.V.	IoT	2019		Modelling, Case study	OR	EN, EC, SO	CE	This paper proposed an IoT-enabled dynamic information-driven optimisation method for logistics management vehicles' to improve utilisation rate and reduce the costs and fuel consumption
8	Zahraee S.M., Golroudbary S.R., Shiwakoti N., Kraslawski A., Stasinopoulos P.	Biomass	2019	Malaysia	Modelling, Simulation, Case study, Second-hand data	GS	EN	LZCP	This paper aimed to assess the effect of certain interventions on the environmental sustainability of the palm oil biomass supply chain with a dynamic stock-and-flow simulation model to estimate the GHG emissions to design an effective sustainable strategy for the biomass industry in Malaysia
9	Zhao R., Liu Y., Zhang N., Huang T.	Big data	2017	China	Modelling, Case study	OR, GS	EN, EC	CE	This study offered a multi-objective optimization model and a case study of the sanitary appliance supply chain network to provide insight into green SCM while minimizing the inherent risks that generally associated with carbon emissions and economic cost
10	Huang Y., Gao K., Wang K., Lv H., Gao F.	Cloud computing	2022	China	Modelling, Case study	OR	EN, EC	CE	In this paper, a formulation of a coordination problem by a three-stage cloud-based management system was presented, using a hierarchical ATC model and a case study to prove that it can closely achieve optimisation results with lower CO2 emissions
11	Palak, G; Eksioglu, SD; Geunes, J	Biomass	2014	USA	Modelling, Case study, Second-hand data		EN, EC	LZCP	This article studied the supplier and transportation mode selection problem under a number of carbon regulatory mechanisms in a biomass supply chain
12	Damoah, IS; Ayakwah, A; Tingbani, I	AI, drone	2021	Ghana	Case study, Interview	GS	EN, EC, SO	LZCP	This study examined the adoption of AI-enhanced medical drones in the healthcare supply chain and found that they not only improve the SC of healthcare services, but also contribute to sustainability
13	Jensen J.K., Govindan K.	Biomass	2014	Denmark	Case study, Interview, Second-hand data	GS	EN, EC	LZCP	The objective of this paper was to assess the financial impact of food processing companies associated with bioenergy applications and greenhouse gas emissions
14	Singh, A; Kumari, S; Malekpoor, H; Mishra, N	Big data, cloud computing	2018		Modelling, Case study		EN, EC, SO	CE	This paper focused on eco-friendly supplier selection for beef cattle by abattoirs and processors, showing how the carbon footprint generated by beef farms can be taken into account along with breed, age, diet, average weight of cattle etc. and price through a big data cloud-based framework

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Table A1

No.	Authors	Technology	Year	Location	Method	Enablers	Outcomes	Practices	Objectives
15	Sundarakani, B; Ajaykumar, A; Gunasekaran, A	Big data, Cloud computing, Blockchain	2021	United Arab Emirates	Case study	TD	EN, EC	CE	This paper highlighted the key role of analytics in the supply chain space, demonstrating the implications of big data and blockchain analytics in logistics and supply chain
16	Tawiah, V; Zakari, A; Li, G; Kyiu, A	Blockchain	2022	USA	Modelling	TD	EN, EC, SO	CE	This research examined the impact of blockchain technology on the environmental efficiency of the firms with the data of 103 large US-listed firms between 2015 and 2019
17	Zvezdov D., Hack S.	ICT	2016	France	Case study, Interview, Multi-data source	TD	EN, EC	CE	This paper analysed the ERP system in a multinational company to leverage existing information assets for a highly automated monthly CF solution of a large product portfolio
18	Singh A., Mishra N., Ali S.I., Shukla N., Shankar R.	Cloud computing	2015	UK	Case study	LCA	EN	CE	This article proposed an integrated approach of optimizing and measuring carbon footprint of entire beef supply chain by using Cloud Computing Technology
19	Melander L., Pazirandeh A.	Big data	2019	Sweden	Case study, Interview, Secondary data	LCA, TD, GS	EN, EC	CE	The study explored green innovation collaboration based on 11 case studies conducted in high-tech companies and found that firms share green innovation knowledge through horizontal collaboration and their extended networks, and that digitization, connectivity and big data can improve environmental sustainability
20	He, QR; Chen, PK	Battery-electric	2022	China	Modelling, Case study, Survey	TD	EN, EC	LZCP, CE	This paper built a supplier evaluation system for Chinese electric vehicle battery manufacturers, based on green collaboration, to control carbon emission problem in production
21	Behnamfar, R; Sajadi, SM; Tootoonchy, M	AI	2022		Modelling, Simulation	TD, OR	EN, EC	LZCP	This study used machine learning method to evaluate and prove the influence of carbon emission control policies on firms' production and inventory management
22	Xing K., Qian W., Zaman A.U.	Cloud computing	2016	Australia	Case study, Second-hand data	LCA, TD	EN	CE	Based on cloud manufacturing paradigm and previous studies, this paper proposed a multimodal and multilevel cloud platform for supply chain members to access, and share dynamic life cycle information and evaluate their environmental performance
23	Lamba K., Singh S.P.	Big data	2019		Modelling	OR	EN, EC	CE	This paper modelled the supplier selection problem for multi-period, multi-product, multi- sourcing scenario, incorporating the carbon emissions using a cap-and-trade policy
24	Ravigné E., Da Costa P.	Biomass	2021	France	Simulation, Case study	GS	EN	LZCP	This article offered a microsimulation of the adoption of compressed natural gas (bio-sourced and fossil) in heavy-duty vehicles based on real French data on industrial flows in 2018 from the automotive manufacturer Renault and pointed out only bio-sourced gas can be favourable
25	Yao	CCUS	2021	China	Simulation, Second-hand data	GS	EN, EC	LZCP	This paper applied a System Dynamics method to analyse technical and economic feasibility of applying carbon capture from the perspective of iron and steel supply chain, and identified three key variables of the system
26	Vallentin D., Viebahn P.	Solar energy	2010	Germany	Case study, Second-hand data	GS	EN, EC	LZCP	The paper focused on the economic opportunities of German technology providers, analysed possible value creation effects resulting from a global deployment of CSP until 2050
27	Lundie S., Wiedmann T., Welzel M., Busch T.	Wind energy	2019	International	Modelling, Case study		EN, EC	LZCP	This paper aimed to support firms' sustainability using an extended multi-regional input-output model to analyse the global supply chains of products and projects for selected impact indicators, with a case study of a single wind energy company
28	Tanaka, K; Inoue, T; Matsuhashi, R; Yamada, K	Solar energy	2018	Japan	Case study, Second-hand data	TD	EC	LZCP	This research traced worldwide flow as related to Japan for the manufacture and use of solar power systems and estimated detailed retrospectively induced economic costs, combining process-engineering approaches with existing value chain analysis
29	Olson E.L.	Solar energy	2014	USA	Case study, Second-hand data	GS, LCA	EN, EC, SO	LZCP	This research used a Green Innovation Value Chain (GIVC) provides a possible framework to determine the diffusion prospects of the photovoltaic solar power chain through environmental and financial comparisons to conventional alternatives across the separate chain links comprised of manufacturers, distributors, customers, government, and the environment

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Table A1

No.	Authors	Technology	Year	Location	Method	Enablers	Outcomes	Practices	Objectives
30	Ponstein H.J., Meyer-Aurich A., Prochnow A.	renewable energy	2019	Italy	Modelling, Case study, Survey, Interview, Second-hand data		EN	LZCP	The LCA method has been proposed in this study to analyse the GHG emissions and energy requirements in the post-harvest life of apples in two commercial apple packinghouses and point out the importance of packaging and transport tools
31	Diniz, EH; Yamaguchi, A; dos Santos, TR; de Carvalho, P; Alego, AS; Carvalho, M	Blockchain, Renewable energy	2021	Brazil	Interview, second-hand data	TD	EN, EC	LZCP, CE	This research used a Design Science Research (DSR) methodology to combine the knowledge of business participants and environmental experts to understand project issues, propose and evaluate a blockchain-based artefact, and analyse its contribution
32	Patchell J., Hayter R.	Cloud computing, Renewable energy	2021	USA	Multiple secondary data	GS	EN, EC, SO	LZCP, CE	Using Williamson's framework of institutional change, the four interdependent institutional levels of embedded values, regulatory environment, governance and resource allocation have been linked to explain firms' powering cloud data centres (DCs) with renewable energy (RE)
33	Kaur H., Singh S.P.	Big data	2018		Modelling	TD	EN, EC	CE	This paper proposed an environmentally sustainable procurement and logistics MINLP and MILP model for a supply chain, with a heuristic to solve the large sized problems involving big data
34	Llopis-Albert C., Rubio F., Valero F.	EVs, Big data, Cloud Computing	2021	Spain	Case study, Interview, Survey, Second-hand data	TD	EC	LZCP, CE	The study presented an application of fuzzy-set qualitative comparative analysis to analyse the future impact of digital transformation on business performance models and the different actors' satisfaction in the automotive industry
35	Bach, H; Bergek, A; Bjorgum, O; Hansen, T; Kenzhegaliyeva, A; Steen, M	Battery-electric	2020	Norway	Case study, Interview	GS	EN, EC	LZCP	This article introduced the Technology Innovation System (TIS) framework to battery power and hydrogen energy solutions for Norwegian coastal marine transport, distinguishing between different innovative system functions
36	Khan, SAR; Razzaq, A; Yu, Z; Miller, S	Blockchain	2021	China and Pakistan	Survey	TD	EN, EC	CE	This study investigated the role of blockchain technology in the circular economy practices of companies involved in cross-border supply chain operations within China and Pakistan and its impact on ecological performance, further leading to organisational performance
37	Mastos, TD; Nizamis, A; Vafeiadis, T; Alexopoulos, N; Ntinas, C; Gkortzis, D; Papadopoulos, A; Ioannidis, D; Tzovaras, D	IoT	2020	Greece	Case study	TD	EN, EC	CE	The aim of this paper was to evaluate solutions developed for SSCM in relation to the Industry 4.0 standard, focusing on the use of IoT for scrap metal management and examining the role of the Internet of Things in SSCM
38	Cantillo, V; Amaya, J; Serrano, I; Cantillo-Garcia, V; Galvan, J	AFVs	2022	Colombia	Modelling, Case study, Survey	TD	EN, EC	LZCP	This paper presented the results of an assessment of the demand for trucks using alternative fuels in Colombia. Attributes related to cost are most relevant when selecting a truck, with emission levels being a secondary consideration, as are technical support, equipment, technology and manufacturer brand
39	Bento N., Fontes M., Barbosa J.	Renewable energy	2021	Portugal	Conceptual study, Survey, Secondary data	GS	EN, EC	LZCP	This research conducted a survey of 237 companies that have participated in R&D and demonstration activities in marine renewable energy technologies in Portugal and study the factors for using renewable energy
40	Shen B., Ding X., Chen L., Chan H.L.	Renewable energy	2017	China	Case study, Interview, Secondary data, Modelling	GS	EN, EC	LZCP	In this paper, two case studies of Chinese textile companies were conducted to examine the impact of energy consumption constraints on their production and operations management, and a simple analytical model of a low carbon supply chain was developed
41	Jajja, MSS; Hassan, SZ; Asif, M; Searcy, C	Battery-electric	2021	Pakistan	Case study, Interview, Survey	GS	EN, EC	LZCP, CE	This paper developed a framework to explore the readiness of the upstream value chain players of battery electric vehicles in Pakistan and provided a discussion on pathways for the transition
42	Gružauskas V., Baskutis S., Navickas V.	autonomous vehicles	2018	Lithuania	Interview, Simulation, Secondary data		EN, EC	CE	The authors developed an economic model of food supply chain, with the use of a specialist interview and literature analysis, to achieve cost effective performance and sustainable supply chain
43	Velenturf A.P.M.	Biomass	2016	UK	Case study, Interview, Secondary data	GS	EN, EC	LZCP	This article compared five case studies and discussed the ways companies develop relations with biowaste resource suppliers or clients, identified two networking strategies and proposed insights

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Table A1

No.	Authors	Technology	Year	Location	Method	Enablers	Outcomes	Practices	Objectives
44	Subramanian N., Abdulrahman M.D., Zhou X.	Cloud computing	2015	China	Survey, Conceptual study	TD	EN, EC	CE	This study developed and tested a conceptual model for empirically examining the green and cost benefits of integration between cloud service providers and small and medium-sized logistics service providers in China
45	de Vargas Mores G., Finocchio C.P.S., Barichello R., Pedrozo E.A.	Biomass	2018	Brazil	Case study, Interview	GS, TD	EN, EC	LZCP	This study conducted an in-depth case study was conducted with a Brazilian petrochemical company to analyse the innovation process in the production of green plastic with renewable resource
46	Adaloudis, M; Roca, JB	3DP	2021	Europe	Interview	GS, TD	EN, EC, SO	CE	This study applied grounded theory methods to analyse the trade-offs of using 3 D concrete printing between environmental, economic, and social sustainability, and how firms ’ decisions impact these trade-offs
47	Yu Y., Yazan D.M., Bhochhibhoya S., Volker L.	ICT	2021	The Netherlands	Modelling, Case study, Interview, Simulation	TD	EN, EC	LZCP, CE	The research tackled the CE challenge and explored the industrial symbiosis based on the Recycled Concrete Aggregates (RCA) in the context of a concrete waste supply chain in the Twente region of The Netherlands
48	Hussain Z., Mishra J., Vanacore E.	Biomass	2020	UK	Case study, Interview	TD	EN, EC	LZCP	This paper highlighted how biological waste materials can be used in SME for generating the much needed energy and obtaining nutrient-rich compost for agriculture through anaerobic digestion with a case study

Notes: For enablers, TD denotes technical development, OR denotes optimization research and GS denotes government support; for Outcomes, EN, EC and SO denote environmental, economic and social outcomes; for practices, CE denotes carbon efficiency and LZCP denotes low- or zero- carbon production