Technological Forecasting & Social Change 219 (2025) 124262

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

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

Achieving sustainable carbon-neutral supply chain: A perspective of integrating blockchain technology☆

Aditi Saha [a], Rakesh D. Raut [a], Mukesh Kumar [b], Sanjoy Kumar Paul [c], Yangyan Shi [d,e,*], Bhavin Shah [f], Sudishna Ghoshal [g]

[a] Department of Operations and Supply Chain Management, Indian Institute of Management (IIM), Mumbai, Vihar Lake, Powai, Mumbai, Maharashtra 400087, India
[b] Department of Mechanical Engineering, Ganga Memorial College of Polytechnic, Harnaut, Nalanda, 803110, India
[c] UTS Business School, University of Technology Sydney, Sydney, Australia
[d] College of Business Administration, Capital University of Economics and Business, Beijing, China
[e] Macquarie Business School, Macquarie University, Sydney, Australia
[f] Operations and Supply Chain Management Group, Indian Institute of Management Sirmaur, Dhaula Kuan-173031, Distt. Sirmaur, Himachal Pradesh, India
[g] T A Pai Management Institute Bengaluru, Manipal Academy of Higher Education, Manipal, India

ARTICLE INFO

Keywords:
Food industry
Blockchain technology
Carbon-neutral supply chain
Sustainability
Structural equation modeling

ABSTRACT

With the global shift towards a carbon-neutral supply chain (CNSC), blockchain technology (BT) is becoming increasingly significant. The food supply chain (FSC) significantly generates carbon emissions. This study evaluates how the integration of blockchain technology (IBT) is feasible to attain a CNSC. This study also finds the nexus among the sustainable development goals and how they behave between IBT and CNSC. This study presented a new framework based on the resource-based view and dynamic capability, which was tested using structural equation modeling (SEM). A comprehensive online survey was conducted utilizing a questionnaire that gathered responses from 200 individuals employed in the agricultural and food sectors. The finding reveals that the implementation of disruptive BT has a beneficial impact on the FSC by reducing emissions, ensuring safety, improving supply chain performance, minimizing food waste, and boosting consumer trust. Nonetheless, two variables, namely enhance supply chain performance, and build consumer trust, do not contribute to achieving a CNSC, as they enhance operational efficiency and trust, which might not directly result in a decrease in carbon emissions. The study enriches the literature on IBT in FSC to attain a CNSC while making the supply chain network more transparent, agile, and sustainable. It also challenges conventional wisdom by revealing factors that do not lead to a CNSC and guides policymakers to develop strategies to attain a CNSC.

1. Introduction

With an increasing population and growing economy, the world faces the challenge of curbing carbon emissions while its economy booms. COP21 (UNFCCC) has committed to meeting its climate change targets by 2030 with 45 % reductions in emissions and net zero emissions by 2050 as part of the Paris Agreement (Zhang et al., 2021; Net Zero Coalition, 2022). Over 70 countries, including China, the United States, and the European Union, have committed to achieving net-zero emissions by 2050, accounting for approximately 76 % of world emissions. According to the Food and Agriculture Organisation (FAO), the food supply chain (FSC) is on the verge of being the most significant contributor to greenhouse gases (GHGs) from the agri-food system. Additionally, the FAO claims that approximately 14 % of all food produced worldwide is lost before it reaches the retailer, which can occur during on-farm activities, storage, and delivery (FAO, 2019a). Also, food waste generates 3.3 billion tons of carbon dioxide annually worldwide (FAO, 2019b). However, a more sustainable and low-carbon economy can be achieved using Blockchain technology (BT) in the FSC. This technology can improve efficiency, reduce waste, and promote transparency and accountability. These alterations are in line with the larger aims of ecological preservation and can contribute to the

☆ This article is part of a Special issue entitled: 'Management Perspective' published in Technological Forecasting & Social Change.

* Corresponding author at: College of Business Administration, Capital University of Economics and Business, Beijing, China; Macquarie Business School, Macquarie University, Sydney, Australia.

E-mail addresses: aditi.saha.2020@iimmumbai.ac.in (A. Saha), rraut@iimmumbai.ac.in (R.D. Raut), kumarmukesh12me@gmail.com (M. Kumar), sanjoy.paul@uts.edu.au (S.K. Paul), ys102@hotmail.com (Y. Shi), bhavin.shah@iimsirmaur.ac.in (B. Shah), sudishna.ghoshal@manipal.edu (S. Ghoshal).

https://doi.org/10.1016/j.techfore.2025.124262
Received 30 November 2024; Received in revised form 19 June 2025; Accepted 23 June 2025
Available online 3 July 2025

accomplishment of the UN's sustainable development goals (SDGs). Thus, this study contributes to exploring the role of a prominent disruptive technology, i.e., BT, for the carbon-neutral supply chain (CNSC) in between the mediation of several sustainable development practices.

Incorporating sustainability and green practices in supply chain is essential for attaining the environmental, economic and social sustainable goals (Corallo et al., 2023) as well as adding a competitive advantage (Pullman et al., 2009; Ingenbleek and Krampe, 2023). Recent studies have shown that global food systems' environmental impact extends beyond farmers and food suppliers (Saberi et al., 2019; Taghikhah et al., 2021; Mangla et al., 2022). Thus, sustainability issues need to be considered in the broader context of the entire FSC. Organisations need more transparency, real-time analytics, and product and inventory tracking to address food waste and consumer needs. Research from Sapio, on behalf of Zetes, reveals that the current levels of supply chain visibility need to be improved, as a staggering 94 % of organisations surveyed said they need more transparency throughout their supply chain. Only 30 % of businesses have a complete view of products in transit. This makes addressing food waste at each stage of the supply chain difficult. By 2030, SDG 12 calls for a reduction of 50 % in global food waste by retailers and consumers (Lu et al., 2022). Consequently, companies are trying to increase supply chain efficiency, reduce food waste, and make supply chains more sustainable and carbon-friendly.

Emerging technologies like BT can improve the flow and success of supply chains, attain sustainability (Fayezi et al., 2021; Matos et al., 2022), and guide future policies for food systems. BT is a distributed ledger system where the data are stored in blocks that contain a digital signature and timestamp, making the blocks virtually immutable (Parmentola et al., 2022). The integration of BT (IBT) in the food industry can increase consumer trust, production speed, and product efficiency, which helps to meet societal goals. According to Brandenburg (2015), decentralised supply chains incentivise carbon emission reduction without affecting the economic performance of supply chains. In addition to improving global FSC, it can make them more transparent and traceable, enable faster and more cost-effective product delivery, improve real-time coordination between trading partners, and significantly improve record-keeping for all parties involved. Sharing data among the participants in the chain will foster collaboration to address the problem of food loss. By reducing food wastage, IBT will help to gain insights into and improve processes, storage, and logistics. This will enable the attainment of the economic goal.

Moreover, the IBT can facilitate new green production by monitoring and storing data-related activities responsible for excessive carbon emission and environmental degradation. It can also collect real-time data on the whole FSC network and analyze green or low-carbon data for timely decision-making (Saberi et al., 2019), fulfilling the SDGs. Thus, BT has a vast potential to decarbonise the FSC by monitoring, tracing, and reducing emissions. It can transform the FSC, help achieve sustainability, and fulfil a few SDGs by regulating wastage, optimising the supply chain resources, maintaining efficacy, and ensuring a transparent collaboration among the stakeholders for promoting a low-carbon supply chain. Further automated carbon credit tracking systems and smart contracts help in incentivizing sustainable practices, further accelerating the transition towards a CNSC. As environmental protection and SDGs guidelines and regulations become stricter, manufacturers might adopt technological innovations such as BT or upgraded equipment to prevent carbon emissions and pollution (Wang et al., 2021) and head towards a CNSC.

Although previous literature reviews and empirical studies (Feng et al., 2020; Queiroz et al., 2021; Saberi et al., 2019) have discussed integrating BT to attain a sustainable supply chain, the literature seems to be fragmented when it comes to discussing FSC. Most studies focus on BT adoption benefits and challenges in FSC (Feng et al., 2020; Kumar et al., 2023b). It is in agreement with Wamba et al. (2020), who point out that despite the significant attention BT has received, limited research is available in the field of supply chain management, particularly from a sustainability perspective (Benstead et al., 2022). Various research has discussed sustainability, SDGs, BT, and FSC (Parmentola et al., 2022; Calandra et al., 2023; Elahi et al., 2022; Tsolakis et al., 2021; De Villiers et al., 2021; Mangla et al., 2022; Virmani et al., 2022; Mishra et al., 2023). However, there is a gap in the literature when it comes to fully integrating this concept comprehensively. Fewer authors (Singh et al., 2022; Wang et al., 2021; Ball-Burack et al., 2022; Malliaroudaki et al., 2022; Mishra et al., 2023) have discussed the carbon-neutral and low-carbon supply chain concepts in various supply chains, but very few have discussed in the FSC domain (Lin and Guan, 2023; Acampora et al., 2023). The literature shows that although the disruptive BT is being studied in abundance, sustainability and the carbon-neutral quotient are still in a nascent phase. The benefit of integrating BT in FSC that can lead to CNSC complying with SDGs needs to be studied in detail as the world is moving towards a more sustainable economy. This study identifies the research gap that points to a lack of studies emphasising carbon-neutral implementation in the FSC in support of disruptive BT. It also recognises that despite addressing BT and SDGs in some papers, they have not been connected to achieving a CNSC. In addition, it has yet to be explored how adopting BT compliance with SDGs in FSC will lead to achieving a CNSC. Thus, the following research questions (RQs) are framed to fill the research gaps.

RQ1: How does BT help the FSC to improve transparency, traceability, and operational efficiency towards reducing food loss and wastage, thereby meeting the SDGs?

RQ2: How does BT integrate into the FSC to achieve SDGs through a carbon-neutral transition of supply chain?

The study presents an empirical analysis to develop a research model with the help of resource based view (RBV) and dynamic capability view (DCV) theory that help identify the FSC resources and capabilities to gain an edge in the competitive and volatile market. A questionnaire-based survey on 200 Indian agri-food firms helps to verify the research hypothesis to answer these research questions. The factors identified from the literature are aligned with the SDGs that help to achieve CNSC. The factors were determined that focus on utilizing BT's unique resources and capabilities that can lead to competitive advantage in achieving CNSC. The results contribute to understanding how the various sustainable development factors transformed digitally through using disruptive BT to achieve CNSC. The analysis of the study also determines, do the IBT help sustainable development factors to fulfil the SDGs and reduce wastages, some failed to meet the criteria for achieving CNSC. These findings provide a new and interesting insight that contributes to the literature by providing a holistic perspective to the food manufacturers, industrialists, and practitioners in determining how the IBT in FSC will help them achieve a CNSC, increase transparency and efficiency, and reduce food wastage to attain a sustainable supply chain.

The remaining sections of the paper are organised as follows. The literature review is discussed in Section 2. The conceptual framework and research hypotheses are discussed in Section 3. Section 4 discusses the research methodology. Section 5 discusses the analysis and findings of the study. The discussion and implications of the study are outlined in Section 6. 7 concludes and outlines the study's limitations and future research direction.

2. Literature review

This section briefly discusses the research investigating how the IBT in FSC helps attain the SDGs and the significance of a CNSC in FSC. Furthermore, this section also explains broadly the theoretical aspects of the study.

2.1. Integrating BT in FSC and aligning with SDGs

In the business world, an innovation that could displace current systems and technologies is referred to as disruptive technology

(Saadatmand and Daim, 2019). These technologies are disruptive because they have the power to fundamentally alter social and economic conventions, market behaviour, and business practices. Common examples include smartphones, the Internet of Things, blockchain technologies, etc. (Saadatmand and Daim, 2019). Blockchain technology has been documented as beneficial for the food industry, especially in terms of advanced tracing capabilities, increased food safety and security, and enhanced consumer trust. BT is a publicly accessible and decentralised ledger database that maintains authenticated records of all executed and shared transactions (Kumar et al., 2022b). It helps build a network of participants to address the intricacies of sharing data across the geographically decentralised supply chain (Brookbanks and Parry, 2022). The IBT helps maintain food quality and safety, scale up innovation and infrastructure, reduce spoilage and wastage of food and lower carbon emissions (Biglari et al., 2022), which further helps align with the SDGs. The SDGs of the United Nations call for the development of humankind and the preservation of the environment in developed, developing, and underdeveloped countries (UNDP, n.d.- https://www.undp.org). The area under productive and sustainable agriculture encompasses environmental, economic, and social dimensions. A study by Jiang et al. (2019) shows a significant rise in research exploring sustainability across different scales of the supply chain. Businesses are combining economic goals with social and environmental goals as part of business development (Engwall et al., 2021; Van Wassenhove, 2019) as more corporations announce plans to become carbon neutral. Several multinational companies have focused on social and environmental sustainability, for example, by modernising farms like Nestlé and establishing a recycling chain like Tetra Pak (Jiang et al., 2019). Mangla et al. (2022) have discussed the IBT in FSC to achieve a sustainable supply chain. Other studies (Tsolakis et al., 2021; De Villiers et al., 2021) have discussed how the IBT will help fulfil the SDGs in the Thai fish industry and start-up businesses. Seventeen SDGs are directly or indirectly related to the food industry (FAO, 2015). This research identified critical studies examining how blockchain may be applied and implemented within food supply networks and aligns it with the SDGs 3 (Good health and well-being), 9 (Industry, innovation, and infrastructure), 12 (Responsible consumption and production), and 13 (Climate action). The SDG 2030 agenda emphasises sustainable agriculture as a fundamental step towards securing food security and reducing food waste, aiming to attain a CNSC.

2.2. Significance of carbon-neutral supply chain in FSC

Carbon neutrality is achieved by achieving a carbon footprint as close to zero as possible, with any remaining emissions re-absorbed by the ocean and the forest (Net Zero coalition UN). The transition to a carbon-neutral world is one of the most difficult challenges faced by humankind. In order to achieve it, the firms must completely transform how they produce, consume, and transport their goods through the supply chain (Lin and Guan, 2023). A quarter of all greenhouse gas emissions are attributed to our food system. Emissions will rise shortly unless significant changes are made in food production and the supply chain. To achieve this goal, there must be a net reduction in global carbon dioxide emissions (Rogelj et al., 2021).

Achieving these national targets becomes nearly impossible without significant reductions in agricultural emissions and increases in substantial sequestration with the addition of integrating digital technologies. Due to the complexity of the FSC, emissions are generated from retail, transportation, consumption, waste management, industrial processes, and packaging. Additionally, the activities within the FSC are approximately 5 % to 10 % of GHG emissions (Acampora et al., 2023). Reducing GHG emissions, air pollutants, and waste from the entire FSC will contribute to attaining a CNSC and satisfying SDGs. Hence, sustainability must be emphasised for a CNSC (Virmani et al., 2022). Peng et al. (2018) state that many manufacturers are leaning towards achieving a low-carbon or carbon-neutral FSC as government protocols and consumer preferences are inclined towards it. Multiple organisations have set an estimate to cut the average world carbon footprint from four tons to two tons by 2050. According to TraceX technologies, the IBT is essential in helping organisations achieve a CNSC (TraceX, n.d.- https://tracextech.com). As a result, to meet the target, BT, as a distributed and irreversible database, can provide a better and more efficient management tool for carbon emissions and supply chain management (Liu et al., 2019) in the FSC.

2.3. Theoretical background of the study

Disruptive technologies are essential for promoting food sustainability as they tackle intricate problems and generate novel prospects. The utilization of AI and sensors assists food processors in improving sorting efficiency and reducing food waste. These systems have the ability to detect inedible by-products that can be recycled, hence decreasing total waste. Blockchain technology guarantees transparency and traceability in the supply chain, thereby mitigating food fraud and enhancing sustainability. Theoretically, disruptive BT is an enabler of the supply chain, but to systematically study IBT to align with SDGs and achieve a CNSC, the study relies on the derived RBV and DCV theory. The RBV theory defines the competitive advantage obtained from the IBT in the FSC, and the DCV theory focuses on BT's ability to adapt, innovate, and change in response to the FSC's external market conditions and evolving environments.

The RBV is derived from Penrose's (1959) studies, which demonstrated that the capacity of a firm and its resources determine its competitive advantage. They further argue that the resilient traits of a firm can be found in its best resources and routines. Thus, innovation allows companies to develop and create unique resources that help improve a firm's performance and survival. It is clear from Conner's (1991) paper and other updates (Mahoney, 2001; Makadok, 2011) that RBV is a valuable theoretical framework for analysing the different dimensions of sustainable performance in firms since it complements other organisational economics and strategy theories (Epelbaum and Garcia Martinez, 2014). In Mao et al. (2017), the angle of interdependence between carbon emissions reduction and a firm's performance was assessed using a natural RBV. The study showed that improving processes may have a positive effect on reducing carbon emissions. Thus, this study incorporates variables such as reducing carbon emissions, enhancing supply chain performance, and building consumer trust based on the RBV theory, which helps in elucidating how strategic capabilities, valuable resources, and sustained competitive advantage obtained by BT help in mitigating environmental problems and improving operational efficiency.

Kumar et al. (2023a) state that DCVs are used where the capabilities are built under strong dynamic conditions. According to Teece et al. (1997) and Rice et al. (2015), dynamic capabilities refer to an organisation's ability to build, integrate, and reconfigure its resource base over time as a response to changing circumstances. DCV theory gives the SC a dynamic view of the FSC and how volatility affects it, leading to a CNSC. As defined by Simon et al. (2015), it refers to the ability and processes of an organisation to configure its resources to accommodate future changes. The supply chain can function better if the resources and/or capabilities are non-replaceable, unique, advantageous, and inimitable (Dubey et al., 2020). Thus, to further study and enhance the variable, DC theory is used to define variables, such as promoting food safety and quality and preventing food losses, that justify the dynamic capability of the FSC and how the IBT helps in ensuring the resilience and sustainability of FSC while maintaining safety and quality of the products.

Thus, the RBV and DCV approach helps in elucidating a comprehensive framework on how the IBT influences and reinforces the variable carbon emission, supply chain performance, consumer trust, food losses and food safety and quality, ultimately leading to the achievement of CNSC. The two theories underpin the transformative potential of the IBT in decarbonising the FSC and aligning with the SDGs. The synergy between strategic and unique resource management (RBV) and adaptive capabilities (DCV) position BT as a critical enabler of sustainability, efficiency and resilience in modern FSC.

3. Conceptual framework and hypotheses development

The model has adopted the contingent perspective of the RBV and DCV theories, which is infused into the conceptual framework to study the integration drivers of the disruptive BT. The RBV highlights the importance of BT as a unique resource that can provide a competitive advantage. At the same time, the DCV emphasises the need for firms to develop dynamic capabilities to sense, learn, adapt, and implement BT effectively in a constantly changing business environment. Combining these two views can help FSC leverage BT to create and sustain a competitive edge in their respective domain. Fig. 1 depicts the research framework and the interactions between the integrated elements.

Firms recently utilized disruptive technologies in FSC. Disruptive technologies have the potential to help companies achieve a CNSC by increasing transparency and efficiency in the movement of goods. Companies can trace the movement of goods from the point of origin to the point of consumption, enabling them to optimise their supply chains and reduce the carbon emissions associated with transportation and other logistics. Blockchain can help companies offset their carbon emissions by enabling them to track and record their emissions and purchase carbon credits (Zhang et al., 2022). This can help companies to offset their carbon emissions and achieve CNSC. Further, it pushes the supply chain towards reducing losses and carbon emissions, using sustainable solutions, and gaining societal acceptance. BT moves towards attaining a low-carbon or CNSC, benefiting the people, planet, and economy.

The individual variables that help to achieve the three areas (environment, economic and social) of sustainability and fulfil the SDGs, with the help of BT, are discussed and hypothesised below. These variables also lead the FSC to attain CNSC.

3.1. Reduce carbon emission (RCE)

Emissions of GHGs from food systems constitute a significant portion of global environmental factors. The life cycle of an agri-food product goes through several stages, each having different environmental impacts. It is therefore important to consider impacts at each stage of the food production process, including those resulting from indirect inputs (e.g., GHG emissions from energy use, transportation, chemical fertilizer and pesticides). To alleviate these environmental factors, agricultural producers must work with other supply chain actors, consumers, and policymakers to address them (OCED, 2022). Innovative enabling

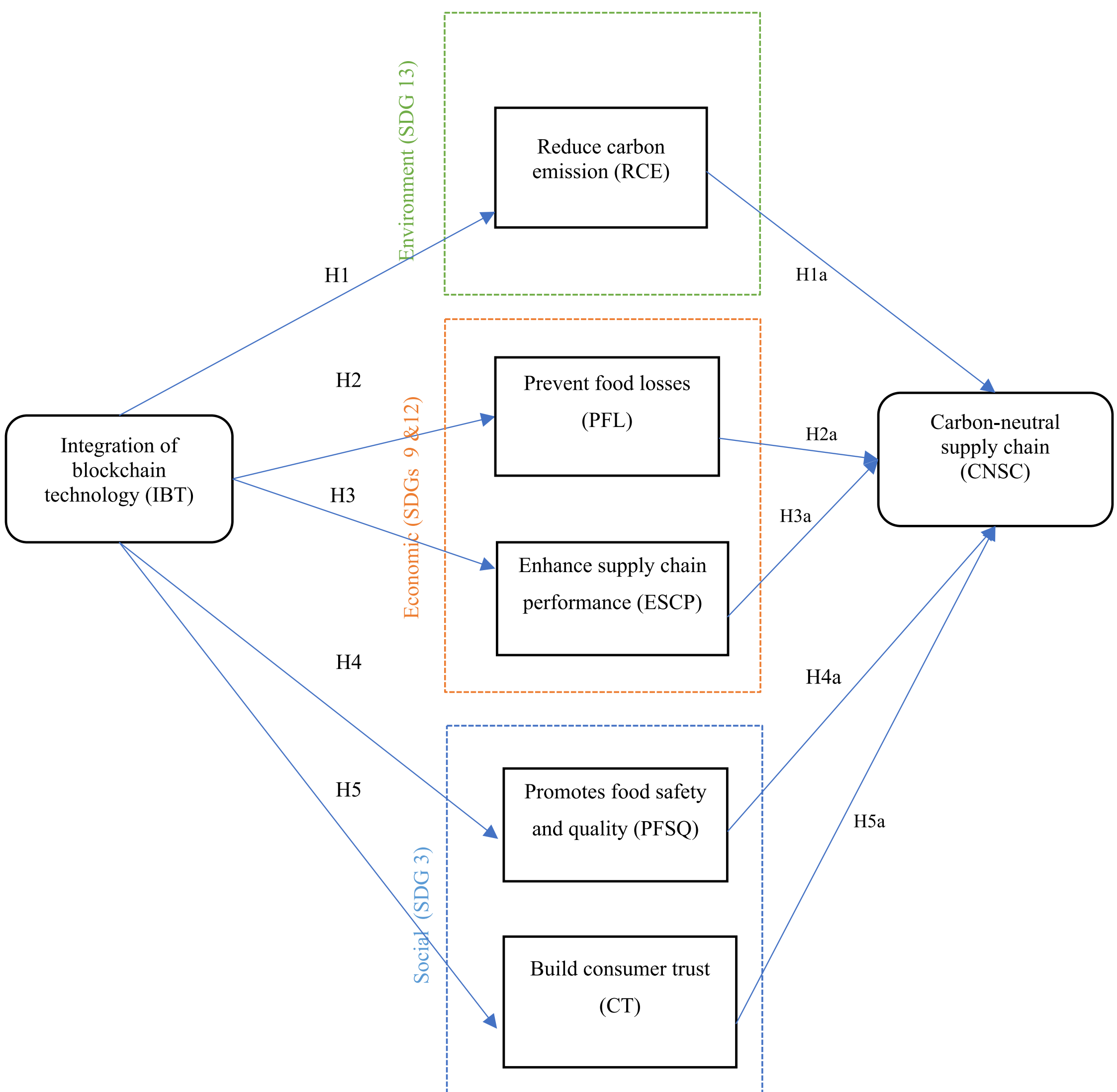

Fig. 1. A conceptual framework for attaining a CNSC in FSC.

technologies help to mitigate the carbon emission problem and help in fulfilling SDG 13 (Nylund et al., 2022). The RCE can be analysed through the RBV theory lens, which emphasises the strategic significance of a firm's distinctive resources and capabilities in attaining a sustainable competitive advantage. By inculcating RBV in RCE, organisations can leverage their distinct set of resources to develop and innovate sustainable practices that lower their environmental footprint. It also contributes to attaining SDG 13 (Climate Action) as it combats climate change and enables the reduction of emissions. FSC produces 13.7 billion tons of carbon dioxide yearly (UN News, 2021), and the supply chain's land use and farm stages cause over 80 % of the greenhouse gas emissions from food. Introducing BT to low-carbon FSC can assist in making low-carbon decisions and reducing total supply chain emissions (Wang et al., 2020), leading to a CNSC. BT can assist in product traceability and tracking carbon footprints, thus solving the problem of consumers' green trust in green and low-carbon products. It also helps monitor and control the use of chemicals and pesticides in farmlands and land transactions. The IBT can reduce paper consumption, as the data is stored in blocks and is accessible to all participants (Saha et al., 2022). Thus, we propose the hypothesis:

H1: The integration of blockchain technology has a positive impact on reducing carbon emission.

Aligning with these internal resources, FSC can create value for themselves. BT's real-time features and tamper-proof nature enable governments to obtain timely carbon emission information from enterprises in the emissions reduction process. The government can implement green supervision and restrict and encourage enterprises to reduce their carbon emissions based on the environmentally friendly information provided by BT (Manupati et al., 2020), which ultimately leads to achieving a CNSC. The IBT will help achieve a CNSC. Thus, we propose hypothesis H1a quoting that the inclusion of BT helps to reduce carbon emission, which helps to achieve a CNSC.

H1a: Reducing carbon emission has a positive impact on CNSC.

3.2. Prevent food losses (PFL)

Economic sustainability in the FSC refers to the ability of the supply chain to operate financially viable over the long term. It ensures that food products' production, distribution, and consumption are financially sustainable and efficient, reducing the losses and considering the costs associated with these activities and the revenue generated. In the FSC network, many fruit and vegetable losses occur due to improper handling, monitoring, and transportation of goods (Raut et al., 2019). Food losses lead to economic losses, according to FAO. BT, by its decentralised and transparent nature, helps prevent losses and aligns with the DCV theory. The IBT in FSC will help build a resilient supply chain network to promote sustainability and foster innovation, which helps in fulfilling SDG 9 (Industry, innovation, and infrastructure). It will also help to address wastage occurring at various points of the supply chain by attaching a digital identity to the product, along with the batch number and expiration date, so it becomes easy to track and trace them. The inclusion of BT can also address the pilferage of food by integrating it with IoT, which helps to decrease product theft and limit food recalls by mitigating the damage caused by them, preventing food losses and reducing costs, leading to SDG 12 (Responsible consumption and production). This exemplifies the sensing aspect of the DCV theory. Hence, we propose the hypothesis:

H2: The integration of blockchain technology has a positive impact on preventing food losses.

Food waste reduction is critical in ensuring the sustainable use of natural resources. The supplier and consumer can also track the dates of the product's origin, expiry, and shipment, leading to less wastage and product recalls. Product warehouse management can also be integrated with the BT for better food monitoring, tracking, and transportation (Kumar et al., 2023b). Thus, BT showcases how dynamic capabilities can be harnessed to prevent losses by enabling agile, data-driven decision-making, reinforcing the symbiotic relationship between technological innovation and organisational adaptability. Reducing losses and wastages helps enhance the ability of the supply chain to attain a CNSC. So, we state the following hypothesis.

H2a: Preventing food losses has a positive impact on CNSC.

3.3. Enhance supply chain performance (ESCP)

In the realm of SCM, an organisation can leverage its distinct resources, such as efficient processes, a skilled workforce and valuable relationships with suppliers and partners. The RBV theory highlights that firms that strategically deploy their resources to enhance SCP will be better positioned to meet market demands, respond to disruptions, and create enduring competitive advantage in a dynamic business landscape. BT can ESCP by increasing transparency, traceability, and security by recording and tracking transactions, enabling supply chain stakeholders to see the movement of goods in real time. Supply chain performance helps to measure efficiency using various tools, techniques, and indicators that measure the performance of the entire chain and consequently measure the dimensions of sustainability (Aman and Seuring, 2022). Thus, we say that the IBT leads to innovation in the supply chain, optimising the resources and helping achieve SDGs 9 and 12. Thus we propose the hypothesis:

H3: The integration of blockchain technology significantly enhances supply chain performance.

Using BT in supply chains can dramatically improve the delivery and traceability of products, improve coordination between partners, and make financing more accessible, thereby enhancing the chain's performance (Li and Fang, 2022). The IBT in FSC also improves operational and strategic level capabilities like process improvement, reduced time, quality compliance, flexibility, and cost (Nandi et al., 2020). The IBT enables the automation of various supply chain processes, reducing the need for manual intervention and improving efficiency. It also helps trace and track logistics and warehouse management, easing the operation (Kumar et al., 2023b). Optimising the supply chain performance enables the supply chain to achieve a sustainable supply chain that helps to reduce emissions and further leads to CNSC. Thus, we propose the following hypothesis.

H3a: Enhancing supply chain performance has a positive impact on CNSC.

3.4. Promotes food safety and quality (PFSQ)

The social dimension of sustainability is crucial to the FSC. Regarding social sustainability, companies primarily make their purchasing decisions in line with their supply chain responsibility. Social sustainability should include human and labour rights, food quality, food safety, vulnerable groups, and final customers through international instruments. Ensuring social sustainability involves all actors and having good traceability and management systems from the beginning of the supply chain to the end. A transparent and traceable supply chain made possible by BT can promote food safety and quality. By leveraging BT's capabilities, FSC can enhance its adaptive capacity in response to the changing business environment. BT enables food companies to trace food products from farm to consumer and ensure that they are sustainably sourced and efficiently transported. As FSC integrates BT into its operations, it embodies the reconfigurability aspect of DCV, adapting its processes to incorporate this technology and creating a more responsive supply chain. The IBT leads to many benefits by increasing food safety, security, visibility, transparency, traceability, credible financial transactions, and speedy process handling. It also reduces food spoilage and wastage, preventing fraud and contamination. Through BT-based data exchange, the FSC can be made more sustainable and transparent, and other issues such as waste reduction, food safety, and quality can also be addressed, thereby satisfying the criteria of providing quality food and maintaining the good health of the consumers complying with SDG 3

(Good health and well-being). Thus, we propose the hypothesis:

H4: The integration of blockchain technology significantly promotes food safety and quality.

A BT-based solution in FSC enhances performance, management, and system security for trading partners while protecting their business operations and supply chains. The IBT can improve supplier-customer communication by sharing transparent information about the product's origin and process using smart packaging to provide quality information (Sander et al., 2018). Moreover, the continuous learning inherent in DCV is evident as companies refine their understanding of BT's potential applications in enhancing food safety practices, enabling a proactive and iterative approach to risk management. While attaining the PFSQ and SDG with the help of BT, we try to study whether it will also promote a CNSC. In accordance with the statement above, we propose the following hypothesis H4a:

H4a: Promoting food safety and quality has a positive impact on CNSC.

3.5. Build consumer trust (CT)

Consumer trust in the FSC, or loss of it, has become a primary concern. The food and beverage sector has significantly declined trust from 2017 to 2018 (Macready et al., 2020). In today's global landscape, where food products are relentlessly marketed with sweeping claims about their nutritional benefits, eco-friendliness and provenance, the issue of trust in food chain actors is a serious concern. Consumer confidence in their ability to make informed food choices may also decrease due to a lack of trust in food chain actors. CT can be effectively supported by RBV, which emphasises firms' unique resources like transparent communication, exceptional customer services, quality assurance processes, and ethical practices. RBV emphasises the importance of firms investing in resources that enhance CT and strengthen their brand reputation, leading to a sustainable competitive advantage in the marketplace. The IBT will promote transparency and give users control over their data, securing transparent information and rebuilding trust in the FSC. Thus, the IBT complies with SDG 3 by ensuring consumer well-being and building trust. Thus, we propose the hypothesis:

H5: The integration of blockchain technology has a significant positive impact on building consumer trust.

The IBT and smart contracts can be applied in SCM systems as part of the price tracking section. As a result, prices are more transparent, and excessive price increases are deterred (Yoo and Won, 2018). The BT traceability fosters accountability between agriculture and supply chain stakeholders, delivering credential data to consumers along the line. Confidence in the integrity of food products is built upon trusting actors in the food supply system. Building trust will lead to good quality and waste reduction, promoting a CNSC. As such, we propose the hypothesis:

H5a: Building consumer trust has a significant positive impact on CNSC.

4. Methods

Based on an exhaustive literature review this study developed a research framework having seven constructs and ten hypotheses. To test and validate the proposed hypothesis, a questionnaire-based survey in the Indian agri-food sector has been performed. We followed the structural equation modeling (SEM) approach. In the process of applying SEM first items are validated from proper loading to the constructs through exploratory factor analysis.

4.1. Case illustration

India aims to be digitally advanced and carbon neutral. India, a prominent global economic power boasting the 5th largest economy and ranking the 2nd largest agriculture producer (Economic Survey, 2022–23; Forbes India, n.d.-https://www.forbesindia.com), has set its sights on ambitious objectives of digital advancement and carbon neutrality. The transformative shift towards a digitised economy serves as a pivotal driver and holds paramount significance within India's strategy to accomplish carbon neutrality. In this context, BT emerges as an instrumental tool in paving the way towards achieving SDGs.

The government's launch of the digital agriculture mission, in collaboration with prominent industry and public sector stakeholders such as Cisco, Ninjacart, Jio Platforms, ITC, and the National Commodity and Derivatives Exchange (NCDEX) E Markets Limited (NEML), is expected to bring about innovative approaches for advancing digital agriculture in India. Additionally, introducing the National Agri Stack and Senor-based smart agriculture tools in February 2023 further strengthens efforts to drive data-focused agriculture initiatives (PIB, 2021). Therefore, an empirical survey-based study was conducted on the Indian agri-food industry to explore relevant factors for the IBT in the AFSC.

4.2. Instrument development and data collection

Through an examination of contemporary literature on disruptive technologies, FSC, carbon neutrality, and sustainability, we found various constructs, which are elaborated in Table A1 of the Appendix. The framework employed seven constructs and 31 items for the questionnaire's development. Nonetheless, the construct RCE (Liu et al., 2019; Wang et al., 2020) involved inquiries regarding paperless transactions, the utilization of zero-carbon technology, the mitigation of nitrogen oxide emissions from agricultural fertilizers, and the reduction of greenhouse gases and carbon footprints, with responses measured on a five-point Likert scale. The constructs prevent food losses, derived from Raut et al. (2019) and Kumar et al. (2022a, 2022b), together with elements such as monitor real-time data, stop food pilferage, prevent food wastage, and align supply chain demand, were assessed using a five-point Likert scale. Constructs that enhance supply chain performance, as derived from Aman and Seuring (2022) and Li et al. (2021), include items such as the ability to track and trace previously unavailable data, reduction of food processing time, supply chain integration, and operational efficiency that promotes food safety and quality, which were assessed using a five-point Likert scale in the survey questionnaire. Consumer trust was established based on the works of Macready et al. (2020) and Yoo and Won (2018), while the IBT was derived from Wang et al. (2020) and Li et al. (2021). Additionally, constructs related to CNSC were informed by Zhang et al. (2022) and Qin et al. (2021) and assessed using a five-point Likert scale.

The chosen items were utilized to build the questionnaire. A two-step questionnaire has been used, wherein the initial phase collects demographic data and presents ethical guidelines ensuring that no personal information of respondents, including their organisation name or personal details (name and contact information), would be disclosed. In the second phase, one question for each item was formulated in English. The questionnaire was reviewed by English-proofing professionals to eliminate double-barreled sentences and ambiguity. The respondents were selected using a purposive sampling strategy, which involves choosing participants according to certain criteria related to their technological expertise (Hadjielias et al., 2022). The FSC comprises various organisations collaborating through distinct processes and activities to deliver products and services to the market, hence fulfilling customer expectations (Ahumada and Villalobos, 2009). The study encompasses the food sector, aiming to incorporate all facets of the industry, including fruits, vegetables, dairy, beverages, and agri-food retail. The diversity of the selection illustrates the heterogeneity of the sample data.

The questionnaire was initially distributed to 50 experts. Data derived from the responses of 20 experts were used for the assessment of the reliability of each construct using Cronbach's alpha (Cronbach, 1951; Koufteros et al., 1998), and convergent validity was tested as well examining factor loadings and correlations. Subsequent to the successful completion of the preliminary pilot testing, the questionnaire was distributed to 424 designated expert respondents engaged in the agricultural and food sectors. Experts are selected based on a minimum of five years of experience, possession of at least a bachelor's degree, and current employment within the FSC. Industry profiles were sourced from the CMIE database and the Government of India website, while expert contact information was acquired from LinkedIn professionals. The survey questionnaire was disseminated to experts via mail and LinkedIn professionals. The data collection occurred from March 2022 to August 2022. From a total of 424 in the initial three-month period, we received 160 responses; hence, a second round of requests was sent via mail to the non-respondents. After one month of sending the second round request, we obtained an additional 51 responses. Upon thorough examination, we identified 11 responses that were inadequate due to insufficient completion of the survey. This study has 200 precise expert responses, with an average response rate of 47.17 %. Among the total respondents, 112 (56 %) were male and 88 (44 %) were female. A meticulous sampling methodology was employed, encompassing diverse sectors of the food industry, surveying professionals engaged in fruit and vegetable production (26 %), the dairy sector (31.5 %), the beverage industry (29 %), and food retailers (16 %) functioning at various levels within this extensive domain. This methodical approach contributed essential insights that improved the analysis's reliability and generalizability. Additional demographic information is thoroughly included in Table 1.

4.3. Bias countermeasures

To ensure the validity of the results and minimize the potential influence of the non-response bias (NRB), the early and the late respondent discrepancies were checked (Armstrong and Overton, 1977). The independent *t*-test results showed no significant difference in the average score of the observed items, implying the absence of NRB. The common method bias (CMB) may exist in data as it was gathered from a single respondent survey, as well as dependent and independent factors both gathered in single instruments. Hence, several procedural steps were undertaken to mitigate any potential biases (Dubey et al., 2022). Based on expert feedback (experts with academic and industrial backgrounds), the questions were rewritten to make them simpler and more concise, to reduce the likelihood of problems during data collection. Double-barrel questions causing CMB were also minimized (Podsakoff et al., 2012). Harman's single-factor test to measure CMB was incorporated since researchers find it useful for single-informant surveys (Kumar et al., 2023a). Results indicated that a single factor explained 26.226 % of the total variance, a value below 30 %, which reduces the possibility of CMB and validates our questionnaire. To find the common latent component in our study, we use a confirmatory factor analysis (CFA) model in AMOS. This means coming up with a single factor that all the items have in common and making links between each item and the common factor. When the CFA model was run, it was seen that all of the model fit indices, including the GFI, TLI, CFI, and RMSEA, were out of the acceptable level suggesting there is no effect of common factor in our study. So, these results show that the common method bias doesn't have a big effect on our research model. The variance inflation factor (VIF) was calculated so that worries about multicollinearity in the variable could be found and dealt with. Our calculations give us a VIF number >1, which is within the allowed range. The variance inflation factor should be between 1 and 5, which means that multicollinearity is not affecting our work.

Table 1
Demographic profile.

Items		N (200)	% age
Age	25–35	107	53.5 %
	36–55	57	28.5 %
	56–75	36	18 %
	Total	200	
Gender	Male	112	56 %
	Female	88	44 %
	Total	200	
Educational Qualification	UG	65	32.5 %
	PG	90	45 %
	PhD	45	22.5 %
	Total	200	
Years of Experience	0–5	28	14 %
	5–10	54	27 %
	10–15	67	33.5 %
	15–20	51	25.5 %
	Total	200	
Food industry types	Fruits & vegetables	52	26 %
	Dairy	63	31.5 %
	Beverages	58	29 %
	Food retail	32	16 %
	Total	200	

4.4. Analysis tool

The research adopts a three-step SEM methodology involving questionnaire design, data collection, and exploratory factor analysis (EFA). Secondly, CFA was used to specify the number of factors required in the data to measure the variables. The last step was to develop the structural model. EFA explains observed variable variance by using latent variables underlying intercorrelated variables. It is used to estimate the tentative number of reliable factors or constructs in a data set, whereas CFA has been used to verify the construct of an observed set of items. SEM was used to test the hypothesis after validating the measurement model (Kumar et al., 2022b). Moreover, SEM is acclaimed for its capability to address the missing data (Fornell and Larcker, 1981) and its resilience towards deviations from normality assumptions (Hair, 2017). These aspects are particularly crucial when dealing with the analysed dataset (Al-Shboul and Alsmairat, 2023).

5. Data analysis and findings

5.1. Measurement model analysis

SEM was used to test the study's hypothesis and was tested with the help of AMOS 18.0 software. The SEM model helps to analyze the observed and latent variables by measuring and analysing their relationships (Kline, 2015; Chin, 1998). The AMOS software is equipped with various drawing tools that help examine the path diagram of SEM. The study uses SEM with factor analysis to understand the variables that lead to the IBT in the food industry and achieving CNSC. The AMOS software created the path diagram for SEM, shown in Fig. 2. The Kaiser-Meyer-Olkin (KMO) sampling adequacy test revealed a high level of shared variation and a relatively low level of uniqueness of variance (0.868). Bartlett's test for sphericity (Chi-square = 4988.251, df = 465) (Bentler, 1990; Rakshit et al., 2022) is strongly supported. To assess the reliability and validity of the model, CFA was performed (Skowronski et al., 2021). Statistically, the model fits the data well, "Root means a square error of approximation" (RMSEA) = 0.048, "comparative fit index" (CFI) = 0.96, "Chi-square" =1.462 (<3.0) (Hair Jr. et al., 2010). The items exhibited strong factor loadings (all loadings >0.4; *p*-values 0.001), which indicates that they are valid and convergent (Hair Jr. et al., 2010). Table 2 shows the survey constructs consisting of variables and items mapped according to the relevant SDG and includes the analysis's loading factor.

The assessment of convergent validity is an essential aspect in evaluating the effectiveness of the new scale. Table 3 presents comprehensive data on this concept, including Cronbach's alpha (α), composite reliability (CR), and average variance extracted (AVE). The findings reveal that all the variables exhibit high internal consistency, with Cronbach's alpha value exceeding 0.7. Additionally, all constructs' average variance extracted (AVE) surpasses the minimum threshold value of 0.5, indicating robustness as the latent variables accounted for more than half of the variance in their observable measures (Hair Jr. et al., 2010). The composite reliabilities exceeded the recommended

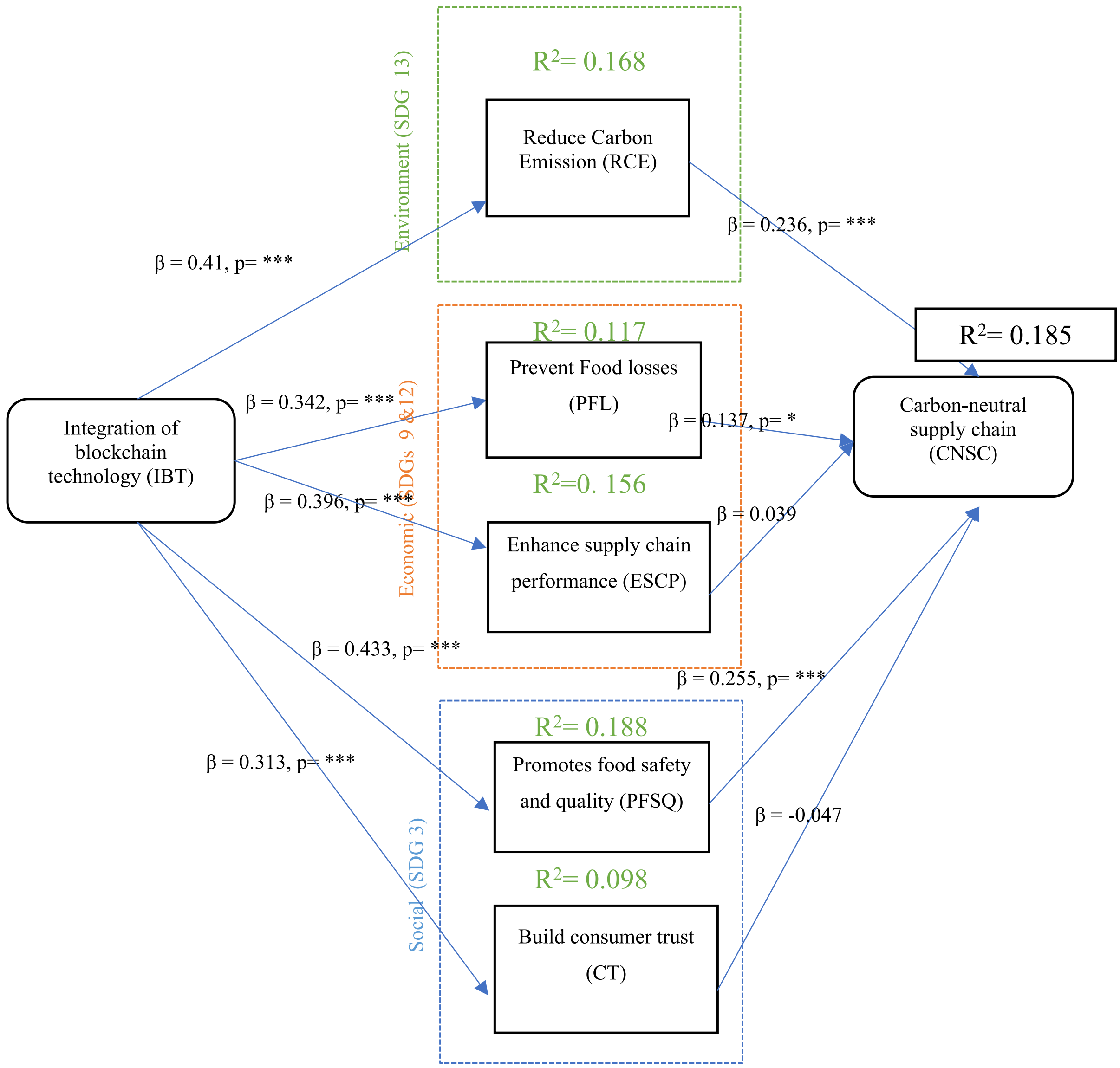

Fig. 2. Measurement model showing SEM path diagram.

level of 0.7 (Nunnally and Bernstein, 1994).

It is essential to consider discriminant and convergent validity, as these measures are used to determine whether constructs that should be connected are unrelated. Fornell-Larcker criteria can be used to assess discriminant validity. A construct's correlation with its indicators (i.e., the square root of AVE) is supposed to be higher than its correlation with any other construct, according to the Fornell-Larcker criterion (Fornell and Larcker, 1981). All constructs had strong discriminant validity (see Table 4), as root AVE values exceeded off-diagonal correlations (Barclay et al., 1995).

5.2. Structural model assessment

Table 5 illustrates the study's path coefficients, t-statistics, and significance levels (*p*-values). The t statistics act as a beneficial tool for a smaller sample size as it provides an accurate confidence interval and a lower p-value to show the credibility of the data. According to the analysis, hypotheses H1, H2, H3, H4, and H5 are significant to our analysis that the IBT in FSC enhances the supply chain and complies with SDGs 3, 9, 12 and 13. The IBT significantly influences the environmental factor RCE fulfilling SDG 13 with $\beta = 0.41$ and p significant at <0.001. The IBT influences the economic factors PFL and ESCP satisfying SDGs 9 and 12 with $\beta = 0.342$ and $\beta = 0.396$ and significance value <0.001. The social factors PFSQ and CT are also observed to be significantly influenced by the IBT with $\beta = 0.433$ and $\beta = 0.313$ with p significant at <0.001. Similarly, hypotheses H1a, H2a, and H4a are significantly accepted, but H3a and H5a show a non-significant relation, resulting in rejecting them despite H3a showing a positive non-significant relationship. Thus, it can be observed that the variables, RCE ($\beta = 0.236$) and PFSQ ($\beta = 0.255$) with significance <0.001, and PFL ($\beta = 0.137$) with significance <0.1, positively influence the CNSC that was considered based on the remark of Greenland et al. (2016) on the *p*-value. However, variables ESCP and CT do not influence the attainment of the CNSC.

6. Discussions

The study empirically investigates whether the IBT complies with the SDGs factors and can lead to attaining CNSC. We find that H1 and H1a show that the IBT positively influences the RCE, further influencing CNSC. Also, the IBT explains 16.8 % of the total variance of reduced carbon emission ($R^2 = 0.168$), suggesting a significant amount of variance explained as the relationship is significant with a p-value <0.001. It further contributes to attaining a CNSC, which is justified by H1a and

Table 2
Items used to measure each survey construct and loadings.

Constructs		SDG	Items/survey questions	Loadings
Reduce carbon emission (RCE)	RCE1	SDG 13	We use paperless transactions to reduce carbon emissions.	0.925
	RCE2		We actively use zero-carbon technologies across our supply chain.	0.904
	RCE3		Our agricultural processes aim to reduce nitrogen oxide emissions from fertilizer use.	0.915
	RCE4		We are committed to reducing greenhouse gas emissions and overall carbon footprint.	0.857
Prevent food losses (PFL)	PFL1	SDGs 9, 12	We monitor real-time data to prevent food losses throughout the supply chain.	0.771
	PFL2		Our systems effectively prevent pilferage of food during storage and transport.	0.769
	PFL3		We implement practices that minimize food wastage.	0.744
	PFL4		Our supply chain is optimized to accurately match demand and supply, reducing food loss.	0.706
Enhance supply chain performance (ESCP)	ESCP1	SDGs 9, 12	We are able to track and trace previously unavailable data across the supply chain.	0.908
	ESCP2		We reduce the time taken to process and deliver food products.	0.807
	ESCP3		Our supply chain is well-integrated across all operational stages.	0.925
	ESCP4		Our operational efficiency is high.	0.722
Promote food safety and quality (PFSQ)	PFSQ1	SDG 3	We use smart packaging technologies to help reduce food waste.	0.933
	PFSQ2		Our systems ensure continuous monitoring of food quality.	0.860
	PFSQ3		We maintain secure and reliable data to support food safety.	0.778
	PFSQ4		We ensure full traceability of food products across the supply chain.	0.735
	PFSQ5		Our operations help minimize food fraud and reduce the costs associated with product recalls.	0.433
Build consumer trust (CT)	CT1	SDG 3	Our supply chain maintains a high level of transparency for stakeholders and consumers.	0.921
	CT2		We proactively address consumer concerns regarding food safety and sustainability.	0.916
	CT3		We provide accurate and reliable product information to consumers.	0.894
	CT4		Our supply chain adheres to fair-trade and ethical sourcing standards.	0.869
	CT5		We offer incentives to promote sustainable and ethical farming practices.	0.849
Integration of blockchain technology (IBT)	IBT1	SDGs 3, 9, 12, 13	Blockchain technology helps us ensure the traceability of products across the supply chain.	0.908
	IBT2		Our blockchain system enhances the reliability of supply chain data.	0.883
	IBT3		We use blockchain for secure storage and protection of supply chain information.	0.697
	IBT4		Blockchain enables tamper-proof and real-time sharing of supply chain data.	0.656
	IBT5		Our firm has sufficient infrastructure and skills to use blockchain technology.	0.856
Carbon-neutral supply chain (CNSC)	CNSC1	SDGs 3, 9, 12, 13	Our supply chain practices support decarbonization efforts.	0.698
	CNSC2		We take steps to ensure that our supply chain operates sustainably.	0.863
	CNSC3		Our carbon-reduction initiatives improve overall supply chain performance.	0.953
	CNSC4		We are actively working towards achieving a carbon-neutral supply chain.	0.938

Table 3
Measurement model results – convergent validity.

Constructs	α	CR	AVE	MSV
Reduce carbon emission (RCE)	0.947	0.925	0.757	0.135
Build consumer trust (CT)	0.95	0.951	0.796	0.091
Integration of blockchain technology (IBT)	0.905	0.837	0.562	0.112
Carbon-neutral supply chain (CNSC)	0.924	0.906	0.660	0.165
Promote food safety and quality (PFSQ)	0.874	0.911	0.719	0.147
Enhance supply chain performance (ESCP)	0.909	0.883	0.611	0.166
Prevent food losses (PFL)	0.836	0.947	0.818	0.166

Table 4
Measurement model results – discriminant validity.[a]

Constructs	CNSC	CT	PFL	IBT	ESCP	PFSQ	RCE
CNSC	0.870						
CT	0.089	0.892					
PFL	0.217	0.143	0.750				
IBT	0.335	0.301	0.334	0.813			
ESCP	0.182	0.177	0.116	0.383	0.848		
PFSQ	0.367	0.300	0.216	0.406	0.381	0.782	
RCE	0.349	0.174	0.161	0.395	0.208	0.408	0.904

[a] Diagonal elements are the square root of AVE.

shows a positive relation. The results concur with other studies that BT helps to reduce emissions by identifying GHG reduction opportunities, setting reduction targets, and tracking performance, thereby facilitating adherence to the ecological regulations by contributing to the sustainability of the environment (Wang et al., 2020; Sadawi et al., 2021; Saha et al., 2022). Thus, the result of the current study showcases the generalizability of attaining RCE through the IBT in the current scenario. FSC is a disintegrated chain and includes multiple partners. The IBT in FSC will help to monitor and observe the entire supply chain data and might indicate where excess emission or wastage occurs, helping to reduce the carbon footprint (Shakhbulatov et al., 2019). This will lead to reducing carbon emissions and can assist in attaining SDG13, which focuses on adapting to climate change and reducing emissions. The IBT can optimise pesticides, fertilizers, antibiotics, and irrigation, as it stores the data in blocks, leading to less paper usage and acting as a valuable resource towards attaining CNSC. It may also help to reduce the carbon footprint by capturing the contributing area and using integrated and zero-carbon technologies to reduce the emissions leading to CNSC. Su

Table 5
Path coefficients, t-statistics, and *p*-values.

Hypothesis	Path	Standardized path coefficient (β)	t-statistics	p-value	Decision
H1	RCE <— IBT	0.41	5.256	***	Accept
H2	PFL <— IBT	0.342	4.009	***	Accept
H3	ESCP <— IBT	0.396	4.871	***	Accept
H4	PFSQ <— IBT	0.433	5.327	***	Accept
H5	CT <— IBT	0.313	4.066	***	Accept
H1a	CNSC <— RCE	0.236	3.216	***	Accept
H2a	CNSC <— PFL	0.137	1.802	*	Accept
H3a	CNSC <— ESCP	0.039	0.547	0.584	Reject
H4a	CNSC <— PFSQ	0.255	3.355	***	Accept
H5a	CNSC <— CT	−0.047	−0.674	0.501	Reject

"***Significant at P-value <0.001; ** signifies p-value <0.01 t-statistics >1; * signifies p-value <0.1, β strongest relationship (0 to 1)".

and Moaniba (2017) provided empirical evidence as to how innovation in climate change technologies helps in responding to climate change while reducing greenhouse gas emissions.

Hypotheses H2 and H3 also show that the IBT significantly influences the variables PFL and ESCP, and H2a shows that PFL further leads to a CNSC. Also, the IBT explains 11.7 % of the total variance of preventing food losses as $R^2 = 0.117$. The result helps justify RQ1, which implies that IBT helps reduce food wastage. The finding is consistent with previous studies (Raut et al., 2019), which implicitly state that the IBT helps lower wastage. This is achieved as the IBT enables timely purchase and usage of items before expiration (Li et al., 2021). The DCV theory highlights the advantage of IBT for creating better transparency and food loss prevention in the dynamic market of the FSC. Smart packaging enabled by IBT reduces food wastage by providing more accurate information regarding the status of food products, preventing food from being discarded needlessly (Mustafa and Andreescu, 2018). Firms can acquire detailed information on the shelf life of food products to better manage their inventory and transportation, improve profits and avoid wastage, contributing towards the broader goal of achieving CNSC, thereby advancing sustainability in FSC. Thus, it can be observed that the IBT contributes to lowering the wastage in the supply chain, contributing towards the economic sustainability of the FSC, thereby fulfilling the SDG 12 target by reducing losses and proper consumption of resources.

Also, the IBT explains 15.6 % of the total variance of the enhanced supply chain performance variable as $R^2 = 0.156$ indicates the IBT has a better influence in achieving ESCP than PFL as R^2 for PFL is 0.117 in the economic dimension. This can be attributed to many unaccountable and uncontrolled factors where technology fails to measure or prevent the wastage in FSC. Food losses are influenced by factors like improper handling and demand-supply variation due to volatile market and storage conditions. Though the IBT can track and trace food losses, it technically cannot prevent spoilage or wastage due to human inefficiency, lack of infrastructure and transportation disorganisation. The IBT provides better supplier coordination and inventory management by providing real-time data, leading to increased supply chain efficiency. Wamba et al. (2020) and Yousefi and Mohamadpour Tosarkani (2022) provide empirical support on the same ground, stating that the IBT helps enhance supply chain performance. The IBT can ease logistical procedures by combining RFID and IoT to improve visibility, live tracking, and storage. In addition to preserving transparent and irreversible records of transactions and operations, the IBT can help businesses quickly detect and isolate hazardous hotspots and reduce the need to shut down the entire supply chain. Our study enriches the study by showing how the IBT leads to ESCP, which further adds value to the SDG 9 initiative. The IBT enables the FSC stakeholders to connect, interact and exchange information faster and accurately, increasing the supply chain's efficacy Vu et al. (2023) and helping in building the economic viability of the FSC. ESCP does not help achieve CNSC. Though BT is observed to increase the efficiency of the supply chain, the driver ESCP is not leading to achieving a CNSC. The reason could be that the FSC, being a demanding supply chain, reaps more on improving the supply chain's efficiency and profit (Kittipanya-ngam and Tan, 2020; Sarkis, 2020). ESCP tends to prioritize conventional performance measurements like cost reduction, lead time reduction and quality improvement (Govindan et al., 2022), which may not directly address environmental sustainability, leading to achieving CNSC. On the other hand, PFL leads to achieving a CNSC as reducing losses can be monitored by technology and increased trends of waste management practices like recycling and composting and circular economy initiatives. Thus, while the IBT enhances SC performance and infrastructure upliftment aligning with SDG 9, its actual potential lies in enabling PFL, preventing food losses, and increasing food safety and security, thus facilitating the achievement of SDG 12. Therefore, the IBT plays a critical role in transitioning towards a more sustainable FSC, ultimately facilitating the realization of CNSC.

Therefore, in order to promote food safety and quality, the IBT explains 18.8 % of the variance of PFSQ as $R^2 = 0.188$. Further, the analysis states that the IBT significantly influences societal factors, such as PFSQ and CT, while PFSQ further helps achieve CNSC. In contrast, it is observed that CT does not influence CNSC. While building consumer trust, the IBT explains only 9.8 % of the variance. Also, together with all the predictors, it explains 18.5 % of CNSC variable. Since the quality of the food remains a priority in FSC and the IBT helps in specific and targeted recalls, assists in identifying key bottlenecks, discourages adulteration of food products, identifies weak links when they occur, and provides quality information from beginning to end to the consumer (Mondal et al., 2019). Pakseresht et al. (2023) views align in a similar line that the IBT has a major role in obtaining food safety and quality. By reducing food waste and food recalls and identifying exploitation and fraud, the IBT also assists in promoting food safety and security and enforcing human rights, which can further assist in achieving CNSC.

Blockchain-based data makes it easier for farmers to process agricultural claims and facilitate payments between FSC firms. The IBT is also imperative for increasing consumer trust and minimizing financial exploitation (Friedman and Ormiston, 2022). It adheres to fair-trade standards and increases consumer trust by providing a traceable and transparent supply chain, promoting social sustainability, and leading to SDG 3. Customers can participate in product design and process decisions by digitally encapsulating the information required to manufacture, deliver, and use the unique product. The involvement of customers is just one example of how the IBT opens new opportunities for collaboration and external engagement (Holmström et al., 2019), enhancing and creating opportunities for FSC stakeholders. Even though the IBT shows benefits and trust for the technology, BT is an advanced technology and a decentralised one, consumers have yet to fully believe in the full advantage of the technology, further negating the relation of CNSC. While BT promises traceability, information sharing and provenance, being a budding technology, it still lacks logistics and carbon information transparency as multiple chain actors make it difficult to track (Zhu et al., 2024). Also, information disclosure needs consensus and transparent commitments from the stakeholders, where there might be a potential risk of data being omitted. Ultimately, CT is driven by how much they perceive the utility of the technology and how it helps lower carbon emissions along with transparency in the information. Since carbon-neutral capital investments are high and rely more on government policy, social capital, and stakeholders' commitment, consumers tend to be sceptical about investing in such high stakes (Wu et al., 2023). The finding suggests that though they believe the IBT can change the FSC, lowering the carbon emission is yet to be seen. Consumers' concerns about social welfare and eco-friendly farming methods (Li et al., 2021) and creating awareness about blockchain in developing countries would help to achieve CNSC in the future.

Thus, the IBT acts as an enhancer for reaching the CNSC, which achieves the SDGs. While its ability to strengthen operational efficiency, lower human involvement, transparency and traceability is commendable, the effectiveness of achieving CNSC is shaped by stakeholders' commitments, regulatory frameworks and government and industry policy.

6.1. Theoretical implications

This research contributes to the literature by providing a nuanced understanding of how integrating disruptive technologies like the IBT in the FSC helps fulfil the SDGs and achieve the CNSC. From a theoretical point of view, the study uses a combination of constructs and theories from various sources, including RBV and DCV, that provide an answer to the research question relevant to achieving CNSC. By employing an interdisciplinary perspective, it becomes possible to examine the interplay between different concepts and theories that lead to CNSC. This approach has the potential to generate insights that can be used to tackle the significant challenges in achieving the CNSC (Wang et al., 2020; Ingenbleek and Krampe, 2023).

Previous research has recognized the technological evolution in attaining sustainable performance with the help of RBV theory (Epelbaum and Garcia Martinez, 2014), but with the changing scenario, the DCV theory is not inculcated. This research delves into the application of RBV and DCV theories to support the variables that comply with SDGs 3, 9, 12, and 13 and are influenced by disruptive technology. Though BT has been identified as the facilitator of achieving carbon neutrality (Zhang et al., 2022; Qin et al., 2021), this study helps in identifying the contributors that help in achieving CNSC in AFSC. Moreover, our results support the perspectives in which RBV and DCV theory are likely to complement each other (Lin and Wu, 2014; Wu, 2010). By empirically establishing the link between the BT-driven variables, the research reinforces the notion that BT is a technological solution and an environmental and sustainability enabler.

The study's results provide insight regarding the variables that contribute significantly to achieving CNSC. The conventional assumption that ESCP and CT are valuable for firm performance may not directly contribute to CNSC when driven by BT, which is a result worth noticing. This implication explores the intricate dynamics of the supply chain performance, consumer trust and environmental sustainability, potentially leading to nuanced strategies. From a holistic perspective, the research underscores the interconnectedness of the various factors influencing CNSC driven by the IBT. Based on the study insight, the researchers and the professionals should prioritize their efforts and allocate the resources to those factors that have a noticeable influence on achieving the SDGs and CNSC. This refinement contributes to a deeper understanding of how technology-focused initiatives can be customised to address sustainability, which can lead to CNSC.

6.2. Practical implications

The study's practical implications are multifaceted and hold a significant promise for the FSC policymakers and stakeholders involved in the quest for CNSC. From a holistic point of view, the IBT can connect all the decision-makers and stakeholders in a collaborative style and enhance sustainability as well as the carbon neutrality quotient. By systematically incorporating BT into their supply chain, food companies can better understand the key elements of their supply chain by evaluating opportunities for applying BT, engaging relevant stakeholders and recognising the numerous benefits BT offers in promoting sustainable practices. Since the supply chain of the FSC includes multiple members, estimates of the emission data can be acquired through digitalization to reduce carbon emission. Additionally, through strategic efforts to minimize carbon emissions whenever possible, food companies can actively guide their supply chain towards achieving CNSC, supporting SDG 13. Walmart and BMW Group have followed this method (Li et al., 2025). As the FSC is a demanding supply chain building sustainable infrastructure to support innovative technology will lead to less waste of resources and an increase in efficiency, complying with SDGs 9 and 12. Furthermore, BT reinforces food safety and quality, preventing contamination fraud while maintaining transparency aligning with SDG 3. As the application and innovation of the technological practice depend upon the stakeholders' initiatives, the interest of the stakeholders while achieving CNSC must be translated into the whole SC. Thus, food practitioners and policymakers must carefully evaluate the socio-environmental condition and incorporate subsidised strategies for CNSC. As achieving a sustainable supply chain is imperative, adopting a decarbonised technology will benefit the entire ecosystem. The policymakers should jointly work with the government and FSC stakeholders to evaluate and strategize the FSC and check the awareness, preparedness level, and organisation culture for adopting BT and pushing towards a CNSC. In this context, providing a roadmap created by the makers and incentivizing the process will help gain momentum in adopting technology and achieving a CNSC.

7. Conclusions and future research directions

The new disruptive technology i.e., BT significantly provides carbon-neutral solutions as the world moves towards sustainable solutions through opting for sustainable practices in FSC (Wang et al., 2020). The empirical study incorporates the RBV and DC theories to study the BT-driven variables supported by SDGs 3, 9, 12 and 13, that help to achieve a CNSC. As a response to the research question framed in this study, the IBT in the FSC will contribute to addressing the food wastage and carbon emissions produced by the food industry. It will also help to achieve a carbon-neutral economy by reducing the carbon footprint by monitoring and tracking the emissions, use of harmful pesticides, and improper landfills. It will also promote organic farming, incentives to farmers, and consumer trust. National Agricultural Cooperative Marketing Federation of India Limited (NAFED) and Dabur have already planned to implement BT in their honey supply chain to improve the visibility and traceability of the supply chain as well as to maintain quality and prevent adulteration of the honey and beehive products (Dabur India Limited, 2020–21). The initiative will add value in addressing the SDGs as well as pave the way for reducing emissions. CarbonX (an environmental software) has used BT to create a marketplace for carbon credits, allowing companies to offset their carbon emissions by acquiring credits from emission-reducing projects.

The complexity of the FSC network stems from its inclusion of numerous intermediaries; thus, an FSC backed by climate change incentives is more prone to exhibiting carbon and supply change transparency (Villena et al., 2019). The IBT into the supply will enhance the sustainability practices, which will reduce the overall carbon footprints of the products and companies and add a competitive advantage for FSC being an eco-friendly CNSC.

As food is an essential requirement of every living being, the government and food industry practitioners should emphasise digitalising the FSC, leading to better quality, safety, and security. It also leads to reduced food losses and wastage in the supply chain. Additionally, it prevents food from being pilfered or spoilt, contributing to achieving SDG 3 by maintaining food quality and safety and ensuring the well-being of society. Moreover, it will promote international trade by ensuring compliance with food safety regulations and standards that vary from country to country. BT-based FSC provides a remarkable opportunity to foster innovation and resilience within supply chain networks, this transformative process not only promotes sustainable patterns of consumption and production but also effectively mitigates food waste, thus promoting economic dynamism and competitiveness (aligned with SDGs 9, 12).

Through innovative strategies and unwavering commitment to environmental sustainability (SDG 13), the IBT can reduce carbon emissions within the supply chain. The IBT prioritises establishing trust between influential climate change stakeholders by facilitating open and inclusive dialogues among diverse backgrounds, including government officials, NGOs, private corporations, and communities. This strategy promotes collaboration while raising awareness of sustainable development issues. BT actively advocates for a greener future by promoting green finance - supporting investment into eco-friendly projects that generate long-term returns while benefitting our planet's ecosystems and enabling a CNSC.

Therefore, it can be concluded that there is a considerable inclination towards the IBT in FSC to achieve CNSC. The driving factors behind carbon emissions and food losses generally follow a relatively rigid and distinct pattern. In contrast, proximate causes are observable in real-time, represent human economic activity, and are multifactorial. As a result, it is still too early to leverage its final potential. BT, being a young technology and CNSC burgeoning area, achieving a large-scale integration of the technology into the system will call for big changes in the FSC and need government intervention and participation. The government and private sector must create awareness and offer incentives to adopt the technology and observe its outcome.

The present study offers a valuable contribution to the existing literature on the CNSC in the FSC domain. However, despite the significant findings, certain limitations should be acknowledged and considered for future research endeavours. Firstly, it is essential to acknowledge that this study was conducted solely in one developing nation. As such, caution must be exercised when generalising the findings of this research to other nations with varying socio-economic structures and policies concerning sustainability practices. Therefore, conducting similar studies across multiple developing and developed nations using cross-country comparisons would lend a greater depth and understanding of how different environmental contexts influence CNSC strategies and practices. Further mathematical models and predictive analysis could be used to analyze and predict the CNSC in the FSC. Also, the study is sector-specific and can be applied in other sectors.

Similarly, other SDGs could also be studied to observe their effect on FSC and how BT influences it. A longitudinal study can be done to compare the cost of SDG achievements to the amount of available public finances, including government revenue and aid, which is crucial to determining whether underdeveloped and developing countries plan to utilise BT to achieve SDGs for carbon neutrality. The FSC poses unique challenges due to its extensive length and complexity. Achieving an accurate evaluation of the individual contribution by the supplier, manufacturer, and distributor towards food losses and carbon emissions requires careful study. An in-depth understanding will clarify the benefits of the IBT within the sector. A life cycle assessment of the end-to-end FSC will provide a legitimate emission assessment. Even though achieving a CNSC may be a long-term goal, firms may work towards achieving a CNSC and work on different reduction strategies to meet the UN SDGs. This study explores BT as a disruptive technology for the CNSC by opting for sustainable development factors. However, some other disruptive technologies like the Internet of Things and artificial intelligence can be integrated.

CRediT authorship contribution statement

Aditi Saha: Methodology, Investigation, Formal analysis, Conceptualization, Writing – original draft. **Rakesh D. Raut:** Supervision, Software, Resources, Writing – review & editing. **Mukesh Kumar:** Software, Resources, Writing – review & editing. **Sanjoy Kumar Paul:** Validation, Supervision, Writing – review & editing. **Yangyan Shi:** Validation, Resources, Methodology, Writing – review & editing. **Bhavin Shah:** Validation, Writing – review & editing. **Sudishna Ghoshal:** Visualization, Writing – review & editing.

Appendix A

Table A1
Description of the variables.

No.	Variables	Items identified	Description	References (adapted from)
1	Reduce carbon emission	• We use paperless transactions to reduce carbon emissions. • We actively use zero-carbon technologies across our supply chain. • Our agricultural processes aim to reduce nitrogen oxide emissions from fertilizer use. • We are committed to reducing greenhouse gas emissions and overall carbon footprint.	The IBT can help reduce the need for physical documentation, which can be a significant source of emissions. Additionally, blockchain can help facilitate the trading of carbon credits, a mechanism for reducing emissions by allowing companies to offset their emissions by purchasing credits from projects that reduce or remove greenhouse gases from the atmosphere. Also, it can be used to track and verify the sustainability and environmental impact of agricultural practices, such as the use of fertilizers and pesticides, and to certify the origin of food products.	Liu et al. (2019); Wang et al. (2020); Mishra et al., 2023)
2	Prevent food losses	• We monitor real-time data to prevent food losses throughout the supply chain. • Our systems effectively prevent pilferage of food during storage and transport. • We implement practices that minimize food wastage. • Our supply chain is optimized to accurately match demand and supply, reducing food loss.	The IBT helps record and track the movement of food products from farm to table and identifies points more easily in the supply chain where losses occur. This helps to identify and address problems such as spoilage, contamination, and other issues that can lead to food losses. Additionally, BT can be used to record and track food products' storage and handling conditions, which can help ensure that they are being properly stored and handled to minimize spoilage.	Raut et al. (2019)
3	Enhance supply chain performance	• We are able to track and trace previously unavailable data across the supply chain. • We reduce the time taken to process and deliver food products. • Our supply chain is well-integrated across all operational stages. • Our operational efficiency is high.	The IBT can enhance supply chain performance by providing a secure and immutable record of transactions. This helps reduce the risk of fraud and errors and improves the accuracy of supply chain information. It can facilitate faster and more efficient tracking of goods and materials, thereby reducing the time taken for goods to move through the supply chain, leading to faster delivery times and lower inventory costs. It allows all parties in the supply	Aman and Seuring (2022); Li et al., (2021); Nandi et al. (2020);

(continued on next page)

Table A1 (*continued*)

No.	Variables	Items identified	Description	References (adapted from)
			chain to see the same information, which helps to reduce misunderstandings and improve collaboration.	
4	Promotes food safety and quality	• We use smart packaging technologies to help reduce food waste. • Our systems ensure continuous monitoring of food quality. • We maintain secure and reliable data to support food safety. • We ensure full traceability of food products across the supply chain. • Our operations help minimize food fraud and reduce the costs associated with product recalls.	The IBT helps to trace the movement of food products through the supply chain, from farm to fork, allowing for rapid identification and recall of contaminated or defective products. BT ensures that data entered into the system cannot be altered, ensuring the integrity of food safety and quality records. It helps reduce food waste in the context of smart packaging by enabling smart contracts to extend the product's shelf life.	Wang et al., (2021); Sander et al. (2018)
5	Build consumer trust	• Our supply chain maintains a high level of transparency for stakeholders and consumers. • We proactively address consumer concerns regarding food safety and sustainability. • We provide accurate and reliable product information to consumers. • Our supply chain adheres to fair-trade and ethical sourcing standards. • We offer incentives to promote sustainable and ethical farming practices.	The IBT provides a secure and transparent means of tracking the movement and provenance of products, thereby building trust and giving consumers the confidence that the products they buy are genuine and have not been tampered with. It also helps to ensure that fair-trade practices, such as fair wages and working conditions, are followed at each supply chain stage.	Macready et al. (2020); Yoo and Won (2018)
6	Integration of blockchain technology	• Blockchain technology helps us ensure the traceability of products across the supply chain. • Our blockchain system enhances the reliability of supply chain data. • We use blockchain for secure storage and protection of supply chain information. • Blockchain enables tamper-proof and real-time sharing of supply chain data. • Our firm has sufficient infrastructure and skills to use blockchain technology.	BT, a decentralised, distributed technology, can store data in tamper-proof blocks that cannot be altered. It provides transparency and traceability in the whole supply chain, which helps to monitor the real-time data.	Wang et al. (2020); Li et al., (2021);
7	Carbon-neutral supply chain	• Our supply chain practices support decarbonization efforts. • We take steps to ensure that our supply chain operates sustainably. • Our carbon-reduction initiatives improve overall supply chain performance. • We are actively working towards achieving a carbon-neutral supply chain.	The IBT provides a transparent and traceable network that helps to promote sustainable and ethical food practices and provides the carbon footprint of the product, which enables the consumers to make informed choices about the products they purchase, which leads to less wastage and increased efficiency. The IBT also helps decarbonise the supply chain by creating a more efficient and streamlined supply chain.	Zhang et al. (2022); Qin et al. (2021)

Data availability

Data will be made available on request.

References

Acampora, A., Ruini, L., Mattia, G., Pratesi, C.A., Lucchetti, M.C., 2023. Towards carbon neutrality in the Agri-food sector: drivers and barriers. Resour. Conserv. Recycl. 189, 106755. https://doi.org/10.1016/j.resconrec.2022.106755.

Ahumada, O., Villalobos, J.R., 2009. Application of planning models in the Agri-food supply chain: a review. Eur. J. Oper. Res. 196 (1), 1–20. https://doi.org/10.1016/j.ejor.2008.02.014.

Al-Shboul, M.A., Alsmairat, M.A.K., 2023. Enabling supply chain efficacy through SC risk mitigation and absorptive capacity: an empirical investigation in manufacturing firms in the Middle East region – a moderated-mediated model. Supply Chain Manag. Int. J> 28 (5), 909–922. https://doi.org/10.1108/SCM-09-2022-0382.

Aman, S., Seuring, S., 2022. Interestingly it's innovation: reviewing sustainability performance management in the base of the pyramid (BoP). Technovation 112, 102394. https://doi.org/10.1016/j.technovation.2021.102394.

Armstrong, J.S., Overton, T.S., 1977. Estimating nonresponse bias in mail surveys. J. Mark. Res. 14 (3), 396. https://doi.org/10.2307/3150783.

Ball-Burack, A., Salas, P., Mercure, J.-F., 2022. Great power, great responsibility: assessing power sector policy for the UK'S net zero target. Energy Policy 168, 113167. https://doi.org/10.1016/j.enpol.2022.113167.

Barclay, D.W., Higgins, C.A., Thompson, R., 1995. The partial least squares approach to causal modeling: personal computer adoption and use as illustration. Technol. Stud. 2 (2), 285–309.

Benstead, A.V., Mwesiumo, D., Moradlou, H., Boffelli, A., 2022. Entering the world behind the clothes that we wear: practical applications of blockchain technology. Prod. Plan. Control 1–18. https://doi.org/10.1080/09537287.2022.2063173.

Bentler, P.M., 1990. Comparative fit indexes in structural models. Psychol. Bull. 107 (2), 238–246. https://doi.org/10.1037/0033-2909.107.2.238.

Biglari, S., Beiglary, S., Arthanari, T., 2022. Achieving sustainable development goals: fact or fiction? J. Clean. Prod. 332, 130032. https://doi.org/10.1016/j.jclepro.2021.130032.

Brandenburg, M., 2015. Low carbon supply chain configuration for a new product – a goal programming approach. Int. J. Prod. Res. 53 (21), 6588–6610. https://doi.org/10.1080/00207543.2015.1005761.

Brookbanks, M., Parry, G., 2022. The impact of a blockchain platform on trust in established relationships: a case study of wine supply chains. Supply Chain Manag. Int. J> 27 (7), 128–146. https://doi.org/10.1108/SCM-05-2021-0227.

Calandra, D., Secinaro, S., Massaro, M., Dal Mas, F., Bagnoli, C., 2023. The link between sustainable business models and Blockchain: a multiple case study approach. Bus. Strateg. Environ. 32 (4), 1403–1417. https://doi.org/10.1002/bse.3195.

Chin, W.W., 1998. Commentary: issues and opinion on structural equation modeling. MIS Q. 22 (1), vii–xvi.

Conner, K.R., 1991. A historical comparison of resource-based theory and five schools of thought within industrial organization economics: do we have a new theory of the firm? J. Manag. 17 (1), 121–154. https://doi.org/10.1177/014920639101700109.

Corallo, A., De Giovanni, M., Latino, M.E., Menegoli, M., 2023. Leveraging on technology and sustainability to innovate the supply chain: a proposal of Agri-food value chain model. Supply Chain Manag. Int. J. https://doi.org/10.1108/SCM-12-2022-0484.

Cronbach, L.J., 1951. Coefficient alpha and the internal structure of tests. Psychometrika 16 (3), 297–334. https://doi.org/10.1007/BF02310555.

Dabur India Limited. (2020−21). Integrated Annual Report, Great growth comes from greater good, https://www.dabur.com/img/upload-files/142394-Dabur-IR-2020-21.pdf (accessed 26/12/2022).

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.

Dubey, R., Gunasekaran, A., Childe, S.J., Papadopoulos, T., Luo, Z., Roubaud, D., 2020. Upstream supply chain visibility and complexity effect on focal company's sustainable performance: Indian manufacturers' perspective. Ann. Oper. Res. 290 (1–2), 343–367. https://doi.org/10.1007/s10479-017-2544-x.

Dubey, R., Bryde, D.J., Dwivedi, Y.K., Graham, G., Foropon, C., 2022. Impact of artificial intelligence-driven big data analytics culture on agility and resilience in humanitarian supply chain: a practice-based view. Int. J. Prod. Econ. 250, 108618. https://doi.org/10.1016/j.ijpe.2022.108618.

Economic Survey, (2022–23), "India budget", government of India (n.d.). available at https://www.indiabudget.gov.in/economicsurvey/doc/echapter.pdf (accessed 0n 10/10/23).

Elahi, E., Khalid, Z., Tauni, M.Z., Zhang, H., Lirong, X., 2022. Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk: a retrospective survey of rural Punjab, Pakistan. Technovation 117, 102255. https://doi.org/10.1016/j.technovation.2021.102255.

Engwall, M., Kaulio, M., Karakaya, E., Miterev, M., Berlin, D., 2021. Experimental networks for business model innovation: a way for incumbents to navigate sustainability transitions? Technovation 108, 102330. https://doi.org/10.1016/j.technovation.2021.102330.

Epelbaum, F.M.B., Garcia Martinez, M., 2014. The technological evolution of food traceability systems and their impact on firm sustainable performance: a RBV approach. Int. J. Prod. Econ. 150, 215–224. https://doi.org/10.1016/j.ijpe.2014.01.007.

FAO, (2015), Food and agriculture organisation of the United Nations. FAO and the 17 Sustainable development goals. https://www.fao.org/3/i4997e/i4997e.pdf (Accessed on 11/09/2023).

FAO, 2019a. The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction. FAO, Rome, pp. 2–13 (Accessed on 11/09/2023).

FAO, (2019b). Food wastage: key facts and figures. https://www.fao.org/news/story/en/item/196402/icode/ (Accessed on 11/09/2023).

Fayezi, S., Benstead, A., Gold, S., Klassen, R., Van Wassenhove, L., 2021. Modern slavery in supply chains: a soci-technical perspective. Product. Operat. Manag. (Special Edition) 30 (11), 4328–4329. https://doi.org/10.1111/poms.13616.

Feng, H., Wang, X., Duan, Y., Zhang, J., Zhang, X., 2020. Applying blockchain technology to improve Agri-food traceability: a review of development methods, benefits and challenges. J. Clean. Prod. 260, 121031. https://doi.org/10.1016/j.jclepro.2020.121031.

Forbes India, "The Top 10 Largest Economies In The World In 2023". (n.d.). Forbes India, available at:https://www.forbesindia.com/article/explainers/top-10-largest-economies-in-the-world/86159/1 (accessed 10 October 2023).

Fornell, C., Larcker, D.F., 1981. Evaluating structural equation models with unobservable variables and measurement error. J. Mark. Res. 18 (1), 39. https://doi.org/10.2307/3151312.

Friedman, N., Ormiston, J., 2022. Blockchain as a sustainability-oriented innovation?: Opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains. Technol. Forecast. Soc. Change 175, 121403. https://doi.org/10.1016/j.techfore.2021.121403.

Govindan, K., Kannan, D., Jørgensen, T.B., Nielsen, T.S., 2022. Supply chain 4.0 performance measurement: a systematic literature review, framework development, and empirical evidence. Transport. Res. E Logist. Transport. Rev. 164, 102725. https://doi.org/10.1016/j.tre.2022.102725.

Greenland, S., Senn, S.J., Rothman, K.J., Carlin, J.B., Poole, C., Goodman, S.N., Altman, D.G., 2016. Statistical tests, P values, confidence intervals, and power: a guide to misinterpretations. Eur. J. Epidemiol. 31 (4), 337–350.

Hadjielias, E., Christofi, M., Christou, P., Hadjielia Drotarova, M., 2022. Digitalization, agility, and customer value in tourism. Technol. Forecast. Soc. Chang. 175, 121334. https://doi.org/10.1016/j.techfore.2021.121334.

Hair, J.F. (Ed.), 2017. A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM), Second edition. Sage, Los Angeles.

Hair Jr., J.F., Black, W.C., Babin, B.J., Anderson, R.E., 2010. Multivariate data analysis, 7th ed. Prentice Hall, Upper Saddle River, NJ.

Holmström, J., Holweg, M., Lawson, B., Pil, F.K., Wagner, S.M., 2019. The digitalization of operations and supply chain management: theoretical and methodological implications. J. Oper. Manag. 65 (8), 728–734. https://doi.org/10.1002/joom.1073.

Ingenbleek, P.T.M., Krampe, C., 2023. Sustainability in the supply chain – understanding suppliers' resource allocation for sustainability issues. Supply Chain Manag. Int. J> 28 (7), 28–42. https://doi.org/10.1108/SCM-08-2022-0305.

Jiang, Y., Jia, F., Blome, C., Chen, L., 2019. Achieving sustainability in global sourcing: towards a conceptual framework. Supply Chain Manag. Int. J> 25 (1), 35–60. https://doi.org/10.1108/SCM-12-2018-0448.

Kittipanya-ngam, P., Tan, K.H., 2020. A framework for food supply chain digitalization: lessons from Thailand. Prod. Plan. Control 31 (2–3), 158–172. https://doi.org/10.1080/09537287.2019.1631462.

Kline, R.B., 2015. The mediation myth. Basic Appl. Soc. Psychol. 37 (4), 202–213.

Koufteros, X.A., Vonderembse, M.A., Doll, W.J., 1998. Developing measures of time-based manufacturing. J. Oper. Manag. 16 (1), 21–41. https://doi.org/10.1016/S0272-6963(97)00027-2.

Kumar, M., Raut, R.D., Mangla, S.K., Ferraris, A., Choubey, V.K., 2022a. The adoption of artificial intelligence powered workforce management for effective revenue growth of micro, small, and medium scale enterprises (MSMEs). Prod. Plan. Control 1–17. https://doi.org/10.1080/09537287.2022.2131620.

Kumar, M., Raut, R.D., Gunasekaran, A., Venkateshwarlu, M., Choubey, V.K., 2023a. Developing supply chain capabilities through digitalization and viability for controlling the ripple effect. IEEE Trans. Eng. Manag. 1–17. https://doi.org/10.1109/TEM.2022.3233860.

Kumar, S., Raut, R.D., Agrawal, N., Cheikhrouhou, N., Sharma, M., Daim, T., 2022b. Integrated blockchain and internet of things in the food supply chain: adoption barriers. Technovation 118, 102589. https://doi.org/10.1016/j.technovation.2022.102589.

Kumar, S., Raut, R.D., Priyadarshinee, P., Narkhede, B.E., 2023b. Exploring warehouse management practices for adoption of IoT-blockchain. Supply Chain Forum Int. J. 24 (1), 43–58. https://doi.org/10.1080/16258312.2022.2082852.

Li, G., Fang, C.-C., 2022. Exploring factors that influence information resources sharing intention via the perspective of consensus perception of blockchain. Inf. Technol. Manag. 23 (1), 23–38. https://doi.org/10.1007/s10799-021-00338-4.

Li, L., Zhu, W., Wei, L., Liu, Y., Jiang, N., 2025. Digital technology-enabled carbon-neutral management: a mechanism of supply chain digitalization in carbon performance. Technol. Forecast. Soc. Chang. 210, 123834. https://doi.org/10.1016/j.techfore.2024.123834.

Lin, B., Guan, C., 2023. Assessing consumption-based carbon footprint of China's food industry in global supply chain. Sustain. Product. Consump. 35, 365–375. https://doi.org/10.1016/j.spc.2022.11.013.

Lin, Y., Wu, L.-Y., 2014. Exploring the role of dynamic capabilities in firm performance under the resource-based view framework. J. Bus. Res. 67 (3), 407–413. https://doi.org/10.1016/j.jbusres.2012.12.019.

Liu, K.-H., Chang, S.-F., Huang, W.-H., Lu, I.-C., 2019. The framework of the integration of carbon footprint and Blockchain: Using Blockchain as a carbon emission management tool. In: Hu, A.H., Matsumoto, M., Kuo, T.C., Smith, S. (Eds.), Technologies and Eco-Innovation towards Sustainability I. Eco Design of Products and Services, Springer, Singapore, pp. 15–22. https://doi.org/10.1007/978-981-13-1181-9_2.

Lu, S., Cheng, G., Li, T., Xue, L., Liu, X., Huang, J., Liu, G., 2022. Quantifying supply chain food loss in China with primary data: a large-scale, field-survey based analysis for staple food, vegetables, and fruits. Resour. Conserv. Recycl. 177, 106006. https://doi.org/10.1016/j.resconrec.2021.106006.

Macready, A.L., Hieke, S., Klimczuk-Kochańska, M., Szumiał, S., Vranken, L., Grunert, K. G., 2020. Consumer trust in the food value chain and its impact on consumer confidence: a model for assessing consumer trust and evidence from a 5-country study in Europe. Food Policy 92, 101880. https://doi.org/10.1016/j.foodpol.2020.101880.

Mahoney, J.T., 2001. A resource-based theory of sustainable rents. J. Manag. 27 (6), 651–660. https://doi.org/10.1177/014920630102700603.

Makadok, R., 2011. "Invited editorial: the four theories of profit and their joint effects", edited by Barney, J.B., Ketchen, D.J. And Wright, M.*Journal of*. Management 37 (5), 1316–1334. https://doi.org/10.1177/0149206310385697.

Malliaroudaki, M.I., Watson, N.J., Ferrari, R., Nchari, L.N., Gomes, R.L., 2022. Energy management for a net zero dairy supply chain under climate change. Trends Food Sci. Technol. 126, 153–167. https://doi.org/10.1016/j.tifs.2022.01.015.

Mangla, S.K., Kazançoğlu, Y., Yıldızbaşı, A., Öztürk, C., Çalık, A., 2022. A conceptual framework for blockchain-based sustainable supply chain and evaluating implementation barriers: a case of the tea supply chain. Bus. Strateg. Environ. 31 (8), 3693–3716. https://doi.org/10.1002/bse.3027.

Manupati, V.K., Schoenherr, T., Ramkumar, M., Wagner, S.M., Pabba, S.K., Singh, Inder Raj, 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.

Mao, Z., Zhang, S., Li, X., 2017. Low carbon supply chain firm integration and firm performance in China. J. Clean. Prod. 153, 354–361. https://doi.org/10.1016/j.jclepro.2016.07.081.

Matos, S., Viardot, E., Sovacool, B.K., Geels, F.W., Xiong, Y., 2022. Innovation and climate change: a review and introduction to the special issue. Technovation 117, 102612. https://doi.org/10.1016/j.technovation.2022.102612.

Mishra, R., Singh, R., Govindan, K., 2023. Net-zero economy research in the field of supply chain management: a systematic literature review and future research agenda. Int. J. Logist. Manag. 34 (5), 1352–1397. https://doi.org/10.1108/IJLM-01-2022-0016.

Mondal, S., Wijewardena, K.P., Karuppuswami, S., Kriti, N., Kumar, D., Chahal, P., 2019. Blockchain inspired RFID-based information architecture for food supply chain. IEEE Internet Things J. 6 (3), 5803–5813. https://doi.org/10.1109/JIOT.2019.2907658.

Mustafa, F., Andreescu, S., 2018. Chemical and biological sensors for food-quality monitoring and smart packaging. Foods 7 (10), 168. https://doi.org/10.3390/foods7100168.

Nandi, M.L., Nandi, S., Moya, H., Kaynak, H., 2020. Blockchain technology-enabled supply chain systems and supply chain performance: a resource-based view. Supply Chain Manag. Int. J> 25 (6), 841–862. https://doi.org/10.1108/SCM-12-2019-0444.

Net Zero Coalition, (2022). Net-zero commitments must be backed by credible action, https://www.un.org/en/climatechange/net-zero-coalition. Accessed (11/01/2025).

Nunnally, J.C., Bernstein, I.H., 1994. Psychometric Theory, 3rd ed. McGraw-Hill, New York.

Nylund, P.A., Brem, A., Agarwal, N., 2022. Enabling technologies mitigating climate change: the role of dominant designs in environmental innovation ecosystems. Technovation 117, 102271. https://doi.org/10.1016/j.technovation.2021.102271.

OCED, 2022. Environmental impacts along food supply chains: methods, findings, and evidence gaps (OECD food, Agriculture and Fisheries Papers No. 185). https://doi.org/10.1787/48232173-en (accessed 22/01/2025).

Pakseresht, A., Yavari, A., Kaliji, S.A., Hakelius, K., 2023. The intersection of blockchain technology and circular economy in the Agri-food sector. Sustain. Product. Consump. 35, 260–274. https://doi.org/10.1016/j.spc.2022.11.002.

Parmentola, A., Petrillo, A., Tutore, I., De Felice, F., 2022. Is blockchain able to enhance environmental sustainability? A systematic review and research agenda from the perspective of sustainable development goals (SDGs). Bus. Strateg. Environ. 31 (1), 194–217. https://doi.org/10.1002/bse.2882.

Peng, H., Pang, T., Cong, J., 2018. Coordination contracts for a supply chain with yield uncertainty and low-carbon preference. J. Clean. Prod. 205, 291–302. https://doi.org/10.1016/j.jclepro.2018.09.038.

Penrose, E.T., 1959. The Theory of the Growth of the Firm. John Wiley, New York.

PIB (2021). Ministry of Agriculture and Farmers welfare signs 5 MOUs with private companies for taking forward Digital Agriculture. (n.d.). (https://pib.gov.in/pib.gov.in/Pressreleaseshare.aspx?PRID=1754848) (Accessed date 3/3/2025).

Podsakoff, P.M., MacKenzie, S.B., Podsakoff, N.P., 2012. Sources of method Bias in social science research and recommendations on how to control it. Annu. Rev. Psychol. 63 (1), 539–569. https://doi.org/10.1146/annurev-psych-120710-100452.

Pullman, M.E., Maloni, M.J., Carter, C.R., 2009. Food for thought: social versus environmental sustainability practices and performance outcomes. J. Supply Chain Manag. 45 (4), 38–54. https://doi.org/10.1111/j.1745-493X.2009.03175.x.

Qin, L., Kirikkaleli, D., Hou, Y., Miao, X., Tufail, M., 2021. Carbon neutrality target for G7 economies: examining the role of environmental policy, green innovation and composite risk index. J. Environ. Manag. 295, 113119. https://doi.org/10.1016/j.jenvman.2021.113119.

Queiroz, M.M., Fosso Wamba, S., De Bourmont, M., Telles, R., 2021. Blockchain adoption in operations and supply chain management: empirical evidence from an emerging economy. Int. J. Prod. Res. 59 (20), 6087–6103. https://doi.org/10.1080/00207543.2020.1803511.

Rakshit, S., Islam, N., Mondal, S., Paul, T., 2022. Influence of blockchain technology in SME internationalization: evidence from high-tech SMEs in India. Technovation 115, 102518. https://doi.org/10.1016/j.technovation.2022.102518.

Raut, R.D., Gardas, B.B., Narwane, V.S., Narkhede, B.E., 2019. Improvement in the food losses in fruits and vegetable supply chain - a perspective of cold third-party logistics approach. Operat. Res. Perspect. 6, 100117. https://doi.org/10.1016/j.orp.2019.100117.

Rice, J., Liao, T.-S., Galvin, P., Martin, N., 2015. A configuration-based approach to integrating dynamic capabilities and market transformation in small and medium-sized enterprises to achieve firm performance. Int. Small Bus. J. Res. Entrep. 33 (3), 231–253. https://doi.org/10.1177/0266242613495035.

Rogelj, J., Geden, O., Cowie, A., Reisinger, A., 2021. Three ways to improve net-zero emissions targets. Nature 591 (7850), 365–368.

Saadatmand, M., Daim, T., 2019, June. Blockchain technology through the lens of disruptive innovation theory. In: In *2019 IEEE Technology & Engineering Management Conference (TEMSCON)*. IEEE, pp. 1–6.

Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L., 2019. Blockchain technology and its relationships to sustainable supply chain management. Int. J. Prod. Res. 57 (7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261.

Sadawi, A.A., Madani, B., Saboor, S., Ndiaye, M., Abu-Lebdeh, G., 2021. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technol. Forecast. Soc. Chang. 173, 121124. https://doi.org/10.1016/j.techfore.2021.121124.

Saha, A.S., Raut, R.D., Yadav, V.S., Majumdar, A., 2022. Blockchain changing the outlook of the sustainable food supply chain to achieve net zero? Sustainability 14 (24), 16916. https://doi.org/10.3390/su142416916.

Sander, F., Semeijn, J., Mahr, D., 2018. The acceptance of blockchain technology in meat traceability and transparency. Br. Food J. 120 (9), 2066–2079. https://doi.org/10.1108/BFJ-07-2017-0365.

Sarkis, J., 2020. Supply chain sustainability: learning from the COVID-19 pandemic. Int. J. Oper. Prod. Manag. 41 (1), 63–73. https://doi.org/10.1108/IJOPM-08-2020-0568.

Shakhbulatov, D., Arora, A., Dong, Z., Rojas-Cessa, R., 2019. Blockchain implementation for analysis of carbon footprint across food supply chain. In: 2019 IEEE International Conference on Blockchain (Blockchain). IEEE, Atlanta, GA, USA, pp. 546–551. https://doi.org/10.1109/Blockchain.2019.00079.

Simon, A., Bartle, C., Stockport, G., Smith, B., Klobas, J.E., Sohal, A., 2015. Business leaders' views on the importance of strategic and dynamic capabilities for successful financial and non-financial business performance. Int. J. Product. Perform. Manag. 64 (7), 908–931. https://doi.org/10.1108/IJPPM-05-2014-0078.

Singh, J., Pandey, K.K., Kumar, A., Naz, F., Luthra, S., 2022. Drivers, barriers and practices of net zero economy: an exploratory knowledge based supply chain multi-stakeholder perspective framework. Oper. Manag. Res. https://doi.org/10.1007/s12063-022-00255-x.

Su, H.-N., Moaniba, I.M., 2017. Does innovation respond to climate change? Empirical evidence from patents and greenhouse gas emissions. Technol. Forecast. Soc. Chang. 122, 49–62. https://doi.org/10.1016/j.techfore.2017.04.017.

Taghikhah, F., Voinov, A., Shukla, N., Filatova, T., Anufriev, M., 2021. Integrated modeling of extended agro-food supply chains: a systems approach. Eur. J. Oper. Res. 288 (3), 852–868. https://doi.org/10.1016/j.ejor.2020.06.036.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strateg. Manag. J. 18 (7), 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z.

TraceX - Blockchain for Food Supply Chain and Traceability Software". (n.d.)., available at: https://tracextech.com/ (Accessed date – 28/09/ 2023).

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 News (2021), New FAO analysis reveals carbon footprint of agri-food supply chain (https://news.un.org/en/story/2021/11/1105172) (Accessed date 03-03-2025).

UNDP, "Sustainable Development Goals | United Nations Development Programme". (n.d.). UNDP, available at: https://www.undp.org/sustainable-development-goals (accessed 10 October 2023).

Van Wassenhove, L.N., 2019. Sustainable innovation: pushing the boundaries of traditional operations management. Prod. Oper. Manag. 28 (12), 2930–2945. https://doi.org/10.1111/poms.13114.

Villena, V.H., Choi, T.Y., Revilla, E., 2019. Revisiting Interorganizational Trust: Is More Always Better or Could More Be Worse? J. Manag. 45 (2), 752–785. https://doi.org/10.1177/0149206316680031.

Virmani, N., Agarwal, S., Raut, R.D., Paul, S.K., Mahmood, H., 2022. Adopting net-zero in emerging economies. J. Environ. Manage. 321, 115978. https://doi.org/10.1016/j.jenvman.2022.115978.

Vu, N., Ghadge, A., Bourlakis, M., 2023. Blockchain adoption in food supply chains: a review and implementation framework. Prod. Plan. Control 34 (6), 506–523. https://doi.org/10.1080/09537287.2021.1939902.

Wamba, S.F., Queiroz, M.M., Trinchera, L., 2020. Dynamics between blockchain adoption determinants and supply chain performance: an empirical investigation. Int. J. Prod. Econ. 229, 107791. https://doi.org/10.1016/j.ijpe.2020.107791.

Wang, M., Wang, B., Abareshi, A., 2020. Blockchain technology and its role in enhancing supply chain integration capability and reducing carbon emission: a conceptual framework. Sustainability 12 (24), 10550. https://doi.org/10.3390/su122410550.

Wang, Y., Chen, C.H., Zghari-Sales, A., 2021. Designing a blockchain enabled supply chain. Int. J. Prod. Res. 59 (5), 1450–1475. https://doi.org/10.1080/00207543.2020.1824086.

Wu, L.-Y., 2010. Applicability of the resource-based and dynamic-capability views under environmental volatility. J. Bus. Res. 63 (1), 27–31. https://doi.org/10.1016/j.jbusres.2009.01.007.

Wu, Z., Duan, C., Cui, Y., Qin, R., 2023. Consumers' attitudes toward low-carbon consumption based on a computational model: evidence from China. Technol. Forecast. Soc. Chang. 186, 122119. https://doi.org/10.1016/j.techfore.2022.122119.

Yoo, M., Won, Y., 2018. A study on the transparent Price tracing system in supply chain management based on Blockchain. Sustainability 10 (11), 4037. https://doi.org/10.3390/su10114037.

Yousefi, S., Mohamadpour Tosarkani, B., 2022. An analytical approach for evaluating the impact of blockchain technology on sustainable supply chain performance. Int. J. Prod. Econ. 246, 108429. https://doi.org/10.1016/j.ijpe.2022.108429.

Zhang, A., Alvi, M.F., Gong, Y., Wang, J.X., 2022. Overcoming barriers to supply chain decarbonization: case studies of first movers. Resour. Conserv. Recycl. 186, 106536. https://doi.org/10.1016/j.resconrec.2022.106536.

Zhang, S., Wang, K., Xu, W., Iyer-Raniga, U., Athienitis, A., Ge, H., Cho, D.W., et al., 2021. Policy recommendations for the zero energy building promotion towards carbon neutral in Asia-Pacific region. Energy Policy 159, 112661. https://doi.org/10.1016/j.enpol.2021.112661.

Zhu, Q., Duan, Y., Sarkis, J., 2024. Supply chain carbon transparency to consumers via blockchain: does the truth hurt? Int. J. Logist. Manag. 35 (3), 833–864. https://doi.org/10.1108/IJLM-03-2023-0109.

Aditi Saha serves at Department of Operations and Supply Chain Management, Indian Institute of Management.

Rakesh D. Raut serves as Associate Professor at Department of Operations and Supply Chain Management, Indian Institute of Management Mumbai, India.

Mukesh Kumar serves as Principal at Ganga Memorial College of polytechnic, Nalanda, India.

Sanjoy Kumar Paul serves at UTS Business School, University of Technology Sydney, Sydney, Australia.

Yangyan Shi serves at College of Business Adminstration, Capital University of Economics and Business, Beijing, China; Macquarie Business School, Macquarie University, Sydney, Australia.

Bhavin Shah serves as Assistant Professor at Operations and Supply Chain Management Group, Indian Institute of Management Sirmaur, India.

Sudishna Ghoshal serves at T A Pai Management Institute Bengaluru, Manipal Academy of Higher Education, Manipal, India.