Blockchain technology adoption for secured and carbon neutral logistics operations: Barrier intensity index framework

Anchal Gupta
Assistant Professor
Lal Bahadur Shastri Institute of Management,
Dwarka, New Delhi, India, 110075
Email: anchal.gupta1503@gmail.com

Rajesh Kumar Singh
Professor,
Management Development Institute,
Gurgaon, India-122007
Email: rajesh.singh@mdi.ac.in

Muhammad Mustafa Kamal
Operations and Analytics, Management Department, University of Exeter Business School, UK
Email: m.m.kamal@exeter.ac.uk

Abstract

Around 196 countries committed to become part of United Nation's Framework Convention on Climate Change (UNFCC) through Paris Agreement and pledged to achieve carbon neutrality goals by 2050. The organizations have recognised the importance of digital technologies for achieving sustainable goals. To accelerate the transition to low-carbon energy systems, to best of author's knowledge, this is the first attempt which addresses issues of BCT for decarbonization in logistics sector in developing economy using theories like TOE (technological, organizational and environmental) and IRT (Innovation resistance theory). A comprehensive literature review was undertaken using PRISMA to recognise the barriers linked to the blockchain technology adoption for reducing carbon emissions. To prioritize these barriers, inputs from ten experts belonging to different industry verticals and academics were taken. Ordinal Priority approach (OPA) is used to prioritise them. Further, the cause-and-effect relationship among the listed barriers is established using Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique. A real-life case illustration on Indian logistics company has been considered and the barrier intensity index is computed using Graph Theory Matrix approach (GTMA) for the case company. The results suggest that 'Organizational Barriers' are the most crucial category of barriers followed by 'Environmental Barriers'. The results also show that the organizational barriers and environmental barriers belong to the cause group whereas technical and risk barriers are the part of the effect group. Based on the findings of GTMA, it has been observed that the overall barrier intensity index for the case company

lies close to the centre of the worst and best theoretical values. The intensity index value will help case company to position themselves properly to formulate new strategies for secured and carbon neutral operations. Researchers and supply chain practitioners can devise new strategies and policies for achieving net zero goals by understanding the interplay between blockchain technology, organizational policies, and environmental outcomes. This research work can contribute to provide distinct perspective to look upon the BCT adoption issues in developing countries and can assist logistics industry stakeholders to plan and design new integrated BCT systems with carbon reduction initiatives.

Keywords: Blockchain technology, Net zero goals, Carbon neutrality, Sustainability, Logistics, Ordinal Priority Approach (OPA), DEMATEL, GTMA

Introduction

In recent decades, the world has witnessed the accelerating impact of global warming caused due to increase in greenhouse gases (GHG) emissions from human and industrial interventions. To stabilize the climate conditions, the world needs to develop stringent environmental regulations to reduce GHG emissions and henceforth achieving the net zero carbon emission goals (Bag, 2023; Das and Ghosh, 2023; Du et al..2023). Unfortunately, no country in the world has yet achieved the carbon neutrality goals. Around 196 countries have become the part of Paris Agreement and pledged to reach the net zero goals by 2050 (Danigels, 2019; Mishra et al., 2022; Zhang et al., 2022). China, the largest GHG emitter (29.18%) followed by United States (14.02%) and India (7.09%) are the main responsible countries and require strong and sustained carbon reductions to meet sustainable development goals (Worldometer Info, 2022). Apart from the other sectors, the logistics or transportation sector only accounts for 11% of global greenhouse gas emissions, in which 7125 metric tons of carbon emitted through light and heavy vehicles, railways, shipping, aviation, and warehousing (IEA, 2022). This calls for increased need of sustainable logistics which can contribute to achieve carbon neutrality goals. Sustainable logistics can be achieved through various means, such as optimizing routes, using fuel-efficient vehicles, reducing idle times, and using renewable energy sources. In addition, waste reduction and enhanced recycling practices in the supply chain can also contribute to a more sustainable logistics and warehousing system (Goh, 2019; Kouhizadeh et al., 2020). One of the main approaches to sustainable logistics is to shift from traditional fossil fuel-based vehicles to electric vehicles, which emit significantly lower levels of GHGs and air pollutants (Mishra et al., 2022; Virmani et al., 2022). Governments can play a key role in promoting this transition by providing incentives for the use of electric vehicles, such as tax credits, subsidies, and access to charging infrastructure (Xu et al., 2019; Kannan et al., 2022). Another approach to sustainable logistics is to use alternative modes of transportation, such as rail, water, and bike, for short-haul trips, whereever possible (Smokers et al., 2014; Otter et al., 2017). Moreover, Ahsan et al. (2023) conducted a comprehensive review on sustainable rail technologies for achieving net zero goals and compared four rail technologies (Standalone and hybrid hydrogen batteries) from environmental, social, economic and technical perspective. This not only reduces GHG emissions but also helps to reduce congestion and improve local air quality. Bai et al. (2023) explored transportation sector for achieving net zero goals and identified filling technology gaps and improvement in management inefficiencies can be the possible mitigation strategies for reducing carbon emission. Therefore, the use of digital technologies, such as Artificial Intelligence, Blockchain, and the Internet of Things, can help optimize logistics operations and reduce the environmental impact of transportation (Saberi et al., 2018; Tijan et al., 2019; Virmani et al., 2021).

The integration of IoT and Industry 4.0 with Blockchain Technology (BCT) holds great potential for reducing carbon emissions in the supply chain industry (Fernando et al., 2021; Kurramovich et al., 2022). By collecting real-time data through IoT sensors and using AI for optimization and decision making, organizations can make informed choices that minimize their impact on the environment (Gupta and Singh, 2021). Govindan (2023) explored transformation of traditional circular economy practices to smart circular economy through digitalization for achieving SDGs. Furthermore, the use of blockchain technology can provide transparency and efficiency in supply chain operations, which can further support efforts to reduce carbon emissions (Petersen et al., 2018, Cole et al., 2019, Babich & Hilary, 2020). However, the previous research on blockchain technology and its impact on various aspects of the supply chain industry is still in its early stages (Risius and Spohrer, 2017; White, 2017). While there has been some progress in understanding the technical design and features of blockchain technology but there is need for further research on its adoption and implementation issues by businesses in developing nations. From the past studies, it has been noted that the real industrial applications of blockchain are inadequate (Pournader et al., 2020) and only few applications of large scale blockchain technology has been implemented successfully (Babich & Hilary, 2020). By this time, the decentralized nature of blockchain technology has been mainly explored and majorly contributing towards record keeping and managing real-time transactions. However, the shared database is tamper-proof and can be accessed by all parties involved in the supply chain, enabling real-time tracking of products, and reducing the risk of fraud and errors. Overall, the future of blockchain technology in supply chain management seems promising but it will require the development of a supportive ecosystem and the overcoming of technical, organizational, and environmental challenges to realize its full potential (Varriale et al., 2020; Parmentola, et al., 2022; Jamwal et al., 2023; Yontar, 2023). In developing economies, the adoption of blockchain technology in supply chain management is still at infancy level and hurdled through several challenges, such as the high implementation cost, the lack of standardization, and the need for technological expertise (Dujak and Sajter, 2019; Fernando et al., 2021). In addition, some organizations may be hesitant to embrace blockchain technology due to cultural and organizational resistance to change. The lack of understanding and familiarity with the technology among business leaders in developing economies is a significant obstacle to its widespread adoption (Biswas and Gupta, 2019; Kouhizadeh et al., 2020). Furthermore, there is a need for a clear and comprehensive regulatory framework to realize BCT potential for reducing carbon emissions and improving supply chain efficiency.

In literature, several researchers have explored blockchain technologies for its significant benefits and issues with adoption and implementation. For instance, Frizzo-Barker et al. (2020) conducted a comprehensive systematic review on blockchain technology and emphasized on the research gap and necessity of further research in same field especially in context of non-Western countries to understand its socio-economic impact. Bockel et al. (2021) highlighted the importance of blockchain by suggesting it to be one of the possible critical solutions to implement the circular economy and exposed the cruciality in linking sustainable development with blockchain technologies. On similar lines, Parmentola, et al. (2022) analysed 195 past studies on blockchain technology contribution to environmentally sustainable goals for a period of 5 years (2015-2020) and results indicated its contribution in several domains including energy efficiency, sustainable supply chain and smart and reliable manufacturing practices.

Du et al. (2023) established a positive association between green logistics, green innovation and renewable resources to reduce transport-based carbon emissions and identified adverse effects of financial innovation in achieving net zero goals in the context of BRICS-T economies. Thus, to best of author’s knowledge, this is the first study which addresses issues of BCT for decarbonization in logistics sector in developing economy using TOE (technological, organizational and environmental) and IRT (Innovation resistance theory) theories. Because of growing importance of technology and sustainability in this sector, where

63% of the organisations have deployed sustainable logistics practices while only 10% have a mature carbon reduction program (Capgemini - India, 2023), this study can offer valuable insights for BCT challenges faced by logistics sector in sustainability context. Contrary to previous studies (Lohmer and Lasch, 2020; Kannan et al., 2022; Bai et al., 2023; Du et al., 2023; Wachsmut et al., 2023) that majorly emphasized on developed economies, an attempt has been made in this study to explore the applications of blockchain technology in reducing carbon emissions for logistics sector in developing economy. Thus, a developing economy (i.e., India) has been considered as a case in our paper with a particular focus on logistics service providers for their logistics and warehousing operations. Moreover, in past studies, no framework was suggested for adoption of BCT technology for reducing carbon emissions specifically in logistics sector. This study will help researchers and practitioners by bridging the gap in the existing research work. Therefore, this study aims to answer the following research questions:

RQ1. What are the critical barriers to blockchain implementation for carbon neutral logistics and warehousing operations in a developing economy?

RQ2. How can these barriers have prioritized for logistics organizations in a developing economy?

RQ3. What is the causal relationship between identified barriers for blockchain implementation for low carbon economy for logistics and warehousing operations?

RQ4. What strategies can be developed by logistics organizations based on the barrier intensity index for implementing blockchain technology for reducing carbon emissions?

This study will help organizations to understand the interplay between blockchain technology, organizational norms and environmental pressures. The present study will assist organizations in understanding and prioritizing the barriers to BCT adoption for net zero goals based on their criticality. This study not only provides the inputs for prioritization of barriers but also explores the causal relationship among barriers which will help supply chain practitioners in formulating appropriate sustainable polices. In literature, specifically in context of developing countries, hardly any study is found like this research work. For logistics organizations of developing country where blockchain technology and sustainability initiatives are at initial stages, this study can be found beneficial and can help organizations to position themselves and plan their sustainable actions accordingly. The results of the study can suggest new directions for sustainable solutions through technology to the developing economies.

The rest of the paper is organised as follows. Section 2 discusses comprehensive literature review on block chain applications and issues for sustainable supply chain and identification of barriers in implementing blockchain for carbon neutrality using TOE and IRT theories. The research methodology Ordinal Priority Approach (OPA), Decision Making Trial and Evaluation Laboratory (DEMATEL) has been applied and step by step procedure is presented in Section 3. Data analysis and findings have been discussed in Section 4. In section 5, a case illustration on Indian logistics service providers has been considered and barrier intensity index has been evaluated using Graph Theory matrix approach (GTMA). The implications of the study along with conclusion and future scope are discussed in consecutive sections.

2. Literature review

This study adopts a combination of the Technology, Organisation, Environment (TOE) theory and the Innovation Resistance Theory (IRT) to analyse the barriers faced by logistics organisations in adopting blockchain technologies for sustainable logistics. By combining these theories, the analysis of interplay of technology, organization and environment can shed light on the factors that hinder the adoption of blockchain technology for environmental sustainability.

2.1 Technology, Organizational and Environmental (TOE)

It is an organizational level theory proposed by Tornatzky and Fleischer (1990), which has been widely accepted in literature for establishing a multi-perspective system. This theory helps in exploring the organizational factors required for innovation using the facets of technology, organization, and environment. The technology context allows the examination of the features and benefits of blockchain technology, including its potential to improve supply chain visibility, transparency, and efficiency (Dujak and Sajter, 2019; Ali et al., 2021; Yadav et al., 2023). The organizational context enables the assessment of the internal factors affecting the adoption of blockchain technology, such as the company's culture, structure, and resources (Rosli et al., 2012). The environmental context considers the external factors that influence the adoption of blockchain technology in logistics, including the regulatory environment, market competition, and stakeholder pressures (Chiu et al., 2017). In this study, TOE theory has been chosen for several reasons. First, TOE theory takes environmental concern into consideration which is missing in most of the other theories. Second, this theory discusses all outcomes from initiation to the end including all the stages of the innovation cycle. Third, the wide applicability of the TOE theory across various fields, such as e-commerce web services (Aljowaidi,2015), mobile applications (Chiu et al., 2017), cloud computing (Umam et al.,

2020) and drone technology (Ali et al., 2021), further underscores its usefulness in studying the adoption of innovative technologies. In previous studies, no study has been found which has used this theory to study blockchain adoption barriers for carbon neutrality.

2.2 Innovation Resistance Theory (IRT)

This theory proposed by Ram (1987) and focused on the resistance of the users to implement innovation in technology. The customer resistance can be active or passive as per IRT theory. Active resistance refers to resistance that arises directly from the characteristics of the innovation itself and can be studied through functional and risk barriers. Passive resistance, on the other hand, arises from conflicts between the innovation and the existing belief system of the customers. This type of resistance can be studied through psychological barriers, such as image barriers and tradition barriers. IRT takes both functional and psychological barriers into account which can provide a comprehensive understanding of why consumers may resist the adoption of new technologies (Heidenreich and Spieth, 2013; Priyadarshini et al., 2022). Since this study is focused on the barriers of BCT adoption for carbon neutrality, IRT is more relevant theory to understand the resistance better. In past studies, IRT has been applied to digital payments (Kaur et al., 2020), mobile gaming (Oktavianus et al., 2017), food delivery apps (Kaur et al., 2020a) and online travel websites. However, no study has been found in literature that have used IRT for finding resistance to blockchain for reducing carbon emissions.

2.3 Identification of barriers for adoption of blockchain for secured and carbon neutral operations

Firstly, a pilot search was conducted to understand the ongoing research in the field of blockchain, logistics sustainable practices and blockchain applications for sustainability and specifically for decarbonization. Two databases, Scopus and EBSCO were searched thoroughly to obtain the relevant research papers and search syntax has been discussed in Table 1. In this study, PRISMA (Preferred Reporting Items for Systematic Reviews and meta-Analyses) approach was followed to select articles from the databases and then final inclusion of relevant articles in the study. A total of 2236 articles were obtained from Scopus database in the beginning of the search. Then few keywords have been added to limit the search as source type was restricted to “Journal type”, subject was limited to “Business and Management” and “Decision Sciences”, language was selected to “English” and document type was set to “Articles”. After making these changes, 532 articles were obtained from the Scopus database. Initially, EBSCO resulted 231 articles related to our search but after using keywords, 88 articles were obtained from EBSCO. Around 25 articles were added to the study through cross referencing and other sources. All the articles were uploaded to Zotero to remove duplication and finally leaving us with 415 articles. Further, 225 articles were removed from the study based on abstract screening and finally, after full-text screening, it left us with 152 relevant and appropriate articles for the study. The flow of articles selection and inclusion through PRISMA has been shown in Figure 1.

Table 1: Search syntax

Database Selected	**Search syntax**	**Research papers found**
Scopus	TITLE-ABS-KEY(“blockchain technology” OR “emerging technologies” OR “I4.0 technologies”) AND (“carbon neutrality” OR “decarbonization” OR “net zero goal” OR “sustainability” OR “green practices”) AND (“logistics” OR “supply chain” or “warehousing”) AND (“barriers” OR “hurdles” OR “challenges”) AND (LIMIT-TO(SUBJAREA, “BUSI”)) OR (LIMIT-TO(LANGUAGE, “English”)) OR (LIMIT-TO (DOCTYPE,“ar”)) OR (LIMIT-TO (SRCTYPE,”j”))	532
EBSCO	LANG-“ENGLISH” AND DOC-“ARTICLES” AND PUBTYPE-“ACADEMIC JOURNALS”	88

Last accessed on 12th January, 2023.

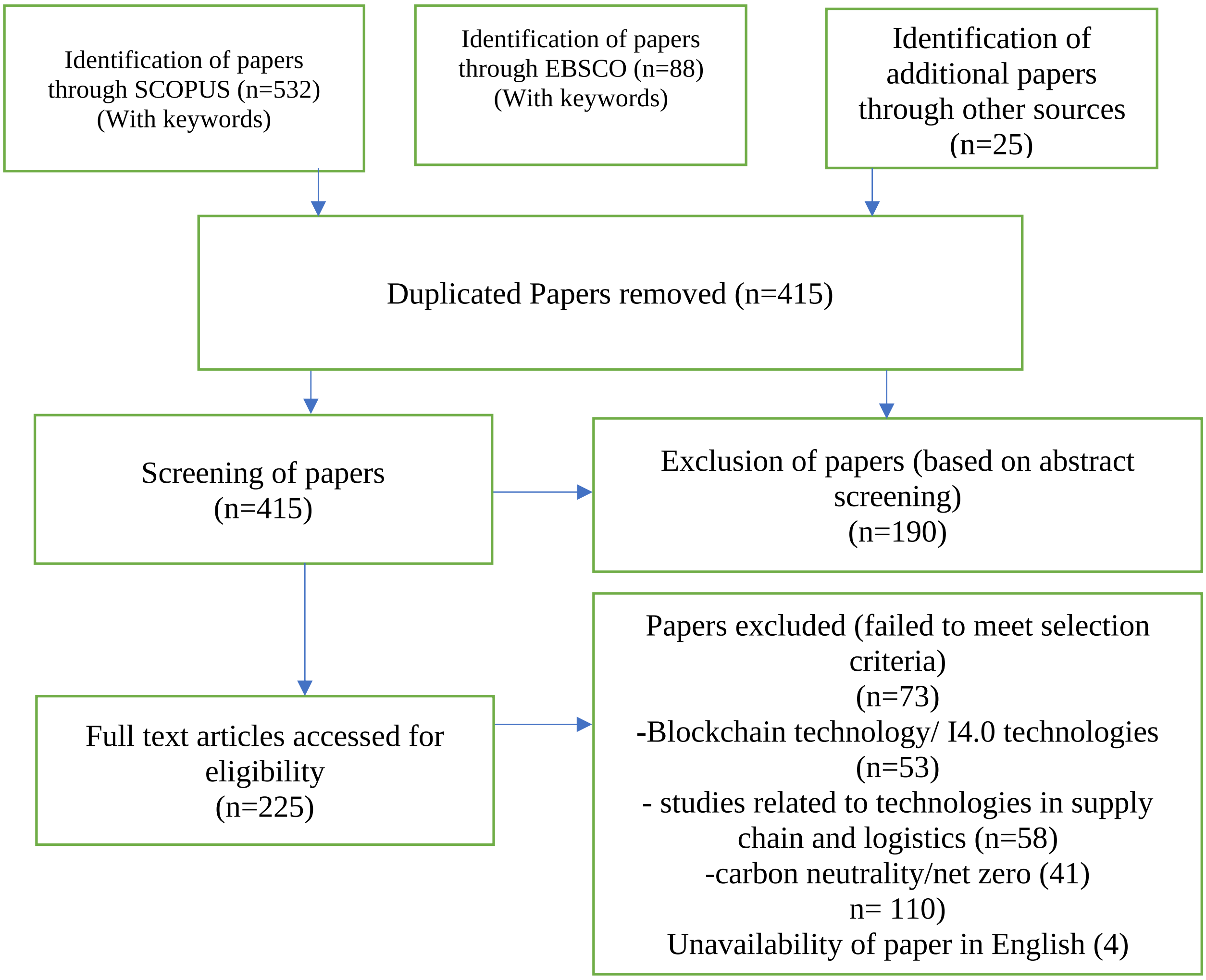

Figure 1: Systematic Literature Review using PRISMA

In this section, a list of 25 barriers have been extracted from TOE and IRT theories and identified from vast literature review. The logistics organizations need to overcome these barriers to adopt BCT for achieving net zero goals.

2.3.1 Technological barriers: The adoption of blockchain technology for carbon neutrality is still in its initial stages and organizations face several technological challenges. Blockchain has limited capabilities with simultaneous multiple transactions which create issue in monitoring real time data generated for carbon emissions at multiple locations (Saberi et al., 2019; Khan et al., 2022). Current blockchain platforms and protocols available with its own standards and specifications which restricts to integrate, communicate, and share data which is extremely important for obtaining accurate carbon emissions reports (Etemadi et al., 2021). The regulatory framework surrounding blockchain is still evolving, and it can be challenging to ensure compliance with existing laws and regulations (Kouhizadeh et al., 2021; Govindan, 2022). While blockchain has the potential to revolutionize carbon neutrality reporting and verification, many technological barriers need to be addressed to ensure its wide adoption. The technological barriers identified through literature review have discussed in Table 2.

Table 2: Technological Barriers for BCT adoption for carbon neutrality

S.No.	Technological Barriers	Explanation	References
1.	Lack of technical skills for BCT implementation for achieving carbon neutrality (TB1)	Being BCT is evolving technology, lack of trained manpower for implementing BCT for reducing carbon footprints.	Lohmer and Lasch (2020); Kouhizadeh et al. (2021); Khan et al. (2022)
2.	Immutability challenge of BCT for achieving energy efficient logistics solutions (TB2)	BCT's immutability can make it challenging to update or modify records, which can be problematic if errors or inaccuracies are discovered	Zheng et al. (2018); Monrat et al. (2019); Etemadi et al. (2021)
3.	Immature BCT for low carbon economies (TB3)	Integrating BCT solutions for decarbonization with existing enterprise systems and workflows can be complex and time-consuming	Saveri et al. (2019); Lohmer and Lasch (2020); Govindan (2022)
4.	Impact of scalability issues of BCT on net zero goals (TB4)	Blockchain systems can be slow and resource-intensive, making it difficult to process many transactions at once which is desirable for carbon emission data	Zheng et al. (2018); Etemadi et al. (2021) Lohmer and Lasch (2020)
5.	Lack of interoperability and standardization of BCT in collaborating stakeholders for sustainability (TB5)	BCT fragmentation create difficulty in sharing data through different systems for transparency and accuracy in carbon emission reporting.	Monrat et al. (2019); Saberi et al. (2019); Govindan (2022)

2.3.2 Organizational Barriers: It refers to the organizational level issues in investing in necessary resources to implement BCT, including technical expertise, personnel training, and hardware and software costs (Baker, 2012). Additionally, stakeholders need to collaborate to develop interoperable BCT solutions for decarbonization that can achieve end-to-end supply chain traceability and transparency (Das and Ghosh, 2023). Therefore, implementing BCT can be expensive, and the costs associated with its adoption may be a barrier for many organizations (Malik et al., 2022; Kumar et al., 2023). Furthermore, the complexity of BCT become more difficult for non-technical stakeholders to understand and adopt. Most importantly, several organizations may not be aware of the potential of BCT to improve supply chain transparency, enhance traceability, and support carbon neutrality goals. BCT adoption in logistics organizations can face several organizational barriers which are retrieved from literature and discussed in Table 3.

Table 3: Organizational Barriers for BCT adoption for carbon neutrality

S.No.	Organizational Barriers	Explanation	References
1.	Inadequate IT infrastructure for implementing BCT for low carbon logistics (OB1)	Lack of storage capacity, limited bandwidth, lack of computing power and cybersecurity risks can make BCT adoption difficult for reducing carbon emissions	Palsson and Johansson (2016); Subramanian and Abdulrahman (2017); Kumar et al. (2023)
2.	Lack of top management vision for Net zero goals (OB2)	Top management has lack of direction and focus towards BCT adoption and implementation for sustainable goals.	Bonsu (2020); Kumar et al. (2023)
3.	High development and maintenance cost involved in BCT implementation (OB3)	The cost of BCT implementation can include hardware, software, and personnel training costs and maintenance cost calls for regular updation and monitoring, which	Kannan et al. (2022); Zhang et al. (2022); Bag (2023)

		many not fit into an organization's budget.	
4.	Rigid organizational culture for technological innovations (OB4)	Implementing BCT may require changes to existing processes and structures, which can be met with resistance from employees.	Zhang et al. (2022)
5.	Lack of investment in Research & Development (R&D) on adoption of BCT for carbon neutrality (OB5)	Cost of implementing BCT for decarbonization can be expensive and challenging for organizations to invest in its research and development specifically at its nascent stage.	Subramanian and Abdulrahman (2017); Olatunji et al. (2019); Bag (2023)
6.	Lack of Government incentive policies for net zero goal using BCT (OB6)	Lack of awareness and clarity of government towards BCT implementation for sustainable development and create major hurdle in devising appropriate rules and regulations.	Kannan et al. (2022)
7.	Non-stringent environment protection laws for carbon neutrality (OB7)	Non-stringent laws lead to lack of accountability and enforcement which in turn leads to poor compliance and limited progress towards achieving carbon neutrality.	Bonsu (2020); Kumar et al. (2023)
8.	Requirement of high computational power leads to huge cost of electricity consumption (OB8)	BCT systems require high performance computing systems and require large amount of electricity which will result in higher electricity bills and environmental impacts due to increased carbon footprints of the electricity generation.	Subramanian and Abdulrahman (2017); Olatunji et al. (2019);

9.	Unorganized and fragmented logistics industry (OB9)	Logistics unorganised structure result in lack of standardization and coordination which lead to inefficiencies, delays and increased environmental impacts.	Gupta et al. (2018)

2.3.3 Environmental Barriers: It refers to the issues generated due to not adoption of eco-friendly strategies and alternatives for implementing technologies. These are the external barriers that deal with suppliers and customers involvement, government support and competition (Priyadarshini et al., 2022). BCT networks such as mining rigs and other computer equipment can get quickly obsolete which result in large amounts of e-waste which can have significant environmental impacts (Kannan et al., 2022). Moreover, many BCT networks still rely on fossil fuels for energy, which can undermine their environmental benefits (Bonsu, 2020; Jayakumar et al., 2022). There are several environmental barriers to BCT adoption that can hinder its effectiveness in achieving carbon neutrality and are discussed in Table 4.

Table 4: Environmental Barriers to BCT for carbon neutrality

S.No.	Environmental Barriers	Explanation	References
1.	Lack of suppliers and customers awareness towards net zero goals (EB1)	Lack of education, training and incentives to suppliers and customers can motivate them to develop joint initiatives aimed at achieving net zero goals through technology	Palsson and Johansson, (2016); Zhang et al. (2022)
2.	Unequal support from all supply chain stakeholders for net zero goals using BCT (EB2)	All stakeholders of supply chain do not share a sense of ownership and shared responsibility for achieving carbon neutrality using BCT	Mishra et al. (2022); Zhang et al. (2022); Kumar et al. (2023)

3.	Lack of control over suppliers of subcontracted services or leased facilities (EB3)	Lack of supplier evaluation processes and limited commitments of suppliers for sustainable development cannot ensure their contribution towards net zero goals	Goh (2019); Nandi et al. (2021)
4.	Lack of coordination, and collaboration among SC stakeholders for using technology for low carbon economies (EB4)	Supply chain partners do not share common goals and standards for using BCT and reducing carbon emissions from logistics and warehousing	Palsson and Johansson, (2016); Olatunji et al. (2019); Zhang et al. (2022)
5.	Lack of effective performance frameworks for measuring impact of BCT on net zero goals across supply chain (EB5)	Organizations find difficulty in measuring the impact and assessing the progress of BCT towards sustainable goals due to lack of effective performance frameworks.	Olatunji et al. (2019); Bonsu (2020); Mishra et al. (2022).
6.	Inability to control excessive carbon emission from non-productive logistics and warehousing operations (EB6)	Due to limited scalability of BCT, addition of more users in network enhance energy consumption and environmental impacts can also increase.	Palsson and Johansson, (2016); Mishra et al. (2022)
7.	Inadequate use of renewable, recyclable, and reusable material in logistics and	Use of wind and solar power can help in reducing high power consumption associated	Bonsu (2020); Jayakumar et al. (2022); Kannan et al. (2022)

	warehousing operations (EB7)	with BCT and can provide green solutions to logistics and warehousing.	

2.3.4 Risk Barriers: It refers to the organization's resistance towards innovation uncertainties. There may be uncertainty around the technical aspects of blockchain technology, and there may be concerns about the feasibility of using blockchain for carbon neutrality. Regulatory barriers to the adoption of blockchain technology for carbon neutrality, particularly issues such as data privacy, security, and ownership can create hurdle (Yontar,2023). Inadequate performance metrics and lack of strict government laws may limit the ability to use blockchain technology in certain contexts. From literature review, the risk barriers have been identified and discussed in Table 5.

Table 5: Risk Barriers to BCT for carbon neutrality

S.No.	Risk Barriers	Explanation	References
1.	Fear of failure of BCT technology for reducing carbon emissions (RB1)	BCT technology is at its initial phase so adoption of BCT technology for sustainability may be risky.	Kumar and Chopra (2022); Yontar (2023)
2.	Negative perception towards BCT (RB2)	Immutable behaviour of BCT has discouraged many organizations to adopt for carbon emission records.	Chengyue et al. (2021); Balzarova et al. (2022)
3.	Paybacks are uncertain (RB3)	Need to conduct cost-benefit analysis and identify key performance indicators before BCT adoption for sustainability	Goh (2019); Zhang et al. (2022)
4.	Risk of cyber-attacks on stored data (RB4)	Robust cyber- security measures, security	Liang et al. (2018)

		protocols, regular audits and risk assessments can help organizations to deal with cybercrime and protect their stored data using BCT	

3. Research Methodology

In this study, an integrated approach of Ordinary Priority Approach (OPA) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) has been employed, and further Graph Theory Matrix Approach (GTMA) has been used to find the barrier intensity index of logistics companies for adopting BCT for carbon neutrality based on identified barriers. OPA has been used to assess and prioritize the identified barriers from literature review by determining the weights of triple components including experts, criteria and alternatives (Ataei et al., 2020), whereas DEMATEL has been used to analyse the cause-and effect relationships among identified barriers (Fontela and Gabus, 1976).

OPA is a simple technique used in Multi-Attribute Decision-Making (MADM) to determine the numerical weights of decision-making alternatives by experts among a set of alternatives based on multiple criteria (Ataei et al., 2020). DEMATEL will help in providing a structured framework for analysing and interpreting this causal relationship and will assist decision - makers to make more informed and effective decisions. Using GTMA, the barrier intensity index has been evaluated through a real-life case illustration on logistics. GTMA involved a diagraph representation of the entire system in form of subsystems and their associations, which helps decision maker to understand the system easily and take appropriate and effective decisions.

In this study, a total of 10 industry experts (Table 6) and 2 academicians with huge experience, vast knowledge, and practical expertise in using blockchain technology for logistics and warehousing and working towards sustainability were consulted. Experts were invited from different industry verticals such as automobiles, retail, electronics, pharmaceuticals, and third-party logistics. These industry verticals were shortlisted based on their application of BCT for sustainability. Before selecting final experts, authors have ensured that the selected experts were either implemented BCT in their respective organizations or in the process of adoption and then further their interest and experience in BCT and sustainability. Out of these ten experts, one belonged to automobile industry based out of Delhi NCR, two experts were associated with pharmaceuticals based out of Bengaluru, three were belonged to the third-party logistics based out of Delhi and NCR and one is from retail and electronics respectively from Maharashtra and Chennai. Two academicians chosen for study also have rich research experience in application of BCT for decarbonization. The wide spread of experts helps researchers to receive varied perspectives from different fields across different locations. Focused group discussions have been done with experts through both offline and online platforms. Semi-structured interviews were conducted to take their inputs on the challenges in adoption BCT for carbon neutrality. A sample size of 10 experts can be assumed satisfactory as in in literature, Murry & Hammons (1995) and Novakowski and Wellar (2008) have showed sufficiency in taking 5 to 15 experts and enough to provide heterogeneity to the panel of experts and able to provide quality results. Moreover. In past studies, most of the studies using MCDM techniques considered the sample size from 5 to 10. Therefore, a sample of 10 experts van be considered adequate for this study.

Table 6: Experts Profile

S.No	**Expert**	**Designation**	**Sector**	**Experience (in years)**
1	E1	Senior Manager	Automobile	15
2	E2	Head IT	Pharmaceuticals	12
3	E3	Senior Manager	Pharmaceuticals	16
4	E4	Assistant GM	Logistics	13
5	E5	Area Manager	Logistics	10
6	E6	Country Head	Logistics	17
7	E7	Senior Head	Retail	20
8	E8	Lead Global	Electronics	18
9	E9	Professor	Academician	25
10	E10	Professor	Academician	22

This study has been conducted in three phases. Firstly, the experts' inputs have been taken to prioritize the barriers using OPA. In second phase, the causal relationship among barriers have been established using DEMATEL based on inputs received from industry experts. Thirdly, a real-life case illustration of Indian logistics company has been considered to understand its barrier intensity index for BCT adoption for carbon neutrality using GTMA. A flow chart showing all steps have been shown in Figure 2.

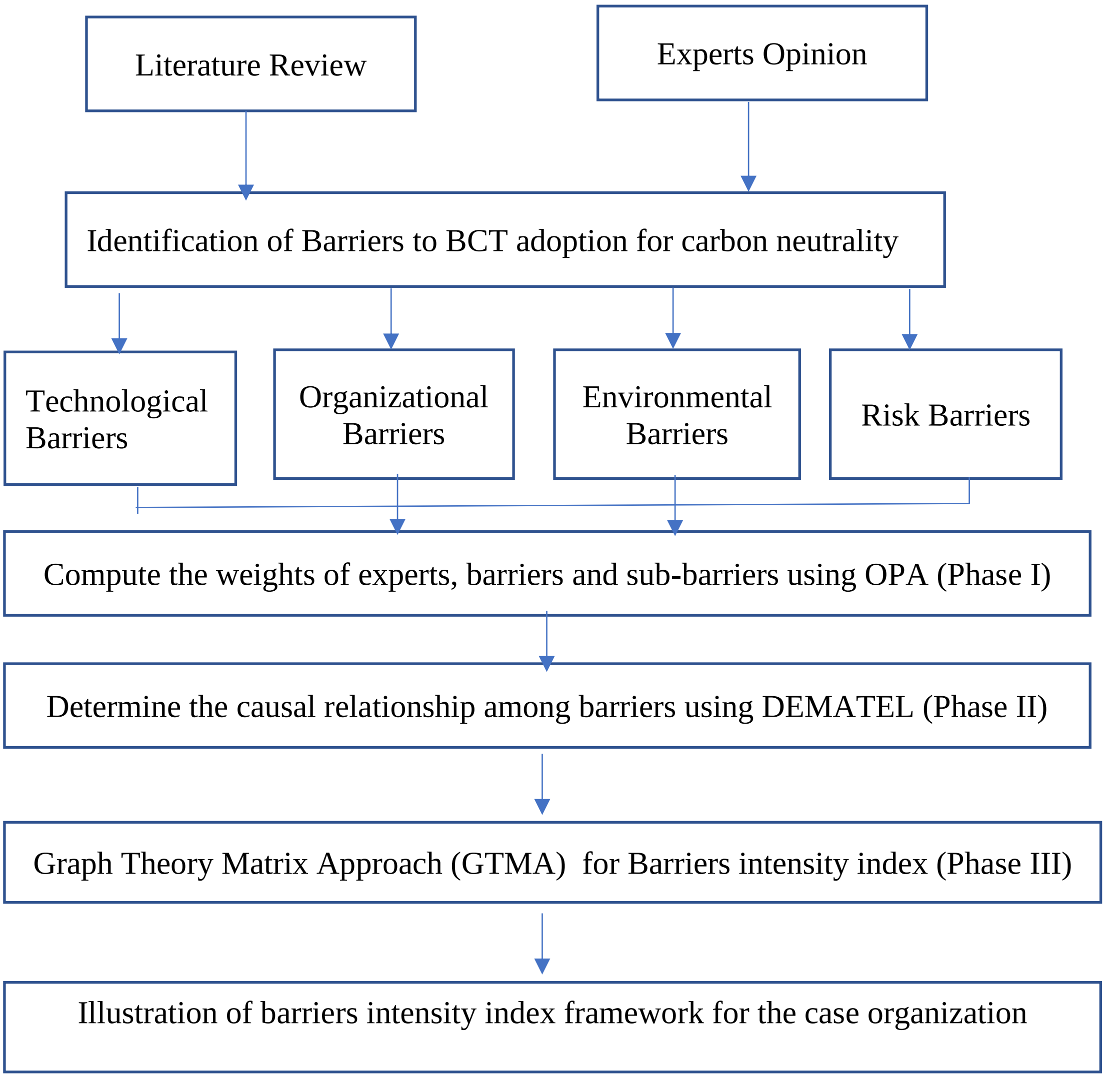

Figure 2: Research Methodology Framework

3.1 Ordinal Priority Approach (OPA)

It is a Multiple Attribute Decision-Making (MADM) method proposed for making both individual and group making decisions (Ataei et al., 2019). In this method, firstly experts were selected and prioritized. Experts' prioritization depends on their experience and knowledge in the same field. After prioritization of the experts, each main barrier and sub barrier have been ranked by each expert. Then, linear programming model of this method is used to solve the stated problem and the weights of experts, barriers and sub-barriers would be obtained simultaneously. A major advantage of this method over other MCDM methods that it does not need any pairwise comparison matrix for computation. It also ignores the development of decision-making matrix, using average and normalization methods for aggregating the opinions of experts in group making decisions. This method requires the valuable insights of industry experts on ranking of criteria and alternatives based on their knowledge and experience. The outcome of this method has been found almost same while compared with outcomes obtained from other popularly known MCDM techniques (Ataei et al., 2019). For this study, this method is preferred as it requires simple comparisons as input data and easy to compute using simple linear programming model. In our study, experts have knowledge and experience in different industry verticals, this method has been preferred choice. The steps involved in OPA have been discussed below. Table 7 highlights some of the studies related to OPA.

Steps of Ordinal Priority Approach are as follows:

Step 1: Determining the main and sub barriers: From literature review and expert opinion, the main and sub barriers are included in decision making process. The hierarchical decision-making structure will help in finding weights of main barriers through weights of sub barriers.

Step 2: Ranking the experts: Experts are selected for the decision-making process based on their knowledge and expertise in the field under study. Experts are also ranked on their experience, current designation, and level of education, etc.

Step 3: Ranking the main barriers: The main barriers are ranked by panel of industry experts. If any of the expert lack sufficient knowledge for any of the barrier or feel critical about its inclusion in the study, the expert is free not to include those barriers in ranking procedure as well as in mathematical model during computation. Experts may give same priority to same barriers then the same inputs would be considered in prioritization process.

Step 4: Ranking the sub barriers in each main barrier: In group decision making, the experts have been asked to rank the sub barriers by considering each main barrier. It may be possible that few sub barriers have given same priority by different experts then the mathematical model will consider the given inputs only.

Step 5: Finding the weights of barriers and sub-barriers: A linear mathematical model has been formulated based on inputs received from experts on barriers and sub-barriers. The mathematical model has been solved to determine the weights of barriers, sub-barriers, and experts. Based on weights determined, the subsequent ranking of barriers and sub barriers have been done.

3.2 Decision-Making Trial and Evaluation Laboratory (DEMATEL)

DEMATEL evaluates the causal relationships among barriers and sub-barriers, classify them into cause-and-effect relationship and finally develop a hierarchical structure for effective solutions (Fontela and Gabus, 1976, Yang et al., 2008). It divides all the factors into cause-and-effect groups which help researchers in constructing cause-effect models (Govindan et al., 2020). It helps in visualizing direct and indirect relationships among these barriers and explore the causal dependency structure among identified barriers. Other MCDM techniques lack in capturing causal relationships which makes DEMATEL an appropriate choice for this study (Kouhizadeh et al., 2019, Kumar et al., 2023). The authors wanted to understand the direct and indirect relationship among identified barriers for adopting BCT for carbon neutrality. For this study, the same experts have been asked to assess the identified barriers and sub-barriers on a scale of 0 to 3 when 0 implies no influence and 3 implies high influence. List of few studies related to DEMATEL has been discussed in Table 8.

Steps of Decision-Making Trial and Evaluation Laboratory (DEMATEL) are as follows:

Step 1: Establish direct pair-wise comparison matrix for all barriers and sub-barriers based on each expert's inputs

Step 2: Average of expert's inputs to get aggregate results and add each row and column to find row sum and column sum respectively

Step 3: Establish the initial influencing matrix by normalizing

Step 4: Determine the total relation matrix and find row and column sums

Step 5: Determine the overall influence and net effect of barriers

Step 6: Identify the cause-and-effect relationship and present with diagram

Table 7: List of research papers using OPA

Objective of the study	**Domain**	**References**
Performance Evaluation of Construction Sub-contractors using Ordinal Priority Approach	Construction	Mahmoudi & Javed (2022)

Evaluating suppliers for healthcare centre using ordinal priority approach	Healthcare	Quartey-Papafio et al. (2021)
Adopting distributed ledger technology for the sustainable construction industry: evaluating the barriers using Ordinal Priority Approach.	Distributed Ledger technology for sustainable construction	Sadeghi et al. (2022)
Prioritizing transport planning strategies for freight companies towards zero carbon emission using ordinal priority approach.	Transportation	Pamucar et al. (2022)
Evaluation of automotive parts suppliers through ordinal priority approach and TOPSIS.	Evaluation of suppliers	Bah & Tulkinov (2022)
Candra, C. S. (2022). Evaluation of barriers to electric vehicle adoption in Indonesia through grey ordinal priority approach. International Journal of Grey Systems, 2(1), 38-56.	E-vehicles adoption	Candra (2022)

Table 8: List of research papers using DEMATEL

Objective of the study	**Domain**	**References**
Analyzing barriers of Green Lean practices in manufacturing industries by DEMATEL approach.	Green lean practices in manufacturing	Singh et al. (2021)

Drivers and barriers of electric vehicle usage in Malaysia: A DEMATEL approach.	E-vehicles usage	Asadi et al. (2022)
Users' intention to continue using mHealth services: A DEMATEL approach during the COVID-19 pandemic	Health services	Alzahrani et al. (2022)
Causal analysis of accidents on construction sites: A hybrid fuzzy Delphi and DEMATEL approach.	Construction	Mohandes et al. (2022)
Prioritizing critical success factors for sustainable energy sector in China: A DEMATEL approach.	Sustainable energy sector	Zhao et al. (2021)

3.3 Graph Theory Matrix Approach (GTMA)

It is a Multi-Criteria Decision-Making (MCDM) technique that uses graph theory and matrix algebra to analyse and evaluate decision alternatives based on multiple criteria. It can handle complex decision-making situations with many criteria and alternatives and can incorporate both qualitative and quantitative data simultaneously (Geetha & Sekar, 2016; Gupta and Singh, 2020). This method is preferred choice for developing a strategic framework for BCT adoption for carbon neutrality and can be better than conventional methods for its representation and quantification. GTMA consists of three steps- diagraph, matrix representation and permanent function calculations. Graphical representation of barriers has been depicted through diagraph for better understanding and visual analysis. Diagraphs characterise the system structure with nodes and edges which signifies the measure and dependence of attributes. Further, the matrix depicts the one-to-one representation of the diagraph. A permanent function is a mathematical expression which can be calculated as same as finding the determinant of matrix, but only positive terms are considered (Muduli et al., 2013). This method is found to be an important decision-making tool which assists in developing associations among variables and evaluate them by forming an index.

After identifying and finalizing the barriers from literature review, they are further categorized using Technological, Organizational and Environmental Theory (TOE) and Innovation Resistance Theory (IRT) theories into four main barriers. Ultimately, a framework has been proposed and barrier intensity index can be calculated by permanent function using Equation (1) through GTMA approach (Jurkat and Ryser, 1966; Gupta et al., 2022).

$$\mathrm{Per}(K) = \prod_{i=1}^{4} K_i + \sum_i \sum_j \sum_k \sum_l r_{ij} r_{ji} K_k K_l + \sum_i \sum_j \sum_k \sum_l (r_{ij} r_{ji} r_{ki} + r_{ik} r_{kj} r_{ji}) K_l + \sum_i \sum_j \sum_k \left(\sum_l (r_{ij} r_{ji}) \times (r_{kl} r_{lk}) + \sum_i \sum_j \sum_k \sum_l (r_{ij} r_{jk} r_{kl} r_{li}) + (r_{il} r_{lk} r_{kj} r_{ji}) \right) \quad \ldots(1)$$

Where r indicates the relative values and K indicates the absolute values of barriers in the matrix and n is taken as number of barriers considered for study. List of studies using GTMA is highlighted in Table 9.

3.3.1 Proposed framework

The barriers in BCT adoption for reducing carbon can be represented in the form of nodes and edges by developing a framework. The nodes show the barriers to BCT adoption for carbon neutrality and the edges show their linkages. XBi shows the inheritance of barriers and rij shows the degree of dependence of ith barrier on jth barrier. It also represents the directed edge from node i to node j. A framework is proposed highlighting the nodes and linkages of main barriers categories and connectivity with sub-barriers as shown in Figure 3.

Table 9: List of research papers using GTMA

Objective of the study	**Domain**	**References**
Modeling and analysis of FMS performance variables by ISM, SEM and GTMA approach	Flexible manufacturing systems	Jian and Raj (2016)
Assessing the best art design based on artificial	Artificial Intelligence and Machine Learning	Wenjing & Cai (2023)

intelligence and machine learning using GTMA.		
Developing a framework for evaluating sustainability index for logistics service providers: graph theory matrix approach	Logistics service providers	Gupta and Singh (2020)
Developing human resource for the digitization of logistics operations: readiness index framework.	Human resource readiness for digitalization	Gupta et al. (2022)
Analysing roadblocks of Industry 4.0 adoption using graph theory and matrix approach	Industry 4.0	Virmani et al. (2021)

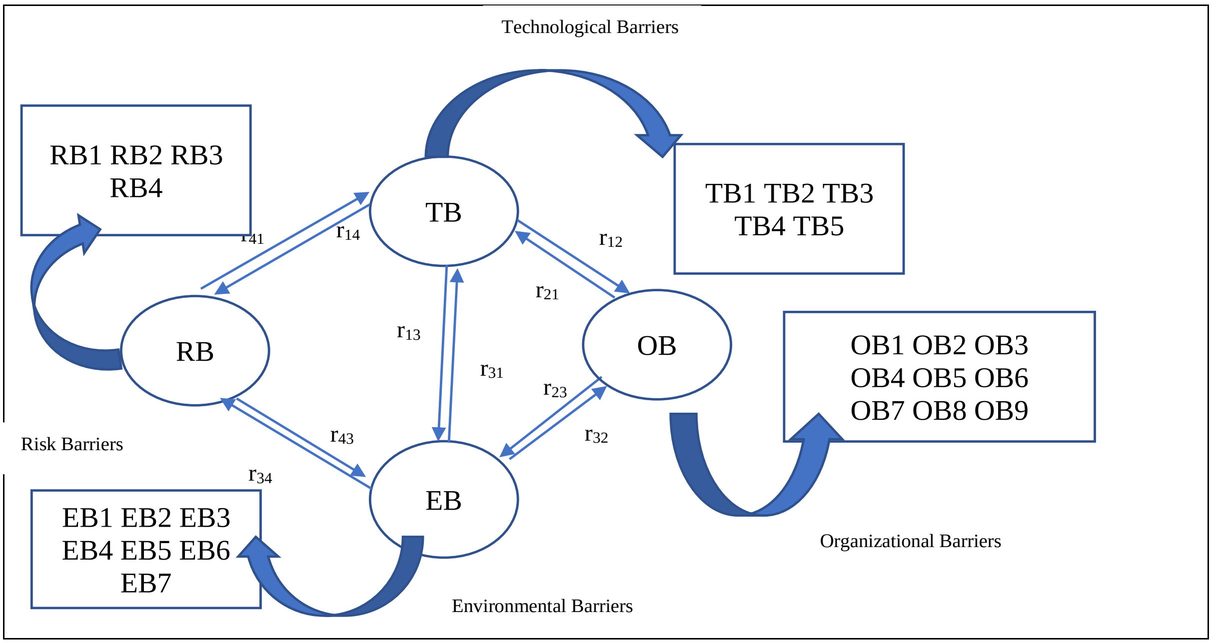

Figure 3: Proposed framework

4. Results and Discussion

In this study, the results have been analysed in three parts. The first part deals with the prioritization of BCT adoption barriers for carbon neutrality. Industry experts' inputs have been taken to rank barriers and sub-barriers and consequently, prioritized using OPA. The second part deals with identifying cause-and-effect relationship among identified barriers using DEMATEL and the third part deals with a case illustration on logistics company to develop a strategic framework and evaluate the barrier intensity index using GTMA.

4.1 Prioritization of Barriers using OPA

For this study, there were 10 industry experts from different industry sectors involved in prioritizing the barriers to BCT adoption for reducing carbon emissions. The authors ranked the experts based on their work experience and considering their profile as follows:

Expert 9>Expert 1>Expert 7 >Expert 8>Expert 2> Expert 3 > Expert 5 > Expert 10 > Expert 4> Expert 6.

Experts have given their inputs on ranking of barriers and the weights thus obtained using OPA as shown in Table 10.

Table 10: The weights and ranking of experts, barriers and sub barriers using OPA

Experts		**Weights**	**Rank**
1	Expert1	0.2816	9
2	Expert2	0.1596	1
3	Expert3	0.1431	7
4	Expert4	0.1008	8
5	Expert5	0.0932	2
6	Expert6	0.0736	3
7	Expert7	0.0647	5
8	Expert8	0.0429	10
9	Expert9	0.0211	4
10	Expert10	0.0194	6
Barriers		**Weights**	**Rank**
1	Technological Barriers	0.179924	3
2	Organizational Barriers	0.520833	1
3	Environmental Barriers	0.236742	2
4	Risk Barriers	0.062500	4
Technological Barriers		**Weights**	**Rank**
1	Lack of technical skills for BCT implementation for achieving carbon neutrality (TB1)	0.45667	1

2	Immutability challenge of BCT for achieving energy efficient logistics solutions (TB2)	0.108182	4
3	Immature BCT for low carbon economies (TB3)	0.238485	2
4	Impact of scalability issues of BCT on net zero goals (TB4)	0.156667	3
5	Lack of interoperability and standardization of BCT in collaborating stakeholders for sustainability (TB5)	0.040000	5
Organizational Barriers		**Weights**	**Rank**
1	Inadequate IT infrastructure for implementing BCT for low carbon logistics (OB1)	0.127461	4
2	Lack of top management vision for Net zero goals (OB2)	0.314330	1
3	High development and maintenance cost involved in BCT implementation (OB3)	0.060626	6
4	Rigid organizational culture for technological innovations (OB4)	0.193118	2
5	Lack of investment in Research & Development (R&D) on adoption of BCT for carbon neutrality (OB5)	0.140929	3
6	Lack of Government incentive policies for net zero goal using BCT (OB6)	0.075441	5
7	Non-stringent environment protection laws for carbon neutrality (OB7)	0.030564	8
8	Requirement of high computational power leads to huge cost of electricity consumption (OB8)	0.045186	7
9	Unorganized and fragmented logistics industry (OB9)	0.012346	9
Environmental Barriers		**Weights**	**Rank**
1	Lack of suppliers and customers awareness towards net zero goals (EB1)	0.266512	2
2	Unequal support from all supply chain stakeholders for net zero goals using BCT (EB2)	0.110668	4
3	Lack of control over suppliers of subcontracted services or leased facilities (EB3)	0.049412	7

4	Lack of coordination, and collaboration among SC stakeholders for using technology for low carbon economies (EB4)	0.331447	1
5	Lack of effective performance frameworks for measuring impact of BCT on net zero goals across supply chain (EB5)	0.053958	6
6	Inability to control excessive carbon emission from non-productive logistics and warehousing operations (EB6)	0.113049	3
7	Inadequate use of renewable, recyclable, and reusable material in logistics and warehousing operations (EB7)	0.074954	5
Risk Barriers		**Weights**	**Rank**
1	Fear of failure of BCT technology for reducing carbon emissions (RB1)	0.168561	3
2	Negative perception towards BCT (RB2)	0.062500	4
3	Paybacks are uncertain (RB3)	0.520833	1
4	Risk of cyber-attacks on stored data (RB4)	0.248106	2

Based on the results shown in Table 10, it can be observed that Organizational Barriers (OB) (0.52) is the most critical barrier followed by Environmental Barriers (EB) (0.236) and then, Technological Barriers (TB) (0.179) are at the third level and the least crucial barriers are Risk Barriers (RB) (0.062). The main hindrance in adopting BCT for sustainable goals is at organizational level. Lack of top management interest and vision (0.314), rigid organizational culture (0.193), lack of investment in exploring technologies for carbon neutrality (0.140), inadequate IT resources (0.127), and lack of government supporting policies (0.075) create major hurdles in implementing technologies for net zero goals. However, India as a part of Paris Agreement pledged to become carbon neutral by 2050, started green initiatives and developed infrastructural development policies to support organizations in achieving their individual sustainable goals.

The use of BCT technology by logistics organizations can reduce paperwork, better record keeping and smooth supply chain and warehousing operations which can further help in reducing carbon reduction. But adoption, implementation, and maintenance of blockchain technology (0.060) become challenging due to is huge initial investment and uncertain profitability. In India, the transport sector is responsible for emitting roughly 286 metric tons of carbon dioxide annually due to non-stringent environmental protection laws (0.030). The complex structure of Indian logistics sector (0.012) makes it further difficult to implement environmental protection laws and fails to encourage organizations to participate in sustainable drive.

Technological Barriers are the second most critical barrier that seeks attention and need to be rectified on priority. Although Indian logistics organizations have started using geographical positioning systems (GPS), barcoding, radio frequency identification (RFID), Electronic data interface (EDI) software and I4.0 technologies but adoption of I4.0 technologies for sustainable practices is at infancy phase. However, in India, few logistics companies initiated with BCT and developing protocols for reducing carbon from fleet and warehousing operations. The major issue is with getting skilled technical manpower (0.456) with experience in working with BCT and can contribute towards achieving net zero goals. Blockchain technology can enhance supply chain integration but is itself under trial and cannot be considered mature (0.238) for efficient energy solutions. Additionally, scalability issues with blockchain (0.156) and could limits its effectiveness in achieving net zero goals. Though immutability feature of BCT (0.108) can enhance security of records saved but at the same time restricts organizations to modify or delete the stored data once it has been recorded. Foe efficient supply chain solutions, it is important for all the stakeholders to collaborate and integrate and work on a common platform to achieve shared sustainable goals but at present, BCT also faces issues with standardisation and interoperability (0.040). The logistics organizations need to address these issues by developing hybrid BCT models that can be compatible with traditional or existing databases and systems.

Environmental Barriers are at third place and need to be resolved to adopt BCT for sustainable development. Suppliers, intermediaries and even consumers- across entire supply chain lack in sharing common vision (0.331) and concern for environment and evolving ways through which carbon emissions can be reduced from the atmosphere. Suppliers usually not prioritize sustainability in their business practices, but lack of awareness (0.266) lead them to continue with use of environmentally harmful materials and processes, which ultimately result in a higher carbon footprint. Logistics and warehousing operations generate significant carbon emissions from both productive (direct movement and delivery) and non-productive ways (0.113) in form of waste generation, energy usage, lighting, employee commuting which become difficult to control and reduce. Use of non-renewable and single time use packaging material (0.074) can increase waste and ending up in landfills which further results in increasing carbon footprints. Logistics companies need to develop strict performance frameworks (0.053) to assess the impact of BCT for carbon reduction and can demonstrate their commitment to sustainability. There is need to bring great change in logistics and warehousing processes by promoting renewable materials such as bamboo, hemp, and recyclable materials such as paper, corrugated carboard for packaging and pallets. The logistics companies need to explore technology to optimize packaging by using minimum amount of material and to reuse containers and pallets multiple times.

Risk barriers are least critical barriers for implementing technology for low carbon economies. The logistics organizations can adopt business carbon-cutting technologies for reducing carbon, but paybacks can be uncertain (0.520), which is a major barrier to its adoption. For using BCT, organizations need to store and share data through cloud computing which may have possibility of cyber-attacks (0.248) and that creates risk in mind of organizations. BCT being new may have risk of failure (0.168) specifically when used for reducing carbon emissions, which restricts logistics companies to adopt. In past studies, few researchers criticize BCT for its immutability and scalability issues (0.062) so this limits the organization to adopt it for carbon neutrality solutions.

4.2 Cause-Effect analysis of barriers using DEMATEL

The inputs on pairwise comparison matrix were also taken by same experts to establish causal relationship among barriers and sub-barriers. Once the barriers and sub barriers were identified from TOE theory and IRT, the pair-wise comparison matrices were developed to capture the relationships among them. A linguistic scale was defined to convert the strengths of the influence relationships amongst factors to a numerical scale from 0 to 3 as shown in Table 11.

Table 11: Linguistic values

Linguistic term	**Numerical value**
No influence	0
Low influence	1
Medium influence	2
High influence	3

Using the importance weight of all experts, the pair wise matrices were aggregated into initial aggregation matrix and total relationship matrix were derived. The sum of rows and columns in the total relationship matrix were named as vectors, R and C, respectively. The values of Ri+Ci and Ri-Ci were also calculated and discussed in Table 12. The cause-and-effect diagram will be plotted based on Ri-Ci values and each positive value represents cause and each negative value represent effect of that barrier on other barriers as shown in Figure 4.

Table 12: Total Relationship Matrix

Barriers	**Row Sum (Ri)**	**Column sum (Ci)**	**Ri+Ci**	**Ri-Ci**	**Cause/Effect**
TB	2.626748	3.825407	6.452154	-1.19866	Effect
OB	3.506767	2.273406	5.780173	1.233361	Cause
EB	3.713951	2.724869	6.438821	0.989082	Cause
RB	2.763674	3.787457	6.551131	-1.02378	Effect
TB1	2.436722	0.986442	3.423164	1.450281	Cause
TB2	1.561826	2.00853	3.570356	-0.4467	Effect
TB3	1.608373	1.460172	3.068545	0.148201	Cause
TB4	1.706789	1.837089	3.543878	-0.1303	Effect
TB5	0.869901	1.891379	2.76128	-1.02148	Effect
OB1	2.267402	1.737932	4.005334224	0.529470622	Cause
OB2	2.734964	0.99237	3.727333785	1.742593451	Cause
OB3	1.970355	2.33255	4.302904829	-0.36219493	Effect
OB4	2.326839	1.194703	3.521541488	1.132136158	Cause
OB5	2.070068	1.553412	3.623480321	0.516656082	Cause
OB6	2.001815	1.784922	3.786737124	0.216893152	Cause
OB7	1.173745	2.495981	3.669725909	-1.32223551	Effect
OB8	1.306004	2.148728	3.454731753	-0.84272420	Effect
OB9	1.072474	2.683069	3.755542216	-1.61059480	Effect
EB1	3.410977	2.036853	5.44783	1.374125	Cause
EB2	3.0568	3.36603	6.622831	-0.30923	Effect
EB3	2.167626	3.854839	6.022465	-1.68721	Effect
EB4	3.674619	1.28778	4.962399	2.386839	Cause
EB5	2.894075	3.767344	6.361419	-0.87327	Effect
EB6	2.976485	2.917579	5.894064	0.058906	Cause

EB7	2.420398	3.370556	5.790954	-0.95016	Effect
RB1	1.588927	2.122023	3.71095	-0.5331	Effect
RB2	1.445097	2.520105	3.965203	-1.07501	Effect
RB3	2.290442	1.008042	3.298484	1.2824	Cause
RB4	1.755954	1.430251	3.186205	0.325704	Cause

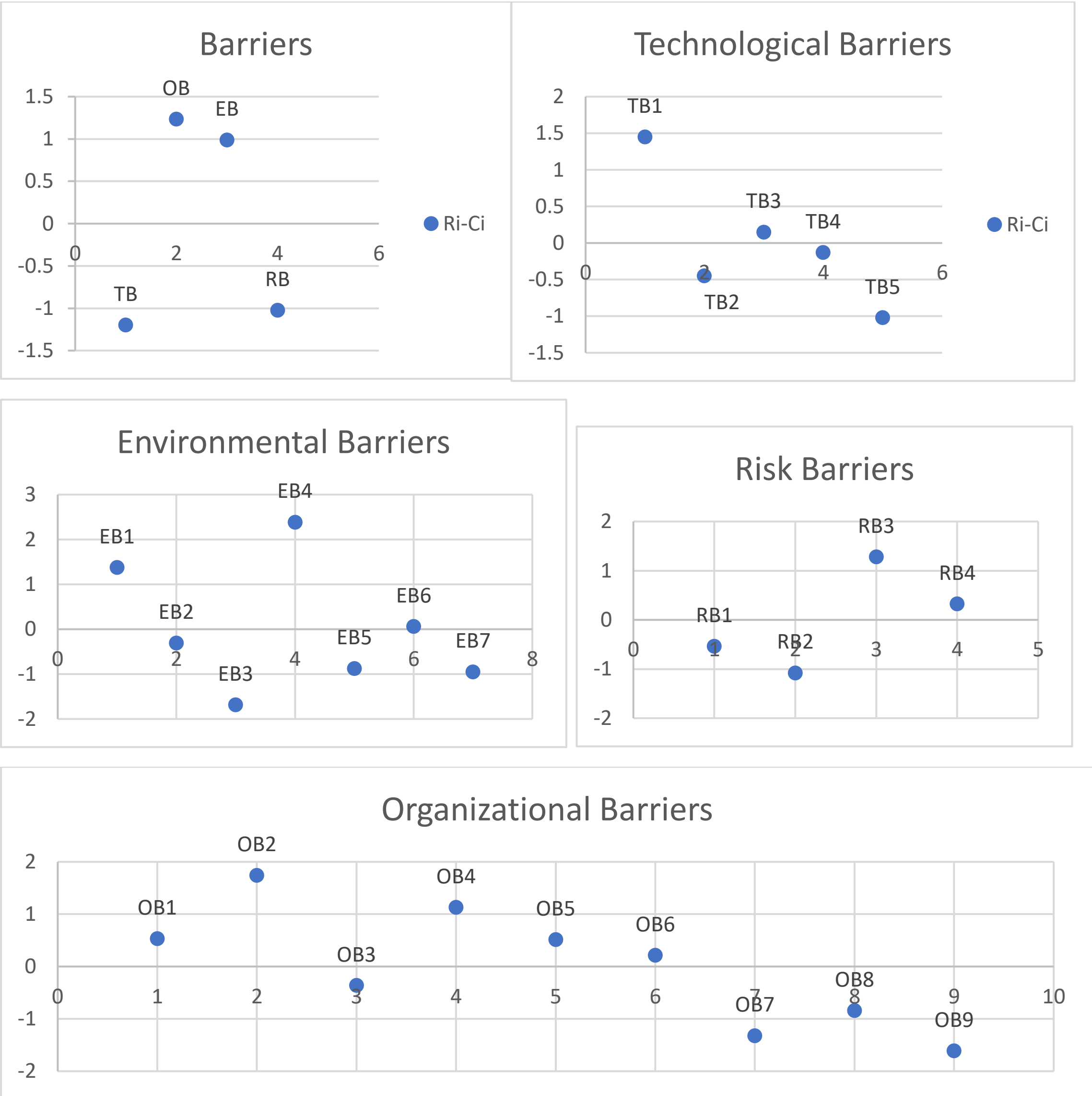

Figure 4: Cause and Effect relationship of barriers and sub-barriers

Based on Table 12 and Figure 4, the causal-effect relationship among barriers and sub-barriers have been established. In Table 12, Ri-Ci values have been calculated for each barrier. If a barrier with R-C > 0 is classified as a cause barrier whereas a barrier with R-C < 0 is classified as effect barrier. Furthermore, the value of Ri+Ci represents the prominence value of each barrier. It means ‘Unequal support from all supply chain stakeholders for net zero goals using BCT (EB2)’ (6.622) has highest correlation with other barriers (Bacudio et al., 2016). Past studies also claimed the importance and role of supply chain partners in sharing the common vision and achieving sustainable goals through shared technological developments (Gupta et al., 2021; Akbari and Hopkins, 2022). In Figure 4, the barriers positioned above the x axis are said to be causal barriers that have maximum impact on other barriers positioned below the x axis and known as effected or influenced barriers. The barrier with highest correlation is located at the rightmost side of the figure whereas the least is at the leftmost side. At the top, primary causal barriers are placed while at the bottom, least influencing barriers are placed (Raghuvanshi et al., 2017).

In figure 4, five graphs have been plotted-one for main barrier and four graphs for sub barriers category. In the first graph, organizational barriers and environmental barriers are the causal barriers and technical and risk barriers are the effect or influenced barriers. It implies that the organization vision and interest towards environmental and sustainable developments can lead to achieve net zero goals and technological hurdles and their associated risks can be then rectified. In second graph, sub barriers related to technological barriers have been discussed as in Table 12. ‘Lack of technical skills for BCT implementation for achieving carbon neutrality (TB1)’ and ‘Immature BCT for low carbon economies (TB3)’ are causal barriers and have effect on ‘Immutability challenge of BCT for achieving energy efficient logistics solutions (TB2)’, ‘Impact of scalability issues of BCT on net zero goals (TB4)’, and ‘Lack of interoperability and standardization of BCT in collaborating stakeholders for sustainability (TB5)’ are influenced barriers. TB4 has the highest impact on all other barriers. This result shows that insufficient technical knowledge of manpower in implementing BCT and immature phase of BCT for carbon neutrality are the major issues which are impacting the immutability, scalability, and interoperability issues of BCT and restricting their use for reducing carbon footprints.

In third graph, ‘Lack of suppliers and customers awareness towards net zero goals (EB1)’, ‘Lack of coordination, and collaboration among SC stakeholders for using technology for low carbon economies (EB4)’, and ‘Inability to control excessive carbon emission from non-productive logistics and warehousing operations (EB6)’ are causal barriers and’ Unequal support from all supply chain stakeholders for net zero goals using BCT (EB2)’, ‘Lack of control over suppliers of subcontracted services or leased facilities (EB3)’, ‘Lack of effective performance frameworks for measuring impact of BCT on net zero goals across supply chain (EB5)’ and Inadequate use of renewable, recyclable, and reusable material in logistics and warehousing operations (EB7)' are influenced barriers. From the outcomes for environmental barriers, it can be observed that contribution and support from suppliers is crucial to ensure and enable digitally sound sustainable supply chain. Supply chain partners collaborative actions and use of BCT technology can control leased or outsourced facilities for excessive carbon and can develop performance assessment frameworks by adopting non-renewable alternative solutions (Kim and Shin, 2019; Nandi et al., 2020).

Similarly, in graph 4, RB3 and RB4 are found to be causal barriers whereas RB1 and RB2 are influenced barriers. 'Negative perception towards BCT (RB2)'has the highest impact on other three barriers. In past studies, several researchers criticise the use of blockchain technology for sustainable goals due to its immutable and scalability issues (Hald and Kinra, 2019; Ganguly, 2022). The similar results are obtained in this study. Due to uncertain paybacks and lack of cyber security of BCT for carbon neutrality create fear of failure and impact organization's investment decision making for technology and sustainable innovations. In graph 5, organizational barriers are discussed. OB1, OB2, OB4, OB5 and OB6 are positioned in upper half of the graph and classified as causal barriers and OB3, OB7, OB8 and OB9 are classified as influenced barriers as positioned in lower half of the graph. 'High development and maintenance cost involved in BCT implementation (OB3)'has the highest impact over other barriers. This result is highly correlated with past studies as huge investment in BCT technology for low carbon solutions is a main driving reason for showing less interest towards sustainable goals (Sadeghi et al., 2022; Khan et al., 2022).

4.3 Framework for barriers intensity index using GTMA- Case illustration

For finding barrier intensity index, a real-life case illustration has been considered of a logistics company named ABC Ltd. The company was founded in 1985 and emerged as India's leading logistics service provider with sustainable supply chain mobility solutions. The company has a turnover of around 6000 crores and equipped with strong dedicated team of more than 20,000 employees. The company provides end to end logistics solutions starting from shipping to storing to assembly line to finally bringing the product to the market and delivering exceptional customer experience in both B2B and B2C spaces through digital innovations. The company has strengthened their extensive transportation network over more than 20,000 pin codes and offer customization with warehousing solutions over 3 million sq. ft. The company have started using blockchain and artificial intelligence for providing smooth end to end logistics solutions and managing data records efficiently. The company recognizes the importance of reducing climate impact and initiated responsible step towards sustainable transportation and warehousing solutions in carbon neutral manner. The company planned to achieve carbon neutrality goal by 2045 using I4.0 technologies. These are one among few Indian logistics companies which worked for carbon reduction and get validated through Science Based Targets Initiative (SBTi). This is the first company which initiated electric vehicles cargo as alternative fuel and adopt energy efficient and exceptionally sustainable solutions for green warehousing. The company works on the principle of reuse, repair and recycle and selects green suppliers, processes, and practices for their sustainable operations. However, the company has initiated in direction of achieving carbon neutrality goals using BCT bur still a long way to go ahead. Therefore, the barriers which hinders its path have identified above. After prioritizing the barriers, GTMA approach is used to develop a self-assessment framework for finding barrier intensity of ABC Ltd. In GTMA, a permanent matrix has been developed by placing sub barriers in the diagonal and other values were found based on correlation among barriers with the consultation of company experts. For diagonal elements, a 5-point scale is used where 1 indicates very low intensity and 5 indicates very high intensity of the barrier and the scale for other values of the remaining cells is mentioned in Table 13. After evaluating the intensity index for all categories of barriers, the overall BCT adoption for carbon neutrality index is calculated. Hence, the permanent matrix of technological barriers has been calculated in Equation 2.

Table 13: Relative Dependence of Barriers

Qualitative Measures of interdependencies	**Relative dependence of sustainable practices**	
	sij	**sji=10-sij**
Two barriers are of equal importance	5	5
One barrier is slightly dependent on the other	6	4
One barrier is very dependent on the other	7	3
One barrier is most dependent on the other	8	2
One barrier is extremely dependent on the other	9	1
One barrier is exceptionally dependent on the other	10	0

Source: Muduli et al., 2013

$$\text{Perm TB} = \begin{vmatrix} TB1 & r^1_{12} & r^1_{13} & r^1_{14} & r^1_{15} \\ r^1_{21} & TB2 & r^1_{23} & r^1_{24} & r^1_{25} \\ r^1_{31} & r^1_{32} & TB3 & r^1_{34} & r^1_{35} \\ r^1_{41} & r^1_{42} & r^1_{43} & TB4 & r^1_{45} \\ r^1_{51} & r^1_{52} & r^1_{53} & r^1_{54} & TB5 \end{vmatrix} = \begin{vmatrix} 5 & 6 & 7 & 9 & 5 \\ 4 & 3 & 5 & 7 & 6 \\ 3 & 5 & 2 & 9 & 8 \\ 1 & 3 & 1 & 4 & 9 \\ 5 & 4 & 2 & 1 & 1 \end{vmatrix} \quad \ldots(2)$$

=198140

Similarly, the permanent function for all other barrier categories is evaluated. The value of permanent function is evaluated for other categories of barriers as follows:

Organizational Barriers (OB): Per (OB)= 383350

Environmental Barriers (EB): Per (EB) = 185487

Risk Barriers (RB): Per (RB) = 11223

Then the overall barrier intensity for implementing BCT for carbon neutrality (BCTCN)for case company is calculated in Equation 3 as follows:

$$\text{Per (BCTCN)=} \begin{vmatrix} TB & r^1_{12} & r^1_{13} & r^1_{14} \\ r^1_{21} & OB & r^1_{23} & r^1_{24} \\ r^1_{31} & r^1_{32} & EB & r^1_{34} \\ r^1_{41} & r^1_{42} & r^1_{43} & RB \end{vmatrix} = \begin{vmatrix} 198140 & 8 & 7 & 8 \\ 2 & 383350 & 8 & 5 \\ 3 & 2 & 185487 & 6 \\ 5 & 5 & 4 & 11223 \end{vmatrix} \quad ..(3)$$

$= 15.812 \text{ X } 10^{24}$

4.3.1 Theoretical Best and Worst Values

The value of BCTCN will lie between two possible cases that is best and worst possible values for the given case.

The theoretical best value for all barrier categories has computed when the diagonal elements of all the sub barriers has kept the best value that is 1 in this case.

$$\text{Per (TB)=} \begin{vmatrix} 1 & 5 & 5 & 5 & 5 \\ 5 & 1 & 5 & 5 & 5 \\ 5 & 5 & 1 & 5 & 5 \\ 5 & 5 & 5 & 1 & 5 \\ 5 & 5 & 5 & 5 & 1 \end{vmatrix}$$

=168376

Similarly, Per (OB)= 318461

Per (EB)= 176921

Per (RB)= 6776

Per (BCTCN)= 6.428×10^{24} (Best Case)

Similarly, the permanent function for theoretical worst value can be obtained by keeping all diagonal elements as 5.

$$\text{Per (TB)}= \begin{vmatrix} 5 & 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 & 5 \end{vmatrix}$$

=375000

Similarly, Per (OB)= 14962500

Per (EB)= 393750

Per (RB)= 15000

Per (BCTCN)= 33.139×10^{24} (Worst Case)

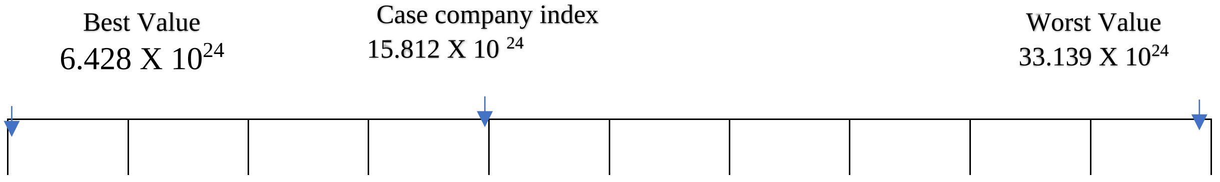

Figure 5: Theoretical best and worst value with case company barrier intensity index

The index value of a barrier represents its intensity of impact on BCT adoption for carbon neutrality. Higher index value implies great impact of the barrier on BCT adoption for decarbonization, whereas low index value means lower impact of that barrier. The best and worst value sets the limits in which index value can lie and change within the specified limits. Experts can consider this range as a threshold value for barriers to BCT adoption and take decisions accordingly. GTMA results were also shared with the case company. Based on results, it was observed that the overall barrier intensity index for the case company lies close to the centre of the range as shown in Figure 5. This indicates that the case company has initiated with the adoption of BCT for reducing carbon emissions but still a long way to go to achieve carbon neutrality goals. For technological barriers, the value of case company (198140) is closer to the best-case value (168376) rather than worst-case value (375000). It shows that the case company has adopted BCT technology and using it for sustainable goals. The case company can reach the benchmarks by developing its infrastructure and trained their manpower with required technical expertise and by improving the technical characteristics of BCT technology. Similarly, for environmental barriers, the case index value (185487) is more than the best-case value (176921) which means case company steps towards using renewable and alternative energy efficient fuels and collaborating with supply chain partners for green initiatives but all initiatives at early stages and demands great effort from case company to set new benchmarks for environmental sustainability.

On contrary, risk barriers case value (11223) is closer to the worst-case value (15000) rather than best-case value (6776). It signifies that the case company has given less importance to risk barriers and still needs to rectify for meeting UN's sustainable goals. But interestingly, this study also ranks risk barriers least as compared to other barriers. Similarly, organizational index values (383350) are closer to worst case values (393750) shows negligence of top management concern towards technology adoption for decarbonization. Thus, ABC Ltd. needs to pay more attention to organizational and environmental barriers for better adoption of BCT for carbon secured logistics systems. These index values can help case company to position themselves in comparison to theoretical best and worst index values. The case company find results useful and decided to formulate new strategies for creating awareness among employees, supply chain stakeholders and customers. The company has also motivated to collaborate with educational institutes and to provide short term training courses to existing employees to upgrade their technical expertise. As the investment is major barrier, so case company has decided to look forward to government green support initiatives to research and maintain BCT and develop protocols to reduce and control carbon footprints.

5. Implications of the study

5.1 Social Implications

Blockchain technology has the potential to develop new applications and systems which can help in reducing the carbon emissions by increasing transparency, traceability, and accountability in supply chains (Saberi et al., 2018; Babich and Hilary, 2020). There can be several social implications which need to be considered while adopting BCT for carbon neutrality (Bonsu, 2020; Wachsmuth et al., 2023). Firstly, there are concerns towards the privacy and security of data stored on BCT. Blockchain systems are decentralized and transparent, that gives access rights of data to each network participants which raises concerns about data privacy and data sharing with unauthorized parties. It becomes important to develop robust security systems and adopt strict privacy measures to mitigate these risks. Secondly, this study can help organizations to sensitize towards negative environmental impacts due to increased carbon in atmosphere. The organizations can adopt socially and environmentally sensitive solutions such as tracking carbon emissions, promoting renewable energy usage by understanding the priority and criticality of barriers. Thirdly, this study can motivate organizations and concerned stakeholders to develop blockchain-based solutions to address climate change. This could lead to new technologies and business models that reduce carbon emissions and promote sustainability.

5.2 Theoretical Implications

The major theoretical implications of finding barriers to adoption of BCT for reducing carbon in logistics is to develop new theories and frameworks to better understand the adoption, implementation, and diffusion of BCT in environmental domains. Several theories such as technology adoption theories, sustainability theories, governance and innovation theories can be emerged and can provide insights to organizations and governments in adopting new technologies faster than others for sustainability purposes (Touboulic and Walker,2015). Another theoretical implication is the need to consider social, economic, and organizational factors that influence BCT adoption in context of reducing carbon in logistics. These factors may include regulatory frameworks, technological readiness, stakeholders' interests, and behavioural economics. Researchers and supply chain practitioners can devise their strategies and policies by understanding the interplay between blockchain technology, social norms, and environmental outcomes.

5.3 Practical Implications

This study can guide policymakers, businesses and blockchain developers in addressing their barriers effectively. Government and regulatory bodies can use these identified barriers for developing their policies and regulations for energy consumption, data privacy and interoperability. BCT developers can emphasis their efforts on developing more energy efficient consensus mechanisms and can target solutions to reduce environmental impact of mining and transaction verification processes. Businesses can adopt more sustainable low energy consumption blockchain designs and can integrate blockchain with renewable energy sources for reducing carbon emissions in mining processes (Sadeghi et al., 2022; Varriale et al., 2020). Interoperability issues can be resolved between blockchains, and legacy systems can be created for broader adoption of blockchain (Monrat et al., 2019; Yontar, 2023). Supply chain stakeholders can collaborate to address barriers based on their prioritization. For example, logistics companies using blockchain can partner with renewable energy sources to reduce carbon emissions or logistics companies can design inclusion of blockchain technologies into existing carbon reduction initiatives (Nandi et al., 2020; Kumar and Chopra, 2022). Logistics industry can form consortia to handle common challenges such as interoperability, scalability, etc. Innovative incentive mechanism can be initiated for development of sustainable blockchains in form of carbon-credits, recognition or token-based awards, which will motivate individuals and organizations to adopt carbon reduction solutions.

5.3 Conclusion, Limitations, and Future Scope of the Study

In conclusion, achieving carbon neutrality in the logistics sector requires a concerted effort from all stakeholders, including governments, organizations, and individuals. By adopting sustainable logistics practices and investing in low-carbon technologies, the world can make a significant step towards achieving its climatic goals and creating a more sustainable future.

In past studies, many scholars have discussed the barriers in adopting BCT. However, hardly any study has discussed the barriers to BCT adoption for achieving carbon neutrality goals in logistics particularly in context to developing economies. Hence this study has given an attempt to bridge the existing research gap by investigating the barriers to BCT adoption for sustainable objectives. In this study, 25 barriers to BCT adoption for reducing carbon emissions were identified from literature review. TOE and IRT theories were considered for categorising these barriers into four categories. The weights of all four barriers categories and sub barriers were analysed and computed using OPA technique for prioritization. The results highlighted that the organizational and environmental category of barriers are the most critical barriers. In sub-barriers, uncertainty of paybacks of investment in BCT and lack of technical skills for BCT implementation for achieving carbon neutrality are the two main critical barriers to BCT adoption which need to be rectified on priority. By working upon these barriers based on their weights, the bottlenecks can be removed and BCT can be used for environmentally sensitive benefits in form of less wastage, less paperwork, saving fuel through smoothly directed supply chains and less fuel consumption. BCT adoption not only provides transparency to the supply chains but also impacts the optimization of transportation routes, fleets, and systems. With these benefits, BCT adoption for decarbonization can surely enable the organizations to meet UN’s sustainable goals by 2050.

Further, the cause-and-effect relationship among barriers and sub barriers have been identified through DEMATEL. The results revealed that organizational and environmental category of barriers belong to causal group whereas technological and risk barriers belong to effect group. When organizations start taking initiative towards environmental concern then automatically their focus and direction brings improvement in processes. It is observed that the sub barrier namely 'unequal support from all supply chain stakeholders for net zero goals using BCT' has highest correlation with other barriers. Based on insights from this study, logistic sector organizations may clearly understand the importance of organizational and environmental barriers and develop relevant strategies for net zero goals. After prioritizing the barriers, a real case illustration has been taken to illustrate a barriers intensity index framework. This case study will help organizations to position themselves in terms of their readiness to adopt BCT for carbon reduction. The proposed framework can help organizations and supply chain professionals to analyse their index value and compare them with theoretical standards and then set their benchmarks accordingly. To conclude, the major contributions of this research work are as follows:

1. This study helps in bridging the research gap in the existing literature by focusing the barriers of BCT adoption for achieving carbon neutrality goals within the logistics sector, particularly for developing economies. It provides a comprehensive understanding of barriers faced by logistics organizations, which may have distinct technological, economic and regulatory characteristics in comparison to developed economies.
2. The identification, prioritization and causal relationship among identified barriers can provide valuable insights for logistics industry stakeholders, BCT developers, government and policymakers. The concerned can work upon issues with blockchain adoption and can plan and design new systems for blockchain integration with renewable energy sources and carbon reduction initiatives.
3. The development of barrier intensity framework can offer practical tools for logistics industry and supply chain practitioners. The real case illustration can be beneficial in setting benchmarks against theoretical standards and assessing their readiness for blockchain adoption for reducing carbon emissions. This contribution leads logistics organizations to measure their sustainable progress and to align with global standards to meet United Nations sustainable goals by 2050.

Despite the significant contributions of this study to extant literature on BCT adoption for sustainability, this study has got few limitations. Firstly, the prioritization, cause-effect relationship of barriers and the proposed framework is highly dependent on expert's inputs. Therefore, the results may be biased, and study cannot be generalised across all sectors. For generalization of findings, multiple case studies or empirical studies can be carried out. This can be an area of extension of current study for future researchers. Future researchers can explore other Industry 4.0 technologies also for reducing carbon emissions.

Conflict of interest statement- It is being certified that authors do not have any conflict of interest in submitting this paper to ANOR.

References

- Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023). A critical review of sustainable rail technologies based on environmental, economic, social, and technical perspectives to achieve net zero emissions.
- Akbari, M., & Hopkins, J. L. (2022). Digital technologies as enablers of supply chain sustainability in an emerging economy. Operations Management Research, 15(3-4), 689-710.
- Ali, S. S., Kaur, R., Gupta, H., Ahmad, Z., & Elnaggar, G. (2021). Determinants of an organization's readiness for drone technologies adoption. IEEE transactions on engineering management.
- Aljowaidi, M. (2015). A study of e-commerce adoption using TOE framework in Saudi retailers: firm motivations, implementation, and benefits (Doctoral dissertation, RMIT University).
- Alzahrani, A. I., Al-Samarraie, H., Eldenfria, A., Dodoo, J. E., & Alalwan, N. (2022). Users' intention to continue using mHealth services: A DEMATEL approach during the COVID-19 pandemic. Technology in society, 68, 101862.
- Asadi, S., Nilashi, M., Iranmanesh, M., Ghobakhloo, M., Samad, S., Alghamdi, A., ... & Mohd, S. (2022). Drivers and barriers of electric vehicle usage in Malaysia: A DEMATEL approach. Resources, Conservation and Recycling, 177, 105965.

- Ataei, Y., Mahmoudi, A., Feylizadeh, M. R., & Li, D. F. (2020). Ordinal priority approach (OPA) in multiple attribute decision-making. Applied Soft Computing, 86, 105893.
- Babich, V., & Hilary, G. (2020). OM Forum—Distributed ledgers and operations: What operations management researchers should know about blockchain technology. Manufacturing & Service Operations Management, 22(2), 223-240.
- Bacudio, L. R., Benjamin, M. F. D., Eusebio, R. C. P., Holaysan, S. A. K., Promentilla, M. A. B., Yu, K. D. S., & Aviso, K. B. (2016). Analyzing barriers to implementing industrial symbiosis networks using DEMATEL. Sustainable Production and Consumption, 7, 57-65.
- Bag, S. (2023). From resources to sustainability: a practice-based view of net zero economy implementation in small and medium business-to-business firms. Benchmarking: An International Journal.
- Bah, M. K., & Tulkinov, S. (2022). Evaluation of automotive parts suppliers through ordinal priority approach and TOPSIS. Management Science and Business Decisions, 2(1), 5-17.
- Bai, C., Chen, Z., & Wang, D. (2023). Transportation carbon emission reduction potential and mitigation strategy in China. Science of The Total Environment, 873, 162074.
- Baker, J. (2012). The technology–organization–environment framework. Information Systems Theory: Explaining and Predicting Our Digital Society, Vol. 1, 231-245.
- Balzarova, M., Dyer, C., & Falta, M. (2022). Perceptions of blockchain readiness for fairtrade programmes. Technological Forecasting and Social Change, 185, 122086.
- Biswas, B., & Gupta, R. (2019). Analysis of barriers to implement blockchain in industry and service sectors. Computers & Industrial Engineering, 136, 225-241.
- Böckel, A., Nuzum, A. K., & Weissbrod, I. (2021). Blockchain for the circular economy: analysis of the research-practice gap. Sustainable Production and Consumption, 25, 525-539.
- Bonsu, N. O. (2020). Towards a circular and low-carbon economy: Insights from the transitioning to electric vehicles and net zero economy. Journal of Cleaner Production, 256, 120659.

- Candra, C. S. (2022). Evaluation of barriers to electric vehicle adoption in Indonesia through grey ordinal priority approach. International Journal of Grey Systems, 2(1), 38-56.
- chains by the neutrosophic analytic hierarchy process. Annals of Operations Research.
- Chengyue, Y., Prabhu, M., Goli, M., & Sahu, A. K. (2021). Factors affecting the adoption of blockchain technology in the complex industrial systems: data modeling. Complexity, 2021, 1-10.
- Chiu, C.-Y., Chen, S., & Chen, C.-L. (2017). An integrated perspective of TOE framework and innovation diffusion in broadband mobile applications adoption by enterprises. International Journal of Management, Economics and Social Sciences (IJMESS), 6(1), 14–39. https://doi.org/ 10.3390/su12177132.
- Cole, R., Stevenson, M., & Aitken, J. (2019). Blockchain technology: implications for operations and supply chain management. Supply Chain Management: An International Journal, 24(4), 469-483.
- Danigels, S. (2021), "Nestle releases strategy to reach 2050 zero net emissions goal" available at: https://www.nestle.com/media/pressreleases/allpressreleases/nestle-climate-change-commitment-zero-net-emissions-2050
- Das, A., Ghosh, A. Vision Net Zero: A review of decarbonisation strategies to minimise climate risks of developing countries. Environ Dev Sustain (2023). https://doi.org/10.1007/s10668-023-03318-6
- Du, J., Cheng, J., & Ali, K. (2023). Modelling the green logistics and financial innovation on carbon neutrality goal, a fresh insight for BRICS-T. Geological Journal, 58(7), 2742-2756.
- Dujak, D., & Sajter, D. (2019). Blockchain applications in supply chain. SMART supply network, 21-46.
- Etemadi, N., Van Gelder, P., & Strozzi, F. (2021). An ism modeling of barriers for blockchain/distributed ledger technology adoption in supply chains towards cybersecurity. Sustainability, 13(9), 4672.
- Fernando, Y., Rozuar, N. H. M., & Mergeresa, F. (2021). The blockchain-enabled technology and carbon performance: Insights from early adopters. Technology in Society, 64, 101507.
- Fontela, E., & Gabus, A. (1976). The DEMATEL observer.

- Frizzo-Barker, J., Chow-White, P. A., Adams, P. R., Mentanko, J., Ha, D., & Green, S. (2020). Blockchain as a disruptive technology for business: A systematic review. International Journal of Information Management, 51, 102029.
- Ganguly, K. K. (2022). Understanding the challenges of the adoption of blockchain technology in the logistics sector: the TOE framework. Technology Analysis & Strategic Management, 1-15.
- Geetha, N. K., & Sekar, P. (2016). Academic Staff Selection using Graph Theory Matrix Approach. Indian journal of science and technology, 9(1), 1-6.
- Goh, S. H. (2019). Barriers to low-carbon warehousing and the link to carbon abatement: A case from emerging Asia. International Journal of Physical Distribution & Logistics Management, 49(6), 679-704.
- Govindan, K. (2022). Tunneling the barriers of blockchain technology in remanufacturing for achieving sustainable development goals: A circular manufacturing perspective. Business Strategy and the Environment.
- Govindan, K. (2023). How digitalization transforms the traditional circular economy to a smart circular economy for achieving SDGs and net zero. Transportation Research Part E: Logistics and Transportation Review, 177, 103147.
- Gupta, A., & Singh, R. K. (2020). Developing a framework for evaluating sustainability index for logistics service providers: graph theory matrix approach. International Journal of Productivity and Performance Management, 69(8), 1627-1646.
- Gupta, A., & Singh, R. K. (2021). Applications of emerging technologies in logistics sector for achieving circular economy goals during COVID 19 pandemic: analysis of critical success factors. International Journal of Logistics Research and Applications, 1-22.
- Gupta, A., Singh, R. K., & Gupta, S. (2022). Developing human resource for the digitization of logistics operations: readiness index framework. International Journal of Manpower, 43(2), 355-379.
- Gupta, A., Singh, R. K., & Suri, P. K. (2018). Sustainable service quality management by logistics service providers: an Indian perspective. Global business review, 19(3_suppl), S130-S150.
- Hald, K. S., & Kinra, A. (2019). How the blockchain enables and constrains supply chain performance. International Journal of Physical Distribution & Logistics Management.

- Heidenreich, S., & Spieth, P. (2013). Why innovations fail—The case of passive and active innovation resistance. International Journal of Innovation Management, 17(05), 1350021.
- Pålsson, H., & Johansson, O. (2016). Reducing transportation emissions: Company intentions, barriers and discriminating factors. Benchmarking: An International Journal.
- Jain, V., & Raj, T. (2016). Modeling and analysis of FMS performance variables by ISM, SEM and GTMA approach. International journal of production economics, 171, 84-96.
- Jayakumar, A., Madheswaran, D. K., Kannan, A. M., Sureshvaran, U., & Sathish, J. (2022). Can hydrogen be the sustainable fuel for mobility in India in the global context?. International Journal of Hydrogen Energy.
- Kannan, D., Solanki, R., Kaul, A., & Jha, P. C. (2022). Barrier analysis for carbon regulatory environmental policies implementation in manufacturing supply chains to achieve zero carbon. Journal of Cleaner Production, 358, 131910.
- Kaur, P., Dhir, A., Ray, A., Bala, P. K., & Khalil, A. (2020a). Innovation resistance theory perspective on the use of food delivery applications. Journal of Enterprise Information Management, 34(6), 1746-1768.
- Kaur, P., Dhir, A., Singh, N., Sahu, G., & Almotairi, M. (2020). An innovation resistance theory perspective on mobile payment solutions. Journal of Retailing and Consumer Services, 55, 102059.
- Khan, S., Kaushik, M. K., Kumar, R., & Khan, W. (2022). Investigating the barriers of blockchain technology integrated food supply chain: a BWM approach. Benchmarking: An International Journal.
- Kim, J. S., & Shin, N. (2019). The impact of blockchain technology application on supply chain partnership and performance. Sustainability, 11(21), 6181.
- Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. International Journal of Production Economics, 231, 107831.
- Kumar, A., Luthra, S., Mangla, S. K., Garza-Reyes, J. A., & Kazancoglu, Y. (2023). Analysing the adoption barriers of low-carbon operations: A step forward for achieving net-zero emissions. Resources Policy, 80, 103256.

- Kumar, N. M., & Chopra, S. S. (2022). Leveraging blockchain and smart contract technologies to overcome circular economy implementationchallenges. Sustainability, 14(15), 9492.
- Kurramovich, K. K., Abro, A. A., Vaseer, A. I., Khan, S. U., Ali, S. R., & Murshed, M. (2022). Roadmap for carbon neutrality: the mediating role of clean energy development-related investments. Environmental Science and Pollution Research, 1-20.
- Liang, G., Weller, S. R., Luo, F., Zhao, J., & Dong, Z. Y. (2018). Distributed blockchain-based data protection framework for modern power systems against cyber attacks. IEEE Transactions on Smart Grid, 10(3), 3162-3173.
- Lohmer, J., & Lasch, R. (2020). Blockchain in operations management and manufacturing: Potential and barriers. Computers & Industrial Engineering, 149, 106789.
- Mahmoudi, A., & Javed, S. A. (2022). Performance Evaluation of Construction Sub-contractors using Ordinal Priority Approach. Evaluation and program planning, 91, 102022.
- Malik, S., Chadhar, M., Chetty, M., & Vatanasakdakul, S. (2022). Adoption of Blockchain Technology: Exploring the Factors Affecting Organizational Decision. Human Behavior and Emerging Technologies, 2022.
- Mishra, R., Singh, R., & Govindan, K. (2022). Net-zero economy research in the field of supply chain management: a systematic literature review and future research agenda. The International Journal of Logistics Management, (ahead-of-print).
- Mohandes, S. R., Sadeghi, H., Fazeli, A., Mahdiyar, A., Hosseini, M. R., Arashpour, M., & Zayed, T. (2022). Causal analysis of accidents on construction sites: A hybrid fuzzy Delphi and DEMATEL approach. Safety science, 151, 105730.
- Monrat, A. A., Schelén, O., & Andersson, K. (2019). A survey of blockchain from the perspectives of applications, challenges, and opportunities. IEEE Access, 7, 117134-117151.
- Muduli, K., Govindan, K., Barve, A., & Geng, Y. (2013). Barriers to green supply chain management in Indian mining industries: a graph theoretic approach. Journal of Cleaner Production, 47, 335-344.

- Murry, J. W., & Hammons, J. O. (1995). Delphi: A Versatile Methodology for Conducting Qualitative Research. The Review of Higher Education, 18(4). https://doi.org/ 10.1353/rhe.1995.0008
- 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 Management: An International Journal, 25(6), 841-862.
- Nandi, S., Sarkis, J., Hervani, A. A., & Helms, M. M. (2021). Redesigning supply chains using blockchain-enabled circular economy and COVID-19 experiences. Sustainable Production and Consumption, 27, 10-22.
- Novakowski, N., & Wellar, B. (2008). Using the Delphi technique in normative planning research: Methodological design considerations. Environment and Planning A, 40(6), 1485–1500. https://doi.org/10.1068/a39267
- Oktavianus, J. ;, Oviedo, H. ;, Gonzalez, W. ;, Putri, A., Pratama, ;, & Lin, T. T. C. (2017). Why do Taiwanese young adults not jump on the bandwagon of Pok´emon Go? Exploring barriers of innovation resistance. Journal of Computer-Mediated Communication, 13(4), 827–855. https://doi.org/10.1111/J.1083-6101.2008.00421.
- Olatunji, O. O., Akinlabi, S. A., Ayo, O. O., Madushele, N., Adedeji, P. A., & Fatoba, S. O. (2019). Drivers and barriers to competitive carbon footprint reduction in manufacturing supply chain: A brief review. Procedia Manufacturing, 35, 992-1000.
- Otter, C., Watzl, C., Schwarz, D., & Priess, P. (2017). Towards sustainable logistics: study of alternative delivery facets. Entrepreneurship and Sustainability Issues, 4(4), 460-476.
- Pamucar, D., Deveci, M., Gokasar, I., Martínez, L., & Köppen, M. (2022). Prioritizing transport planning strategies for freight companies towards zero carbon emission using ordinal priority approach. Computers & Industrial Engineering, 169, 108259.
- 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). Business Strategy and the Environment, 31(1), 194-217.
- Petersen, M., Hackius, N., & von See, B. (2018). Mapping the sea of opportunities: Blockchain in supply chain and logistics. it-Information Technology, 60(5-6), 263-271.

- Pournader, M., Shi, Y., Seuring, S., & Koh, S. L. (2020). Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. International Journal of Production Research, 58(7), 2063-2081.
- Priyadarshini, J., Singh, R. K., Mishra, R., & Kamal, M. M. (2022). Adoption of additive manufacturing for sustainable operations in the era of circular economy: Self-assessment framework with case illustration. Computers & Industrial Engineering, 171, 108514.
- Quartey-Papafio, T. K., Islam, S., & Dehaghani, A. R. (2021). Evaluating suppliers for healthcare centre using ordinal priority approach. Management Science and Business Decisions, 1(1), 5-11.
- Raghuvanshi, J., Agrawal, R., & Ghosh, P. K. (2017). Analysis of barriers to women entrepreneurship: The DEMATEL approach. The Journal of Entrepreneurship, 26(2), 220-238..
- Ram, S. (1987). A model of innovation resistance. ACR North American Advances.
- Risius, M., & Spohrer, K. (2017). A blockchain research framework: What we (don't) know, where we go from here, and how we will get there. Business & information systems engineering, 59, 385-409.
- Rosli, K., Yeow, P., & Siew, E.-G. (2012). Factors Influencing Audit Technology Acceptance by Audit Firms: A New I-TOE Adoption Framework. Journal of Accounting and Auditing: Research & Practice, 2012, 1–11. https://doi.org/10.5171/2012.876814.
- Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2018). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117-2135.
- Sadeghi, M., Mahmoudi, A., & Deng, X. (2022). Adopting distributed ledger technology for the sustainable construction industry: evaluating the barriers using Ordinal Priority Approach. Environmental science and pollution research, 29(7), 10495-10520.
- Singh, C., Singh, D., & Khamba, J. S. (2021). Analyzing barriers of Green Lean practices in manufacturing industries by DEMATEL approach. Journal of Manufacturing Technology Management, 32(1), 176-198.

- Smokers, R., Tavasszy, L., Chen, M., & Guis, E. (2014). Options for competitive and sustainable logistics. In Sustainable logistics (Vol. 6, pp. 1-30). Emerald Group Publishing Limited.
- Subramanian, N., & Abdulrahman, M. (2017). An examination of drivers and barriers to reducing carbon emissions in China's manufacturing sector. The International Journal of Logistics Management, 28(4), 1168-1195.
- Tijan, E., Aksentijević, S., Ivanić, K., & Jardas, M. (2019). Blockchain technology implementation in logistics. Sustainability, 11(4), 1185.
- Tornatzky, L. G., & Fleischer, M. (1990). The processes of technological innovation. Lexington, MA: Lexington Books.
- Touboulic, A., & Walker, H. (2015). Theories in sustainable supply chain management: a structured literature review. International journal of physical distribution & logistics management, 45(1/2), 16-42.
- Umam, B., Darmawan, A. K., Anwari, A., Santosa, I., Walid, M., & Hidayanto, A. N. (2020, November). Mobile-based smart regency adoption with TOE framework: An empirical inquiry from Madura Island Districts. In 2020 4th International Conference on Informatics and Computational Sciences (ICICoS) (pp. 1-6). IEEE.
- Vafadarnikjoo, A. orcid.org/0000-0003-2147-6043, Badri Ahmadi, H., Liou, J.J.H. et al. (2
- Varriale, V., Cammarano, A., Michelino, F., & Caputo, M. (2020). The unknown potential of blockchain for sustainable supply chains. Sustainability, 12(22), 9400.
- Virmani, N., Salve, U. R., Kumar, A., & Luthra, S. (2021). Analyzing roadblocks of Industry 4.0 adoption using graph theory and matrix approach. IEEE Transactions on Engineering Management.
- Wachsmuth, J., Warnke, P., Gambhir, A., Giarola, S., Koasidis, K., Mittal, S., ... & Doukas, H. (2023). Co-creating socio-technical scenarios for net-zero emission pathways: comparison of five national case studies. Renewable and Sustainable Energy Transition, 100064.
- Wenjing, X., & Cai, Z. (2023). Assessing the best art design based on artificial intelligence and machine learning using GTMA. Soft Computing, 27(1), 149-156.
- White, G. R. (2017). Future applications of blockchain in business and management: A Delphi study. Strategic change, 26(5), 439-451.
- Yadav, S., Samadhiya, A., Kumar, A., Majumdar, A., Garza-Reyes, J. A., & Luthra, S. (2023). Achieving the sustainable development goals through net zero emissions:

innovation-driven strategies for transitioning from incremental to radical lean, green and digital technologies. Resources, Conservation and Recycling, 197, 107094.

- Yang, Y. P. O., Shieh, H. M., Leu, J. D., & Tzeng, G. H. (2008). A novel hybrid MCDM model combined with DEMATEL and ANP with applications. International journal of operations research, 5(3), 160-168.
- Yontar, E. (2023). Challenges, threats and advantages of using blockchain technology in the framework of sustainability of the logistics sector. Turkish Journal of Engineering, 7(3), 186-195.
- Zhang, A., Alvi, M. F., Gong, Y., & Wang, J. X. (2022). Overcoming barriers to supply chain decarbonization: Case studies of first movers. Resources, Conservation and Recycling, 186, 106536.
- Zhao, G., Ahmed, R. I., Ahmad, N., Yan, C., & Usmani, M. S. (2021). Prioritizing critical success factors for sustainable energy sector in China: A DEMATEL approach. Energy Strategy Reviews, 35, 100635.
- Zheng, Z., Xie, S., Dai, H. N., Chen, X., & Wang, H. (2018). Blockchain challenges and opportunities: A survey. International journal of web and grid services, 14(4), 352-375.