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Exploring Blockchain Implementation Challenges for Sustainable Supply Chains: An Integrated Fuzzy TOPSIS–ISM Approach

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Abstract: This study investigates the challenges in implementing blockchain technology (BT) in sustainable supply chain management (SSC). The study thoroughly analyzes the literature and expert opinions on BT, SCM, and sustainability. A total of 24 barriers are identified, categorized into the Internet of Things, strategic, supply chain, legislation, and external factors. The findings are evaluated using the Integrated Fuzzy TOPSIS–ISM tool. The results indicate that barriers related to the supply chain have the most significant impact on the adoption of BT in SSC. The study also reveals the interrelation among sub-barriers within the supply chain, providing valuable insights to improve adoption. Finally, a strategic action plan based on a fishbone diagram is provided to reduce the effects of supply chain barriers. This study provides a theoretical foundation for using BT to achieve long-term supply chain goals.

Keywords: sustainable supply chain; blockchain technology; fuzzy TOPSIS; ISM

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1. Introduction

Recently, blockchain technology (BT) has attracted a lot of interest and buzz as a revolutionary innovation. Organizations are now thinking about implementing this technology because of its upsides. Cost reductions, improved accountability and traceability, and increased sustainability are some possible advantages that have been highlighted [1]. Even though most fortune businesses have considered blockchain, the investment has significantly decreased. While blockchain technology has generated considerable interest and promise, the significant drop in investment among large firms can be attributed to several factors, including the technology's complexity and uncertainty, evolving regulatory challenges, the need for a clear return on investment, and competing priorities within organizations. As technology matures and demonstrates its usefulness in specific use cases, we may see an expansion of giant corporations' investment in blockchain, yet more measured and strategic [2].

In recent years, several key findings from numerous industries were examined in previous research to examine the impact of blockchain on a sustainable future. It was discovered that not a single of these examples is in the full execution phase but is instead trapped in the pilot testing phase [3]. The transition of blockchain projects from pilot testing to full adoption for sustainability is frequently delayed by technological, regulatory, resource, and organizational issues. Before proceeding with full-scale adoption, organizations want to ensure that they are well-prepared, can demonstrate the value and return on investment, and have addressed any potential bottlenecks [4,5].

The term "blockchain" refers to autonomous ledgers that store activities as data blocks connected by an encryption reference. The chain extends to the initial block that was the source. Whenever an additional block is added to the system, it is connected to its predecessor. Data that are protected, traceable, verifiable, and accessible are essential [6]. These traits inspired numerous businesses to incorporate blockchain solutions throughout their SCs in order to boost productivity and effectiveness. This reality will serve as yet another impetus for this research, encouraging us to identify crucial elements that speed up the adoption of BT. Over the last 30 years, the sustainability of the SC has grown in significance and become a key factor in driving market and customer satisfaction. The production and delivery of goods and services are carried out as part of an SSC, a network of businesses, individuals, organizations, activities, information, and resources that aims to reduce unfavorable effects on the environment and society while generating profit. Companies should support SCM for social, competitive, and regulatory reasons. Customers want to check the sustainability of the goods they purchase; thus, they need easily available source data [7].

The subsequent step of the research answers the following research questions to accomplish the research goals:

(i) What barriers hinder businesses from adopting and implementing blockchain technology?;
(ii) How do these barriers rank in terms of their significance in adopting blockchain technology?;
(iii) What is the interrelationship among these barriers and how are they interconnected?;
(iv) Is it necessary for businesses to eliminate certain barriers to minimize their impact on other barriers?

This research is primarily motivated by the increasing prominence of blockchain technology in sustainable supply chains. Saberi et al. [8] highlighted its stability, traceability, data integrity, and cryptocurrency capabilities, particularly in settings that eliminate intermediaries. In the context of today's complex, cross-border supply chain networks, Ivanov et al. [9] emphasized the growing challenges in achieving efficient transactions, inventory tracking, and data analysis. Furthermore, Yadav et al. [10] discussed blockchain's pivotal role in resource allocation, transparency, and reducing environmental impacts within supply chains. Lotfi et al. [11] proposed integrating vendor-managed inventory with blockchain to enhance supply chain viability and robustness. These studies demonstrate how blockchain technology has the potential to redefine and improve supply chain management's sustainability and resilience.

In order to participate in some SSC, suppliers are under an obligation to become sustainable on a global and local scale. SC sustainability may be improved using blockchain. Although there are a lot of possible blockchain implications for increasing sustainability in a system, there are not many application scenarios where blockchain is being used to improve sustainability, and businesses are still having trouble dealing with the more comprehensive parts of sustainability. Investment in technology is declining, as was already indicated, with certain exceptions. Both advantages and drawbacks exist with new technology. Power consumption is a significant issue for sustainability within the blockchain. Greenhouse gases rise along with energy use. Distributed ledgers also require more processing power and assets to preserve the confidentiality of the information and avoid duplication, eventually resulting in higher power consumption. These are merely drawbacks related to sustainability, but, as shown in our research, there are also numerous obstacles to the adoption of this technology. The adoption of blockchains has indeed been moderate, despite their potential. We are looking into why this technology, which holds so much potential in the economy, society, and the environment, has reached a standstill. As a result, it is important to understand the potential difficulties and limitations businesses can encounter when deploying this technology.

In this study, we examine the barriers to BT adoption in SSC and their connections. The barriers were collected from a comprehensive literature review. It is nearly impossible to remove every barrier at once. Multi-criteria decision-making (MCDM) procedures may accomplish the ranking and evaluation of inter-relationships among barriers. The capacity of the Integrated Fuzzy TOPSIS–ISM technique to rank significant barriers while capturing their interdependencies led to its selection among other MCDM techniques. The paper investigates these barriers using opinions from SC, sustainability, and blockchain specialists. However, blockchain technology benefits sustainable supply networks in a variety of ways. More effective traceability supports the accuracy of sustainability claims, while better visibility allows for real-time monitoring and problem solving and streamlined organizational processes make cooperation among multiple supply chain stakeholders easier. These benefits lead to more efficient and accountable supply chains, which connect with the broader aims of environmental responsibility and social sustainability [12].

The remainder of the paper is divided into the following sections. We thoroughly examine the recent literature on blockchain and sustainable supply chains in Section 2. A detailed explanation of our research approach and the methods for collecting data and analysis are presented in Section 3. Section 4 describes how to use suitable MCDM techniques. Numerical examples are provided in Section 5 to support our conclusions. We explore the implications of our findings for managerial practices in Section 6. Finally, Section 7 includes an assessment of the research's limitations, a review of its conclusions, and recommendations for prospective future research areas.

2. Literature Review

2.1. Blockchain Technology

The emergence of BT in 2009, through the development of Bitcoin by Nakamoto, was initially focused on financial integration [6]. However, the game-changing aspects of blockchain have encouraged sectors other than the financial industry to adopt it [13]. Many uses of BT have been identified in the literature, including healthcare management [14], the energy sector [15,16], and digital government [17]. Additionally, SC network management has been identified as an enabler for BT, with most of the research focusing on four main themes: trust [18], trade [19], IoT [20], and traceability [1]. In spite of the potential advantages of SC integration with blockchain, barriers to adoption remain a significant challenge, including technological challenges, inadequate standards and trustworthiness, and interoperability [21]. An important research gap exists concerning the comprehensive assessment of barriers hindering the implementation of BT for SCM [22]. While some previous studies have investigated the adoption of BT, only a limited number have specifically addressed the barriers and challenges associated with its implementation, with the majority concentrating on adoption theories [23,24].

2.2. Blockchain Integration in the Management of SSC

BT has gained recognition as a disruptive invention that can improve SSC [8]. The transparency and dependability of sustainable product creation can be increased by carefully monitoring the flows of goods along the SC and integrating BT. This can boost consumer trust by enhancing the credibility of the goods. Furthermore, blockchain can monitor social and environmental factors that could endanger sustainability, promoting both social and environmental sustainability [25]. There are two commonly used types of BT: public/permissionless and closed/permissioned [17]. Public blockchain networks enable anybody to join, access, and use blockchain ledgers. Public blockchains include Bitcoin and other cryptocurrencies. In contrast, private blockchains restrict access only to authorized users, while a hybrid model incorporating both public and private blockchains can be tailored to meet specific business needs. In the area of SCM, numerous use cases recommend adopting a private blockchain setup that allows only approved users with regulated access to exchange data [1]. Apart from SC applications, BT can also transform sustainability management in other areas. For instance, BT can be used to promote sustainability in the energy market by facilitating the sharing of energy in a sustainable manner [26]. The interrelationship of blockchain with the IoT can also help in managing SC issues [27]. BT might also aid in reducing information asymmetries that might limit small businesses and farms' access to chances for social and financial development. Additionally, blockchain can contribute to the sustainability of the socioeconomic system by minimizing illegal, fraudulent, and counterfeiting practices [28].

2.3. Barriers to Adopting Blockchain for SSC

2.3.1. IoT Related Barriers

BT has potential for SCM, but its adoption faces various barriers. Technical limitations like scalability, usability, and interoperability issues hinder implementation [29]. Latency problems result in slower transaction times and fewer transactions [30]. Security concerns, including vulnerability to hacking and system attacks, and conflicts between blockchain organizations can lead to "blockchain splitting" [31]. Limited access to blockchain information and data availability poses another challenge [32]. While data immutability is a key feature, it can be problematic if past errors persist indefinitely. The negative association with illegal activities on the "dark web" may hinder adoption, but increased familiarity and adoption may change public perception over time. The relationships between cryptocurrencies, blockchain technology, and unlawful activity on the "dark web" described are probably because these technologies have been employed in certain illegal transactions due to their pseudonymous nature. Criminals have used blockchain's immutability to hide their operations. Though the technology is neutral, it is important to understand that its implementations can have beneficial or bad effects [33].

2.3.2. Strategic Barriers

The adoption of BT in SCM is influenced by various internal factors and issues within organizations [34]. The implementation of BT requires substantial investments in hardware, software, maintenance, and infrastructure, particularly for larger implementations, posing financial challenges [35]. Additionally, cross-disciplinary involvement is necessary to ensure the integration of BT with environmental management, public relations, and corporate responsibility for sustainability. However, a lack of commitment from middle or upper management can negatively affect the perceived value of blockchain applications in SCM. Furthermore, if sustainability is not seen as a core value by management, the importance of blockchain technology may be overlooked. The lack of understanding and knowledge among enterprises regarding blockchain and sustainability hinders adoption [36]. Moreover, the absence of standardization in BT adds complexity to its adoption in SCM, making organizational adjustments for new blockchain and sustainability standards even more challenging. However, there is a chance that the potential advantages of blockchain technology in achieving sustainability goals may be disregarded or underestimated when sustainability is not seen as a fundamental value by management. Blockchain technology adoption as a tool for sustainability within a company is significantly influenced by management's priorities, vision, resource allocation choices, and influence on organizational culture [37,38].

2.3.3. Supply Chain Barriers

The adoption of BT in SCM is hindered by external barriers that are independent of businesses and technology. Inadequate communication and coordination among partners result in a lack of consumer understanding of the intersection between blockchain and sustainability, posing a significant challenge in SC issues [39]. Businesses often lack sustainability expertise and fail to implement sustainable practices throughout the SC, which complicates the integration of BT [40]. However, businesses are willing to share information if it benefits their consumers and ensures the security and privacy of their proprietary information, which BT can provide through encrypted blockchain and data security measures [41]. The sensitivity of sustainability information due to ethical and legal issues further amplifies these barriers. Reengineering business operations is necessary to overcome the challenges of integrating SC with sustainability and blockchain, but resource constraints may delay improvements in sustainable performance. Cultural and geographic diversity among SC partners can also make BT implementation challenging, as different notions of sustainability, particularly social sustainability, create difficulties in implementing consistent blockchain solutions [42].

2.3.4. Legislation Barriers

A legal barrier in blockchain technology is a problem or issue that prevents blockchain systems' use, adoption, or functioning because laws, regulations, or lack thereof cause it. These obstacles, which affect different parts of blockchain technology, may result from the legal and regulatory frameworks in a certain jurisdiction [43–46]. Government rules are still not totally in favor of BT, which makes it more difficult for it to be adopted in the SC. One major problem is the absence of governmental sustainability laws and frameworks, which hinder the development of integrated systems and blockchain standards [47].

2.3.5. External Barriers

The implementation of sustainability and blockchain in SCM is hampered by external parties from a wide range of sectors, including governments, businesses, institutes, communities, and non-governmental organizations [48]. These barriers may obstruct the integration of sustainability and blockchain, which would eventually impede efforts to grow the economy sustainably and profitably. Another barrier is a lack of market knowledge and unpredictability, which can make companies fear the entry of new sustainable products into the market. This, in turn, makes BT even more necessary for an SSC [23].

However, based on the literature review and expert opinions, the authors identified the set of barriers indicated in Table 1. The data collection strategy, validity, and consistency of the data are outlined in the methodology Sections 3.1 and 3.2.

Table 1. Barriers of implementing BT in SSC.

Primary Factor	Subfactor	Description	References
IoT barriers (B1)	Security challenge	Data security concerns include hacking, inaccurate information dissemination, and sensitive data access.	[49,50]
	Access to technology	Effective blockchain adoption depends on good internet and IT infrastructure access.	[51]
	Technological backlash	Negative perceptions about BT due to its association with cryptocurrencies hinder adoption.	[52]
	Consensus mechanisms	Immutability means records cannot be deleted, but incorrect records can be corrected with their history on the blockchain.	[47]
	Immaturity of technology	The scalability challenge is a technical issue arising from blockchain immaturity.	[36,53]
Strategic barriers (B2)	Financial constraints	High costs limit organization's ability to collect SC information and adopt sustainability practices.	[41,50]
	Unsupportive and uncommitted management	Managers' lack of commitment to sustainability and disruptive technology hinders SCM.	[54,55]
	Absence of BT policies	Defining new policies is necessary for organizations to adopt BT.	[30]
	Complications in changing organizational practices	Blockchain adoption transforms organizational culture with new work guidelines.	[30]
	Absence of resources for BT adaptation	Organizations face challenges in implementing blockchain and measuring sustainability due to a lack of standards.	[56]

Table 1. *Cont.*

Primary Factor	Subfactor	Description	References
SC barriers (B3)	Lack of customers awareness	Customers' lack of understanding of blockchain for SC sustainability practices.	[40]
	Lack of 3Cs	Performance is hampered by a lack of cooperation, coordination, and communication among SC partners.	[57]
	Difficulty in information sharing between SC parties	Data confidentiality, privacy, and financial value may present difficulties for the implementation of blockchain and SSC.	[50]
	Difficulties of integrating BT and sustainability through SCM	Integrating sustainability practices and blockchain into SCs requires technology, materials, and process development.	[58]
	Cultural differences of SC partners	Geographical or cultural differences among SC partners may hinder blockchain adoption.	[59]
Legislation barrier (B4)	Lack of legal framework	Businesses and organizations intending to implement blockchain technology may face confusion and regulatory issues in the absence of a legal framework.	[60]
	Lack of regulatory standards	Governments may be hesitant to promote blockchain and sustainability by creating regulatory standards.	[41,61]
	Smart contracts and legal validity	Traditional legal systems may fail to comprehend or adapt the distinct nature of smart contracts, resulting in confusion and significant legal stumbling blocks.	[50,62]
	Jurisdictional issues	Different countries' rules and regulations may contradict, complicating cross-border transactions and data management.	[45,46]
	Intellectual property rights	Determining ownership and protecting intellectual property assets inside a blockchain ecosystem might be difficult.	[43,44]
External barriers (B5)	Market rivalry and uncertainty	Sustainability and blockchain adoption may impact market competitiveness and involve uncertainty.	[50]
	Absence of involvement by external stakeholders	NGOs and communities may not fully support sustainable practices and BT.	[54]
	Lack of rewards and incentives	The industry lacks leadership in ethical and safe sustainability practices with blockchain.	[54]
	Lack of industry involvement in the adoption of blockchain	Lack of incentivization for sustainable blockchain practices by governments/professional organizations.	[50]

2.4. Research Contributions

This research significantly contributes to sustainable supply chain management and blockchain technology integration. Firstly, it systematically identifies, categorizes, and prioritizes 24 barriers to implementing blockchain technology in sustainable supply chains, shedding light on the complexities that hinder its widespread adoption. Secondly, it employs the Integrated Fuzzy TOPSIS–ISM approach, effectively addressing uncertainties and providing a robust evaluation of the identified barriers, thus enhancing the accuracy and reliability of the findings. Thirdly, this study highlights that supply chain-related barriers are the most influential, emphasizing the critical need to address challenges within the supply chain to advance blockchain adoption in sustainable supply chains. Additionally, the research uncovers intricate interdependencies among these sub-barriers, offering valuable insights for decision-makers. Additionally, utilizing the fishbone diagram, the proposed strategic action plan provides a practical roadmap for mitigating the effects of supply chain barriers, thus aiding organizations in effectively leveraging blockchain technology for sustainable supply chain objectives. However, this research contributes a theoretical framework and practical guidance for enhancing the adoption of blockchain technology in sustainable supply chain management, addressing a significant gap in the literature. Addressing these barriers through the proposed strategic action plan can catalyze blockchain adoption, fostering innovation and improving supply chain resilience and sustainability.

3. Research Methodology

As illustrated in Figure 1, the research framework consisted of three phases that systematically investigate the barriers associated with integrating BT into an SSC. **Phase I** of the framework involved conducting a detailed literature review to identify the barriers to integrating BT into an SSC. This phase allows us to understand the various challenges and difficulties that may arise during the integration process. In **Phase II**, an integrated Fuzzy TOPSIS technique was incorporated to measure and rank the primary barriers identified in Phase I. This technique enables us to evaluate the various barriers based on their relative importance and quantitatively measure their impact on the integration process. To further strengthen the proposed technique, in **Phase III**, the authors used the Interpretive Structural Modelling (ISM) method to determine how the sub-barriers of the ranked primary barrier interact with each other. This phase enables the authors to identify the complex relationships and dependencies between the various sub-barriers and provides a more holistic understanding of the integration challenges.

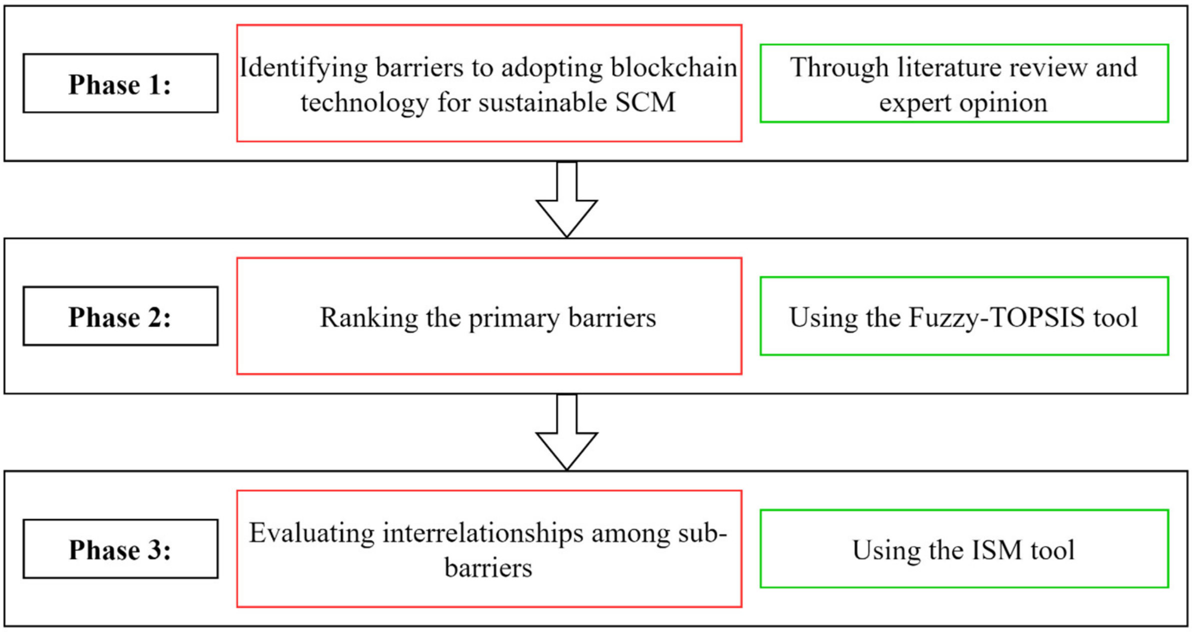

Figure 1. Research framework.

3.1. Data Collection

The purpose of this study was to assess the impact of barriers on the application of blockchain technology in sustainable supply chains. To attain this objective, an extensive literature review was conducted, and consultations were held with experts from the RMG Industry in Dhaka, Bangladesh. The barriers identified for analysis were chosen based on their substantial impact on organizations' adoption of blockchain technology. Furthermore, five industry experts and two academic experts participated in a series of brainstorming sessions to enhance and enrich the ideas gathered from the literature review. Table 2 summarizes the demographic information of the participants in the research study, including their profession/industry, expertise, number, location, and the method used for opinion assessment.

Table 2. Demographic information of participants.

Demographic Information of Participants
Profession/Industry
Experts from the RMG (Ready-Made Garments) Industry in Dhaka, Bangladesh
Expertise
- Field experts (Industry professionals)
- Academic experts (Researchers)
Number of Participants
- 50 field experts for questionnaire
- 30 experts (industry and academia) for reliability and consistency assessment
Location
Dhaka, Bangladesh
Opinion Assessment
- Participants used a five-point Likert scale to assess barriers
- Linguistic terms (e.g., "very low" to "very high influence") were used for assessment

A reliability analysis was performed to evaluate the questionnaire's validity, using a five-point Likert scale to assess the significance and feasibility of the identified barriers. This questionnaire was subsequently forwarded to 50 field experts, who provided feedback on these barriers. Furthermore, the consistency of these barriers was evaluated using Kappa statistics, which were based on replies from 30 industry and academic experts. These experts were asked to evaluate the presence of primary barriers and sub-barriers across five perspectives: managerial, information, integration, production, and environmental. The Kappa index value calculated from their responses was within the significant range (0.21–0.40), confirming the consistency of the highlighted barriers for future investigation. This allows for a reliable assessment of the barriers and their impact on the research objectives.

With the consistency of the identified barriers validated, the study moved on to a Fuzzy TOPSIS analysis. A questionnaire was developed that included linguistic terms ranging from "very low" to "very high influence", and it was then discussed with 30 field experts. These experts were requested to provide their opinions on the identified barriers' impact on sustainable supply chain. The Integrated Fuzzy TOPSIS–ISM approach was employed step by step to fulfill the research objective. This strategy aided in the investigation of interdependencies and influences among the most critical barriers, providing useful insights into their relative importance and impact.

3.2. Data Analysis and Validation

3.2.1. Reliability Analysis

The questionnaire was sent to 50 professionals and academics to examine the feasibility of the listed barriers, and 30 responses were received. This 60% response rate is consistent with the recommended criteria established by Malhotra and Grover [63]; therefore, the data considered for further analysis. Cronbach's alpha coefficient (α) was calculated using SPSS-23 to confirm the reliability of the data collected. The estimated coefficient, 0.759, is within the required range ($0.7 < \alpha < 0.95$), indicating acceptable internal consistency (see Table 3). The mean and standard deviation of the responses were also calculated. These statistical parameters provide a preliminary view into the significance levels of the barriers. For instance, Supply chain- and Legislation-related barriers exhibited higher mean values compared to other barriers. This suggests that these barriers are significant in establishing better sustainable supply chain performance.

Table 3. Reliability and item statistics.

Reliability Statistics				
Cronbach's Alpha 0.759			No. of Items 5	
Item Statistics				
Barriers	Mean	Std. Deviation	Corrected Item-Total Correlation	Respondents
B1	4.6333	0.49013	0.460	30
B2	4.4667	0.50742	0.547	30
B3	4.6333	0.49013	0.792	30
B4	4.7000	0.46609	0.640	30
B5	3.7333	0.86834	0.417	30

3.2.2. Consistency Analysis: Kappa Statistics

The study used Kappa statistics, created by Cohen [64], to ensure the consistency of the identified barriers across different perspectives, including managerial, information, integration, production, and environmental. In the previous literature, Tyagi et al. [65] considered four perspectives, but Hossain et al. [66] considered five perspectives, including environmental perspectives, to strengthen the sustainability performance. Kappa index (k) is a quantitative measure that assesses the level of agreement beyond chance by comparing observed and expected agreement. In this research, it was crucial to evaluate the consistency of each barrier within its corresponding perspective. To achieve this, Kappa statistics were used to analyze the nature of consistency for each barrier under its respective perspective. The findings are presented in Table 4, which indicates the number of experts involved in identifying the barriers within each category. The filled values in the table represent the level of expert agreement for the presence of barriers in the specific category. P_i denotes the degree of expert involvement for the ith barrier, while P_j represents the assignment percentage under the jth category.

Table 4. Opinions of 30 experts under 5 perspectives.

Barriers	**Perspectives**					**Pi**
	P1	**P2**	**P3**	**P4**	**P5**	
B1: IoT-related barrier	3	23	4	0	0	0.464368
B2: Strategic barrier	22	3	2	1	2	0.404598
B3: SC-related barrier	3	23	3	1	0	0.457471
B4: Legislation-related barrier	5	1	0	1	23	0.466667
B5: External barrier	3	2	0	3	22	0.409195
P_j	0.24	0.347	0.06	0.04	0.313	K = 0.222

The value of kappa (k) is calculated as

$$k = \frac{\text{Proportion of the observed agreement} - \text{Chance agreement}}{1 - \text{Chance agreement}} = 0.222$$

Landis and Koch [67] proposed a Kappa value interpretation scale, as shown in Table 5. When 'k = 0.222' is investigated, it is determined that it is related to ensuring that all barriers in their category have a fair degree of consistency. In accordance with the work's methodology, ranking of the primary barriers has been performed utilizing the fuzzy TOPSIS and interrelations among sub-barriers performed using the ISM approach.

Table 5. Scale for interpretation of Kappa statistics.

Values of k	<0	0.1–0.20	0.21–0.40	0.41–0.60	0.61–0.80	0.81–1.00
Interpretation	Poor	Slight	Fair	Moderate	Substantial	Perfect

4. Application of the Proper MCDM Methods

4.1. Fuzzy TOPSIS Approach

This research used the fuzzy TOPSIS method to rank the barriers within a fuzzy environment. The fuzzy TOPSIS method is a Multi-Criteria Decision-Making (MCDM) approach that enables the ranking of barriers based on their relative importance. Among the various MCDM methods, TOPSIS is widely applicable across different fields. Initially designed to rank alternatives based on a predetermined set of criteria, the TOPSIS method offers a straightforward approach to ranking barriers, focusing on their proximity to the positive ideal solution and distance from the negative ideal solution. However, traditional MCDM methods have limitations, as they utilize crisp values that fail to capture the uncertainty and ambiguity inherent in real-world decision problems. Hence, fuzzy MCDM is preferred, as it can account for the uncertainty in complex environments, making it suitable for this study. Several techniques are available for evaluating and ranking barriers, each with advantages and limitations. Hossain et al. [66], for example, used Fuzzy DEMATEL to identify and prioritize factors in Green Lean Supply Chain Management. A similar approach was used by Tyagi et al. [65] to evaluate important enablers for flexible supply chain performance assessment systems. However, one of the most extensively utilized MCDM algorithms is fuzzy TOPSIS. It is distinguished by its computational approach simplicity, capacity to include human preferences, and explicit trade-offs between several criteria [68].

Fuzzy TOPSIS is categorized as a compromising model, acknowledging that, while an ideal solution may not exist, achieving a solution with optimal values is possible. TOPSIS has gained significant attention from scholars and professionals for solving various problems. For example, Baykasoğlu et al. [69] utilized fuzzy TOPSIS to solve truck selection problems, Memari et al. [70] employed it for selecting sustainable suppliers, Malakouti et al. [71] used it to evaluate flexible components, and Zubayer et al. [72] prioritized SC risks, among others. Consequently, this study adopts the Fuzzy TOPSIS method to rank the barriers. The Fuzzy TOPSIS methodology involves several fundamental steps:

Step 1. Construction of Decision Matrix: Initially, a decision matrix is built based on the criteria and alternatives considered in the study. The weight given to each criterion (barrier) and scale used in this study are shown in Tables 6 and 7;

Table 6. Characteristics of criteria.

Sl. No.	Name	Type	Weight
1	Barrier 1	+	(0.200, 0.200, 0.200)
2	Barrier 2	+	(0.200, 0.200, 0.200)
3	Barrier 3	+	(0.200, 0.200, 0.200)
4	Barrier 4	+	(0.200, 0.200, 0.200)
5	Barrier 5	+	(0.200, 0.200, 0.200)

Table 7. Fuzzy scale.

Linguistic Terms	Very Low	Low	Medium	High	Very High
Influence Score	1	2	3	4	5
Membership Function	(1,1,3)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,9)

Step 2. Normalization: The decision matrix is normalized by dividing each element by the corresponding column sum;

Step 3. Weighted Normalization: Following normalization, a weighted normalized decision matrix is formed by multiplying each element in the normalized matrix by its respective weight;

Step 4. Determination of Fuzzy Positive and Negative Ideal Solutions: The fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) are identified;

Step 5. Distance Calculation: Distances between each alternative and both the fuzzy positive and negative ideal solutions are calculated;

Step 6. Closeness Coefficient: A closeness coefficient is computed for each alternative based on the distances obtained;

Step 7. Ranking: Finally, the alternatives are ranked based on their closeness coefficients, with higher values indicating superior rankings.

4.2. Interpretive Structural Modeling (ISM)

The ISM approach is utilized in this research work to analyze the supply chain sub-barriers. After being introduced to the research community, ISM has become a popular tool for engineers, scholars, and academics due to its ability to evaluate the relationships between barriers through a clear methodology, as shown in Figure 2. According to previously used cases, ISM provides advantages when investigating the interrelationships of criteria. Even complex issues can be addressed using ISM to create a well-defined structure with the help of flow charts, which aid decision-makers. This methodology has been applied to various fields, including renewable energy, supply chain, waste management, policy analysis, supplier selection, and other common issues [73,74]. The ISM technique was chosen for this research because it possesses the following features: (a) This methodology establishes whether and how the various barriers are interconnected; (b) An ISM digraph model illustrates the connections between the many barriers of a system; and (c) It aids in determining the direction and chronology of complex interactions between various system barriers. Detailed ISM methodology is described in Section 5.2 of this paper.

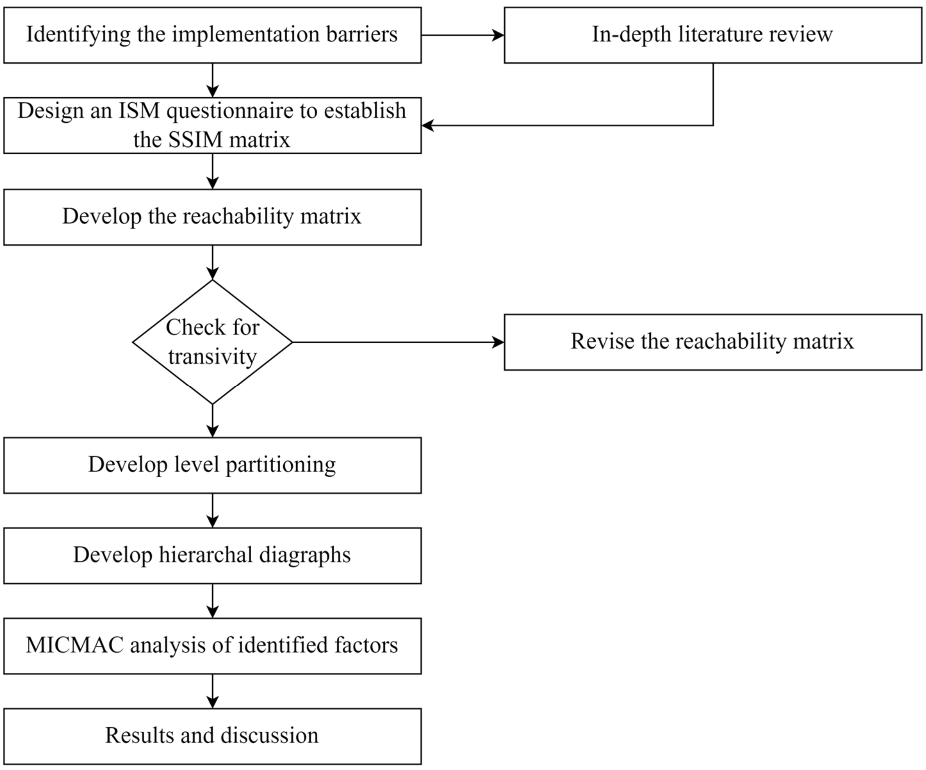

Figure 2. ISM methodology.

5. Numerical Illustration

5.1. Ranking Primary Barriers Using Fuzzy TOPSIS

Field experts and knowledgeable academicians were carefully chosen to implement this research to ensure supply chain management expertise and knowledge are utilized effectively. The aim was to prioritize individuals who directly confront the challenges in the field, enabling a better understanding and more precise interpretation of the research findings. Having more experts provides a more comprehensive evaluation of the barriers. Each expert can bring their unique knowledge, experience, and judgment to the decision-making process, which helps reduce individual biases and increase the rankings' overall reliability [75]. After completing reliability and consistency analyses for the barriers, a questionnaire was designed using a fuzzy linguistic scale, as presented in Table 7. This questionnaire was then administered to 30 field experts, who were engaged in discussions to gather their opinions on the impact of the barriers. We also asked the experts to assess how each barrier affected the others using pair-wise comparisons, and the outcomes are presented as an average decision matrix (**for detailed data and calculation, see** Appendix A Tables A1–A4).

Using Fuzzy TOPSIS Steps 1–3, this research obtained the decision matrix, normalized decision matrix, and weighted normalized decision matrix, as shown in Table 8.

Table 8. Decision metrices using Fuzzy TOPSIS.

			Decision matrix		
	B1	**B2**	**B3**	**B4**	**B5**
B1	(0.000,0.000,0.000)	(3.000,4.714,6.714)	(5.286,7.286,8.143)	(2.429,4.143,5.857)	(3.286,5.000,6.714)
B2	(2.429,3.857,5.857)	(0.000,0.000,0.000)	(4.429,6.429,7.857)	(3.857,5.571,7.571)	(3.286,5.286,7.000)
B3	(4.429,6.143,7.286)	(5.000,6.714,7.857)	(0.000,0.000,0.000)	(3.857,5.857,7.286)	(5.000,6.714,7.571)
B4	(2.429,4.143,6.143)	(2.429,4.429,6.429)	(4.143,6.143,7.857)	(0.000,0.000,0.000)	(4.714,6.429,7.571)
B5	(2.714,3.571,5.571)	(1.286,2.714,4.714)	(4.714,6.429,7.571)	(4.429,6.429,8.143)	(0.000,0.000,0.000)
			Normalized decision matrix		
B1	(0.000,0.000,0.000)	(0.382,0.600,0.855)	(0.649,0.895,1.000)	(0.298,0.509,0.719)	(0.434,0.660,0.887)
B2	(0.333,0.529,0.804)	(0.000,0.000,0.000)	(0.544,0.790,0.965)	(0.474,0.684,0.930)	(0.434,0.698,0.925)
B3	(0.608,0.843,1.000)	(0.636,0.855,1.000)	(0.000,0.000,0.000)	(0.474,0.719,0.895)	(0.660,0.887,1.000)
B4	(0.333,0.569,0.843)	(0.309,0.564,0.818)	(0.509,0.754,0.965)	(0.000,0.000,0.000)	(0.623,0.849,1.000)
B5	(0.372,0.490,0.765)	(0.164,0.345,0.600)	(0.579,0.790,0.930)	(0.544,0.790,1.000)	(0.000,0.000,0.000)
			Weighted normalized decision matrix		
B1	(0.000,0.000,0.000)	(0.076,0.120,0.171)	(0.130,0.179,0.200)	(0.060,0.102,0.144)	(0.087,0.132,0.177)
B2	(0.067,0.106,0.161)	(0.000,0.000,0.000)	(0.109,0.158,0.193)	(0.095,0.137,0.186)	(0.087,0.140,0.185)
B3	(0.122,0.169,0.200)	(0.127,0.171,0.200)	(0.000,0.000,0.000)	(0.095,0.144,0.179)	(0.132,0.177,0.200)
B4	(0.067,0.114,0.169)	(0.062,0.113,0.164)	(0.102,0.151,0.193)	(0.000,0.000,0.000)	(0.125,0.170,0.200)
B5	(0.074,0.098,0.153)	(0.033,0.069,0.120)	(0.116,0.158,0.186)	(0.109,0.158,0.200)	(0.000,0.000,0.000)

Table 9 presents the positive and negative ideal solutions, distances from the positive and negative ideal solutions, as well as the closeness coefficients and ranking order of each barrier. These values were calculated following Step 4, which determines the positive and negative ideal solutions, Step 5, which calculates the distances, and Steps 6 and 7, which compute the closeness coefficient and ranking order of each barrier, respectively.

Table 9. Ranking of the barriers.

	Positive Ideal	Negative Ideal	Distance from Positive Ideal	Distance from Negative Ideal	Closeness Coefficient	Rank
B1	(0.122,0.169,0.200)	(0.000,0.000,0.000)	0.305	0.545	0.642	4
B2	(0.127,0.171,0.200)	(0.000,0.000,0.000)	0.291	0.562	0.658	3
B3	(0.130,0.179,0.200)	(0.000,0.000,0.000)	0.189	0.651	0.775	1
B4	(0.109,0.158,0.200)	(0.000,0.000,0.000)	0.292	0.565	0.659	2
B5	(0.132,0.177,0.200)	(0.000,0.000,0.000)	0.337	0.511	0.602	5

5.2. Identifying the Interrelation of SC Sub-Barriers Using the ISM

This study employs interpretative structure modeling (ISM) to efficiently analyze the SC related sub-barriers. A total of 30 subject matter experts were contacted for this study's survey. A focused group discussion technique was utilized to conduct the discussion. In accordance with the ISM technique, there should be between 10 and 30 survey respondents to ensure consistency in responses [76,77]. The responses were gathered following the discussion. The survey respondents' consensus led to the accomplishing of the desired outcome. A second focused group discussion was conducted to verify the outcome and see whether there was any incompatibility. The next subsections describe the remaining aspects of the ISM approach.

5.2.1. Structural Self-Interaction Matrix (SSIM)

It performs a pair-wise comparison among sub-barriers while forming SSIM. The background was examined using the qualitative relationship of distance. This signifies that one precedent leads to another, and the latter is made possible by a different precedent. If this is not the case, then the precedents are incompatible. ISM looks at how each barrier is connected to the others by asking if there is a relationship between any two barriers (call them i and j) and how that relationship works. The direction of the relationship between the barriers (i and j) is represented by the following four letters: V—Barrier *i* affects barrier j; A—Barrier j affects Barrier i; X—Barriers *i* and *j* affect each other; and O—Barriers i and j are not related. The SSIM for the SC sub-barriers is given in Table 10.

Table 10. SSIM of the SC barriers.

Variables	S1	S2	S3	S4	S5
S1		O	V	V	X
S2			O	V	O
S3				V	A
S4					A
S5					

5.2.2. Final Reachability Matrix (FRM)

The next step is to create a preliminary reachability matrix. The SSIM is converted into the binary values 1 and 0 to create the reachability matrix. The preliminary reachability matrix is analyzed for adjustments and transitivity idea incorporation (if any). According to this concept, if a barrier i is associated with j and j is tied to a third barrier k, then i is unavoidably related to k. As a result, the final reachability matrix is obtained, as shown in Table 11.

Table 11. Final reachability matrix.

Variables	S1	S2	S3	S4	S5	Driving Power
S1	1	0	1	1	1	**4**
S2	0	1	0	1	0	**2**
S3	0	0	1	1	0	**2**
S4	0	0	0	1	0	**1**
S5	1	0	1	1	1	**4**
Dependence Power	**2**	**1**	**3**	**5**	**2**	

5.2.3. Summary of Level Partitioning

Our established precedents all need to be designated at different levels as a further step. Once the reachability matrix has been developed, the reachability and antecedent of each SC barrier are determined. The barriers that can support its integration are present in the antecedent set and the variables it can use to expand upon itself. Following the definition of the variables in these sets, the intersection set of these sets contains all variables. They are added in the highest level of ISM and have the same intersection and reachability barriers. The method continues to define the variables in the following stage once the highest-level barriers have been determined and removed. Until the variable's levels are determined, the cycle is repeated. All three level partitioning iterations are shown in Tables A5–A8 in the Appendix B section. Final level partitions of barriers are presented in Table 12.

Table 12. Final level partitioning of barriers.

Elements (Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1, 5	1, 5	1, 5	3
2	2	2	2	2
3	3	1, 3, 5	3	2
4	4	1, 2, 3, 4, 5	4	1
5	1, 5	1, 5	1, 5	3

6. Results and Discussion

This study first determines the barriers in implementing blockchain-based technology in the management of sustainable supply chain. Twenty-four barriers are classified into five primary barriers: IOT, strategic, supply chain, legislation, and external. The primary barriers are then ranked using a fuzzy TOPSIS technique. Finally, using the interpretive structural modeling (ISM) approach, the hierarchy of supply chain barriers (Ranked 1) is created, and the independent barrier cluster (Key barriers), Dependent barriers cluster, Linkage cluster, and Autonomous cluster are identified. Through the analysis, the findings of this study offer some decision-making insights for implementing BT in SSC.

6.1. Decision-Making Insights 1

This study uses an Integrated Fuzzy TOPSIS–ISM to evaluate and rank the barriers. In Figure 3, it is shown that SC barriers (B3) are the most significant to adopting BT in SSC among the five major types of barriers, as they ranked first in Fuzzy TOPSIS analysis. Therefore, this study suggests that companies can reduce the effect of SC barriers by adopting a strategic action plan. This plan should include measures to increase trust among SC partners, establish standardization and interoperability protocols, and encourage collaboration and knowledge sharing. Further, we identify the interrelation among sub-barriers of SC barriers using the ISM tool.

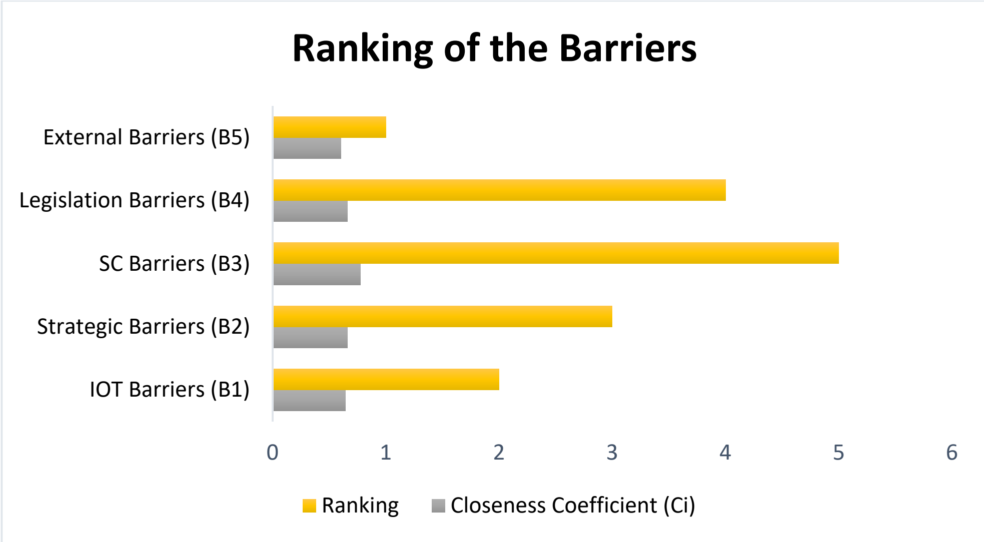

Figure 3. Ranking of the barriers.

6.2. Decision-Making Insights 2

Interactions between the identified supply chain (SC) sub-barriers reveal information about their linkages and how they contribute to implementation issues. Understanding these interconnections allows us to answer questions like, "How do the top-ranked SC sub-barriers influence each other?" and "What are the reasons of implementation difficulties?":

- The term "correlation connection of SC barriers" means separating independent elements from dependent elements. Independent elements are systemic variables that actively affect other system variables. Dependent elements are those that can change depending on other variables in the infrastructure;
- The main independent SC barriers include a Lack of customer awareness and Cultural differences of SC Partners. They are frequently regarded as the most important elements. These barriers contain such great driving power but little dependency power. These barriers frequently turn out to be the main reason behind several other connected elements. These barriers are also the root cause of the main problem;
- The main dependent SC barriers are difficulty sharing information between supply chain parties and integrating BT and sustainability through SCM. These have a low driving force but a high dependency force. Business owners should investigate which lower-level barriers they rely on and start addressing them;
- In the linking group, no SC barriers have both a significant driving power and a strong dependency. Any changes to these SC barriers will have an impact on others as well as on itself. As a result, the nature of these systems will be uncertain, which may influence the stability of the SC resilience. The unavailability of any linkage barriers to SC in this analysis suggests that none of the barriers included in this investigation makes system unstable;
- The autonomous barriers are Lack of 3Cs (cooperation, coordination, and communication). The autonomous barriers with weak driving and dependency power comprise the first group. These barriers have limited, maybe weak, links with the system, from which they are comparatively cut off. All these four categories are shown in Figure 4.

Companies can further reduce the effect of SC barriers by optimizing supply networks based on hierarchical model considerations, as shown in Figure 5. The ISM model SC barriers is created after identifying the reachability matrix. If there is any relationship between the barrier 'j' and 'I', an upward arrow starting from i to j depicts this. The digraph is converted into the ISM model shown in Figure 5 by removing the transitivity, as specified in the ISM technique.

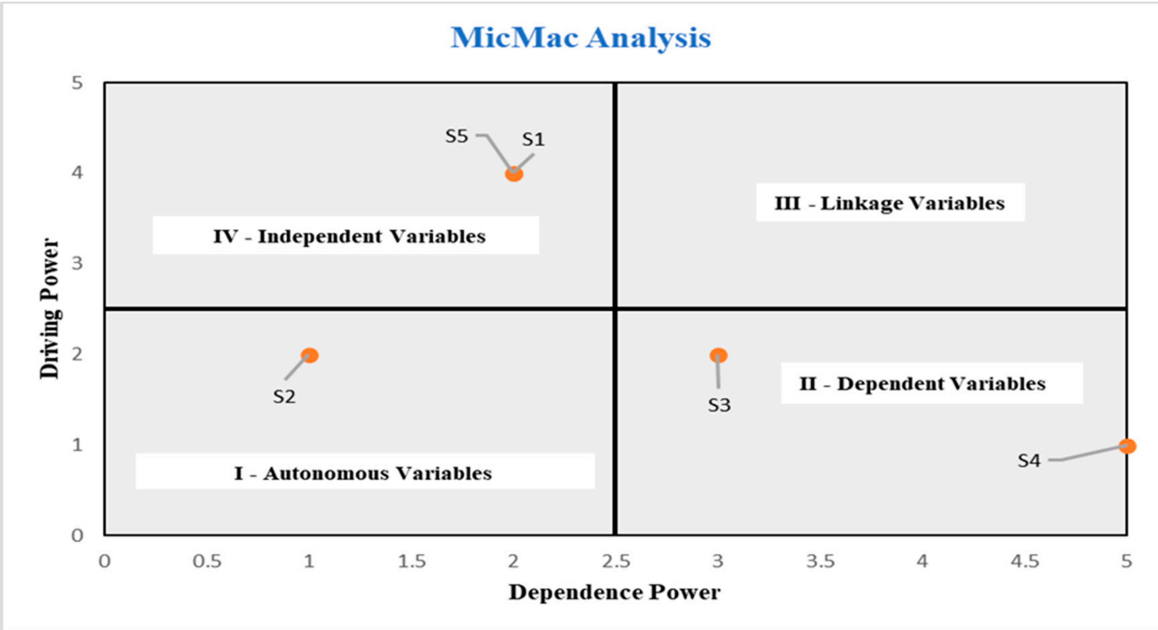

Figure 4. MICMAC analysis.

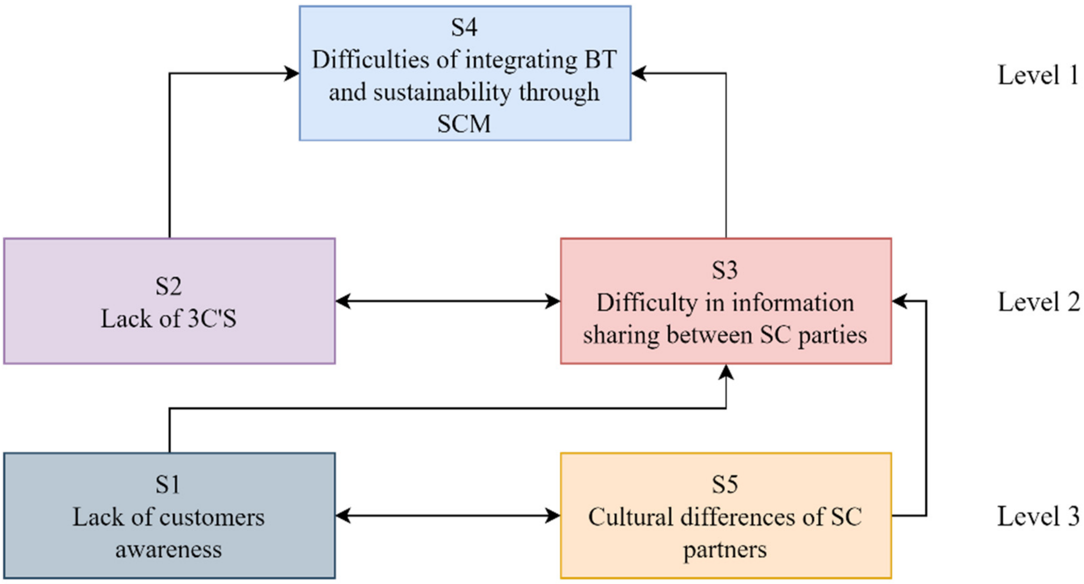

Figure 5. ISM-based hierarchical model.

6.3. Decision-Making Insights 3

Finally, after the evaluation of barriers using the proposed hybrid MCDM method, the SC-related barriers, ranked as number one by Fuzzy-TOPSIS analysis, were addressed through the creation of a fishbone diagram, as shown in Figure 6. Adopting BT into SSC is a systematic process to address supply chain barriers consisting of several key steps. First, the issue was carefully outlined, focusing on the specific challenges in SSC concerning blockchain adoption. Following this, a fishbone diagram was meticulously constructed, featuring major cause categories, such as People, Process, Technology, and Materials, branching out from the central axis. Subsequently, a rigorous process of identification of sub-causes was undertaken through a combination of brainstorming sessions and data analysis, drawing upon industry expertise and research insights, for example, within the "Technology" category, sub-causes like "Lack of information disclosure". These sub-causes were then analyzed and prioritized using the fishbone diagram in conjunction with advanced analytical techniques like Fuzzy TOPSIS and ISM, considering their significance and impact on the overarching problem [78]. Finally, based on the findings of this study, decision-makers and practitioners can work together to create unique strategic action plans. These strategies are specifically designed to minimize the impact of each sub-cause that has been given priority, making it easier to integrate BT into SSCs aligned with the company's unique requirements and objectives. This structured approach ensures that the implementation is well-informed, strategic, and effective in harnessing the potential of blockchain within SSC.

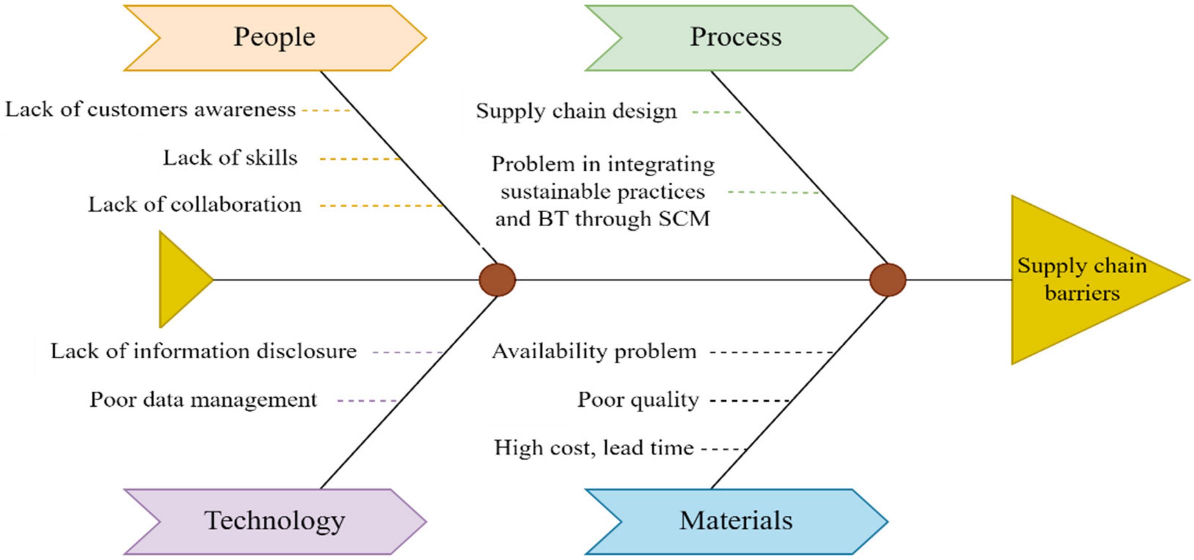

Figure 6. Fishbone diagram of SC barriers.

6.4. Comparison with Similar Studies

It is beneficial to consider related studies to comprehensively understand the challenges in integrating blockchain technology into sustainable supply chains. This makes it easier to identify typical barriers and understand each barrier's relative importance. The main barriers that the study discovered are the Internet of Things (IoT), supply chain, strategic, legal, and external barriers. The study uses a combined Fuzzy TOPSIS–ISM technique to assess the significance of these barriers. The use of an Integrated Fuzzy TOPSIS–ISM approach proposes that the research may include a combination of techniques for analyzing and prioritizing the obstacles or aspects associated with blockchain adoption in the sustainable supply chain.

Similar studies have also explored the challenges of implementing blockchain technology in supply chains and have identified similar barriers. For instance, according to Ioannou and Demirel [79], blockchain has the potential to improve supply chain financing by increasing transparency, lowering transaction costs, and minimizing fraud risks. Kayikci et al. [80] underline the importance of stakeholder participation, technology infrastructure, governance structures, and data interoperability in developing blockchain-based circular supply chains. From a supply chain perspective, Khan et al. [81] identified critical aspects for effective blockchain adoption, such as addressing technology readiness, trust and collaboration, scalability, standardization, and regulatory issues. Sargent and Breese [82] thoroughly analyzed the literature on blockchain challenges in supply chains, mentioning concerns such as scalability, interoperability, data privacy, security, legal and regulatory issues, and reluctance to change.

Sunmola et al. [83] also underlined blockchain's function as a foundation for digital transformation and sustainability in supply chains, supporting openness, accountability, and responsible practices. Khan et al. [43] studied the challenges to blockchain integration in the food supply chain, emphasizing the importance of addressing technological complexity, knowledge gaps, high implementation costs, data privacy concerns, interoperability issues, and change resistance. Mangla et al. [46] presented a conceptual framework for blockchain-based sustainable supply chains, emphasizing the significance of overcoming technology readiness, trust and collaboration, regulatory frameworks, standardization, and scalability constraints. Wang et al. [50] addressed blockchain's disruptive potential in supply chains, emphasizing essential characteristics such as decentralization, transparency, security, and smart contracts. These factors may impact the adoption and application of blockchain technology in supply chains. The previous literature also outlines issues that must be addressed for successful blockchain adoption.

The exact ranks of the barriers, however, may differ between studies. While this study places the supply chain barrier as the most important, followed by legislation, strategic, IoT, and external factors as the least important, other studies may emphasize these aspects differently. These differences may occur due to the specific context, sample size, and methodology used in each research.

7. Conclusions

This research examined how blockchain technology could be used in sustainable supply chains. Blockchain technology allows the creation of transparent, encrypted, and safe decentralized ledgers for sustainable supply chain. By replacing some intermediaries, efficiency can be increased. Given these potential advantages, it is surprising that such technology has not gained widespread use. We looked into what barriers might prevent blockchain technology from being widely used in sustainable supply chain. The literature on innovative business models and technology, such as environmentally friendly and SSC, assisted in the identification of a wide range of barriers. The primary types of barriers identified are IoT, strategic, supply chain, legislation, and external barriers. This study's key goal is identifying the most important barrier and its interactions with other barriers and their prominence. Using opinions from academic and professional specialists, we used the Fuzzy TOPSIS–ISM to rank and examine the relationships in this study. The outcomes of this research can provide valuable assistance to policymakers in making efficient and profitable decisions. Initially, the investigation focused on identifying barriers and prioritizing them through Fuzzy TOPSIS, thus enabling organizations to allocate their resources and time effectively. Additionally, the study established the hierarchical structure of SC sub-barriers through ISM, allowing decision-makers to formulate strategic action plans. Lastly, a fishbone diagram was developed to facilitate strategy-making, especially in addressing SC barriers. The findings of this research reveal that SC-related barriers are the most significant, and the interrelationship among the sub-barriers of SC barriers is also determined to facilitate the adaptation process. The study's strategic action plan, suggested using the fishbone diagram, provides a roadmap for reducing the effect of SC barriers in the adoption process.

7.1. Implications of This Study

This research provides a comprehensive theoretical framework for applying blockchain technology to sustainable supply chains. This research provides valuable insights into the potential barriers and challenges that must be addressed to successfully implement blockchain-based systems in sustainable supply chain. The findings of this study serve as a guide for policymakers, SC managers, and practitioners, offering them guidance in developing strategies and policies to overcome the identified barriers. Understanding and addressing these challenges makes it possible to promote the wider adoption of blockchain-based systems in sustainable supply chain and leverage their benefits. It is crucial to understand their roles and management policy for organizational and SC competitive advantages as well as social and environmental benefits.

7.2. Limitations and Future Directions

Due to the fact that we only looked at a manageable opinion of respondents, our study shares the inherent limitations of exploratory research. It is not feasible to undertake a wide-ranging study that gives enough depth for comprehending these complicated relationships as blockchain technology and sustainable supply chain are still relatively new fields of study. The divergent views of professionals and academics may also result from this technology's novelty. These barriers' evolution and varying prominence and linkages should be studied more thoroughly over time. Exploratory and confirmatory barrier evaluations can validate the observed barrier types, and future research may consider these barriers jointly rather than hierarchically. Assigning weightings to the respondent groups might help capture the results' variations. Exploratory study is essential to examine and analyze these interconnections and overcome these barriers. To successfully integrate BT, it is ultimately necessary to have a deeper understanding of these external obstacles and how to progress beyond them.

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Abbreviations

SC	Supply Chain
SCM	Supply Chain Management
SSC	Sustainable Supply Chain
BT	Blockchain Technology
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
ISM	Interpretive Structural Modeling
MCDM	Multi Criteria Decision Making
IoT	Internet of Things
MICMAC	Cross-Impact Matrix Multiplication Applied to Classification

Appendix A. For Fuzzy TOPSIS

Appendix A.1. Identification of the Factors

This research investigated the barriers that impact the integration of blockchain technology into the sustainable supply chain within the Readymade Garments Industries of Bangladesh through a literature review and discussions with field experts. A series of brainstorming sessions were conducted to strengthen the insights gathered from the literature review, involving five industry experts and two academic experts. For additional information, please refer to the methodology section in the main manuscript.

Appendix A.2. Feasibility and Consistency Test of the Obtained Data

A survey was developed using a Likert scale with five possible values, ranging from 1 (strongly disagree) to 5 (strongly agree). After that, this survey was given to 50 subject-matter experts in order to obtain their feedback and assess the impact and feasibility of the identified barriers. In total, 30 experts responded to the survey; 20 of them were from the industry and 10 were from academia, offering a wide-ranging dataset for study.

Questionnaire:
Q1: How do you rate IoT barrier to the implementation of Blockchain Technology in sustainable supply chain?;
Q2: How do you rate strategic barrier to the implementation of Blockchain Technology in sustainable supply chain?;
Q3: How do you rate supply chain barrier to the implementation of Blockchain Technology in sustainable supply chain?;
Q4: How do you rate legislation barrier to the implementation of Blockchain Technology in sustainable supply chain?;
Q5: How do you rate external barriers to the implementation of Blockchain Technology in sustainable supply chain?

Table A1. Five-point Likert scale.

5	4	3	2	1
Strongly agree	Agree	Neutral	Disagree	Strongly Disagree

Table A2. Survey data obtained from 30 experts.

	B1	B2	B3	B4	B5		B1	B2	B3	B4	B5
1	5.00	5.00	5.00	5.00	4.00	16	5.00	5.00	5.00	5.00	4.00
2	4.00	5.00	5.00	5.00	5.00	17	5.00	5.00	5.00	5.00	3.00
3	4.00	4.00	4.00	4.00	3.00	18	4.00	4.00	5.00	5.00	5.00
4	5.00	4.00	5.00	5.00	5.00	19	5.00	4.00	5.00	5.00	5.00
5	4.00	5.00	5.00	5.00	5.00	20	4.00	4.00	4.00	4.00	3.00
6	5.00	4.00	5.00	5.00	5.00	21	5.00	5.00	5.00	4.00	5.00
7	5.00	5.00	5.00	5.00	4.00	22	5.00	5.00	5.00	5.00	4.00
8	5.00	5.00	5.00	5.00	3.00	28	4.00	4.00	4.00	4.00	3.00
9	5.00	4.00	5.00	5.00	3.00	24	5.00	4.00	5.00	5.00	3.00
10	5.00	4.00	4.00	4.00	3.00	25	5.00	4.00	4.00	4.00	3.00
11	4.00	4.00	4.00	4.00	3.00	26	4.00	4.00	4.00	4.00	3.00
12	5.00	5.00	4.00	5.00	5.00	27	5.00	5.00	5.00	5.00	4.00
13	4.00	4.00	4.00	4.00	3.00	23	5.00	5.00	5.00	5.00	4.00
14	4.00	4.00	4.00	5.00	3.00	29	4.00	4.00	4.00	5.00	3.00
15	5.00	5.00	5.00	5.00	3.00	30	5.00	5.00	5.00	5.00	3.00

Appendix A.3. Expert Opinion on Identified Factors

Please see the main manuscript for more details.

Sample Questionnaire:

- How much barrier B1 is important compared to B1-B5?;
- How much barrier B2 is important compared to B1-B5?;
- How much barrier B3 is important compared to B1-B5?;
- How much barrier B4 is important compared to B1-B5?;
- How much barrier B5 is important compared to B1-B5?

Table A3. Fuzzy linguistic scale.

Linguistic Variable	Very High Influence	High Influence	Medium Influence	Low Influence	Very Low Influence
Influence Score	5	4	3	2	1

Table A4. The decision matrix contains the average of the above 30 expert opinions. This table is converted into triangular fuzzy numbers (TFN) from the 5-point scale.

	B1	B2	B3	B4	B5
B1	(0.000,0.000,0.000)	(3.000,4.714,6.714)	(5.286,7.286,8.143)	(2.429,4.143,5.857)	(3.286,5.000,6.714)
B2	(2.429,3.857,5.857)	(0.000,0.000,0.000)	(4.429,6.429,7.857)	(3.857,5.571,7.571)	(3.286,5.286,7.000)
B3	(4.429,6.143,7.286)	(5.000,6.714,7.857)	(0.000,0.000,0.000)	(3.857,5.857,7.286)	(5.000,6.714,7.571)
B4	(2.429,4.143,6.143)	(2.429,4.429,6.429)	(4.143,6.143,7.857)	(0.000,0.000,0.000)	(4.714,6.429,7.571)
B5	(2.714,3.571,5.571)	(1.286,2.714,4.714)	(4.714,6.429,7.571)	(4.429,6.429,8.143)	(0.000,0.000,0.000)

Appendix B. For ISM Approach

The details of the ISM calculations are presented in the Tables A5–A8 below, which provide a clear and concise overview of the complex relationships between the different SC barriers. Please see the main manuscript for more details.

Table A5. Reachability matrix.

Variables	S1	S2	S3	S4	S5	Driving Power
S1	1	0	1	1	1	4
S2	0	1	0	1	0	2
S3	0	0	1	1	0	2
S4	0	0	0	1	0	1
S5	1	0	1	1	1	4
Dependence power	2	1	3	5	2	

Table A6. Level partitioning iteration 1.

Elements (Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1, 3, 4, 5	1, 5	1, 5	
2	2, 4	2	2	
3	3, 4	1, 3, 5	3	
4	4	1, 2, 3, 4, 5	4	1
5	1, 3, 4, 5	1, 5	1, 5	

Table A7. Level partitioning iteration 2.

Elements (Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1, 3, 5	1, 5	1, 5	
2	2	2	2	2
3	3	1, 3, 5	3	2
4		1, 2, 3, 5		1
5	1, 3, 5	1, 5	1, 5	

Table A8. Level partitioning iteration 3.

Elements (Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1, 5	1, 5	1, 5	3
2				2
3		1, 5		2
4		1, 5		1
5	1, 5	1, 5	1, 5	3

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