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Article

Blockchain driven Traceability Modelling in Tea Supply Chain

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Abstract: Today, Blockchain Technology (BT) in its nascent stage has emerged as a beacon of transformative potential, drawing the attention of researchers and stakeholders worldwide to explore its ability to reshape traditional systems across various sectors. BT is gaining momentum due to trust, transparency, and traceability; however, no study has been conducted to investigate inter-linking among the drivers that drive BT adoption in Tea Supply Chain (TSC). This study aims to better understand the significance of BT integration in TSC by identifying 12 drivers, aligning with existing research and expert opinions. This research employs a hybrid approach that combines Interpretive Structural Modelling (ISM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodology to determine the hierarchical structure and causal relationship among the identified drivers. The study's findings suggest that traceability is the primary reason for BT adoption in TSC, followed by provenance and transparency. This is the first study of its kind to integrate BT in TSC, presenting a novel hierarchical structural model. In this study, the interrelationship and interdependence among the drivers are identified to help policy-makers and decision-makers outline strategies for the adoption of BT in tea sector, ensuring real-time visibility and sustainability.
Keywords: Blockchain technology, ISM, DEMATEL, Tea supply chain, Traceability, Sustainability

1. Introduction

Currently, awareness about health and the environment has raised consumers' concern about food safety standards, quality, and sustainability in agriculture (Parven et al., 2025). Consumers are enquiring how their food products are grown, processed, and delivered, increasing demand for transparency and traceability (Sunny et al., 2020). It's difficult to fully trust present traceability technology as it depends on a centralised client-server model, with consumers and stakeholders relying on a single point of information (Mohanta et al., 2018). If there is an issue with this information point, product information may be lost or tampered with (M. A. Khan & Salah, 2018). As regulatory organisations of traditional supply chains are prone to corruption, error, and hacking, ensuring a reliable trust mechanism that guarantees safety, quality, and traceability remains a significant challenge (Helo & Hao, 2019). In supply chains, these challenges can be resolved by adopting BT, as it has the ability to trace and track the product's origin in real-time (Bhutta & Ahmad, 2021). In a BT-driven system, records are immutable and secured, eliminating reliance on third-party involvement (Sancaktar & Sayar, 2025). With smart contracts, BT promises potential farmers full and timely payment, and more efficiently manages their crops and harvests by monitoring real-time data. BT is likely to transform traditional approach, opening the door to its applications across many different areas (Rani et al., 2025). BT will ensure that its potential participants have confidence in the supply chain traceability by providing tamper-free records, secured shared database and real-time tracking (Pincheira et al., 2023).

BT integration into supply chain management (SCM) aligns with United Nations' Sustainable Development Goals (SDGs). Adoption of BT increases transparency and traceability, assuring that the products are authentic and environmentally friendly, which supports the SDG 12 agenda of green production and consumption, by promoting accountable and sustainable decision-making in the operations of the SCM (Onu et al., 2024; Raman et al., 2023). Additionally, BTs ability to streamline logistics and eliminate waste helps to achieve SDG 9 by fostering innovation and sustainable infrastructure (Nazir & Fan, 2024; Sianaki & Peiris, 2022). Furthermore, BT contributes to the SDG 13 agenda of climate footprint mitigation by tracking real-time carbon emissions, encouraging sustainability (Govindan, 2022; S. A. R. Khan et al., 2024). BT incorporation into supply chains not only tackles current challenges but also offers a pathway to achieve these SDG goals, making it a critical tool for building a sustainable future (Camel et al., 2024; S.-K. Kim & Huh, 2020).

The TSC is very complex, involving multiple processing stages of cultivation, processing, packaging, distribution, and retail. In each stage, there is a risk of vulnerability related to inefficiencies and quality risks. Today, the global tea industry is under growing pressure to guarantee authenticity and sustainability as consumer demand has increased for ethically sourced products (Xu et al., 2023). Traditional TSCs continuously suffer from adulteration, limited real-time monitoring, and poor coordination among stakeholders, which undermines both product quality and consumer trust (Ronoh et al., 2025). BT adoption in the tea industry can support a shift from linear to circular supply chain models by improving real-time visibility and enhancing overall inventory performance (Paul et al., 2022). BT integration in TSC enhances supervision against counterfeiting and offers an effective pathway to build long-term trust in the market (K. Liu et al., 2024). Existing literature on BT primarily focuses on its opportunities, advantages, and concerns related to its application in supply chains (S. Chen et al., 2021; Payandeh et al., 2025; Younis et al., 2024).

1.1. Purpose of the research

India is the second-largest producer of tea globally, holding about 29% of the world's share and 10% of the world's export market. (Hussain et al., 2025). Previous studies have shown that the implementation of BT in TSC offers multiple benefits that lead to improvements in sustainable performance. However, no study has focused on the contextual and interdependence relationship among the drivers, nor has any empirical analysis been done. Additionally, no model has yet been developed that identifies the interrelationship among the influencing and influenced drivers, which this study aims to address. The involvement of multiple interrelated decision-making factors and reliance on the perception of experts often causes intricacy in evaluating the critical drivers. Critically influencing drivers has evolved into a significant pillar for both researchers and stakeholders in adopting BT in TSC. The purpose of the study is to investigate the driving factors that contribute to bridge the current gap and facilitate modelling of a BT-driven traceability framework for the TSC, using ISM and DEMATEL methods for structured analysis. This study intends to explore how BT can be implemented in TSC, as BT is still in its emergent phase for adoption within the Indian context.

1.2. The main objectives of this study are stated below:

- To identify drivers that drive the adoption of BT in TSC according to the previous literatures and experts' opinions.
- To establish the contextual and causal relationships within the identified drivers using the ISM and DEMATEL methods.
- To develop hierarchical structural model and also degree of influence diagram among these drivers to provide practical insights to the decision-makers and the policy-makers for strategic planning.

The remaining sections (Sec.) of this study are organised as follows: Sec. 2 provides a concise literature review and listed 12 identified drivers. Sec. 3 presents an in-depth description of the methodology. Sec. 4 demonstrates an analysis of the ISM-DEMATEL method. Sec. 5 discusses the findings of the study. Sec. 6 summarises the conclusion, implications, limitations and future scopes of the study.

2. Review literature

In this section, researchers have thoroughly reviewed the existing literature by analysing articles that are published in Scopus and Web of Science databases to gain insights in the adoption of BT and its integration in the TSC. Additionally, news articles, trade journals, and various reports from the industry of diverse online and offline sources are reviewed to acquire additional perspectives on the study area. Further, the review of literature is organised into four sub-sections: BT: overview and value proposition, BT adoption in supply chain, BT adoption in TSC and listing of the drivers, and application of ISM and DEMATEL methodologies.

2.1. Overview of BT

BT has evolved as a transformative innovation, revolutionising across different industries with its decentralised and unalterable ledger system (Saberi et al., 2019). It is fundamentally an accounting and finance automation tool that facilitates a secured database that is immutable in nature, where transparent transactions take place without relying on a central authority (Almadadha, 2024). BT features decentralisation, immutability, fault tolerance, tamper-resistance, and transparency, which in turn eliminates reliance on a single trusted authority and also helps in reducing risks of fraud, corruption, and centralised vulnerabilities, enabling applicability in various real-world operations (Eyo-Udo et al., 2025; Habib et al., 2022; Saleh, 2024). Once transactions are recorded in BT, data cannot be deleted or altered, assuring auditability and data integrity (Akram et al., 2024). Every transaction in BT is recorded on a shared ledger, allowing stakeholders to access real-time data (Hader et al., 2022). BT employs cryptographic algorithm to safeguard transaction data against unauthorised alterations, making the whole system trustworthy and secure (Harinath et al., 2024). Beyond foundational applications in cryptocurrencies and financial transactions, BT has served as a transformative solution for industries and organisations that demand secure, transparent, and immutable record-keeping (Almadadha, 2024; Thakur et al., 2025); enabling traceability, reducing operational costs, and establishing decentralised trust mechanisms (Z. Zhang et al., 2024). Implementation of BT has been facilitated across diverse sectors, where data integrity, authenticity, and efficiency are paramount (Brandín & Abrishami, 2021; X. Zhang et al., 2024), such as healthcare (Attaran, 2022), education (Rani et al., 2024), auditing (Guo et al., 2025), and agriculture and food sectors (Bosona & Gebresenbet, 2023).

2.2. BT in supply chain

BT can transform the traditional SCM addressing key challenges such as lack of transparency, inefficiencies, and stakeholder trust issues (Pinto Varela Alberte & de Oliveira Novelli, 2024; Rathnayake et al., 2025). In traditional supply chains, often information is either not shared or misplaced, making it difficult to monitor the commodities' movement in real-time; as a result, the conditions of the products are unknown (Chaker & Damak, 2024). These challenges can be addressed by developing a distributed ledger where all transactions can be recorded, providing visibility to authorised participants, ensuring that every stage of the supply chain operations is transparent and traceable (Balcıoğlu et al., 2024; X. Liu et al., 2021). BT provides a decentralised, immutable, and transparent ledger, enabling all the stakeholders within the system to trace and track the movement of the products' journey from start to end (Pandey et al., 2022; Thanasi-Boçe & Hoxha, 2025). Adoption of BT stops counterfeit goods and also ensures compliance with safety standards, delivering a sustainable supply chain (Kshetri, 2021; Onu et al., 2024). Additionally, BT increases efficiency by using smart contracts' feature of automatic processing, which carries out agreements automatically once predefined conditions are satisfied, thereby lowering costs and saving time. (Wahab et al., 2023). BT also strengthens security by eliminating a single failure point, since data is preserved in a network of distributed ledgers; these recorded data cannot be modified or deleted without being detected. (U. Agarwal et al., 2024). This decentralised approach in BT fosters trust among various participants by providing auditable and transparent records (Singh et al., 2023). BT integration in supply chains is very beneficial in an organisation where ethical sourcing and sustainability are essential (Calvão & Archer, 2021). BT can enhance security, efficiency, transparency, and traceability; thus, it is a promising tool for adoption in the modern-day supply chain, with its applications spanning across various industries like agriculture, automotive, health care, and luxury goods (Al-Farsi et al., 2021; Centobelli et al., 2022a; Mijwil et al., 2025).

2.3. Adoption of BT in TSC

BT represents a modern solution that optimises the TSC operations through the resolution of key challenges of enhancing traceability while promoting transparency and creating trust (Tayal et al., 2021). TSC often lacks visibility and accountability, which involves multiple stages, i.e., cultivation, processing, packaging, and distribution (Y. Liu et al., 2022). Implementing BT in the TSC enables end to end traceability, making sure that all participants have access to reliable and trustworthy information about products origin, quality, and distribution (Paul et al., 2021). BT can offer greater transparency, allowing every consumer to verify the provenance and sustainability details of the tea products purchased (Nygaard, 2024). In BT, smart contracts have a smart feature to automate processes, which ensures efficiency and reduces the need for intermediaries, along with payments and quality verification (Channi & Kumar, 2025). BT also features real-time data sharing that enables stakeholders to regulate and optimise supply chain operations (Z. Zhang et al., 2024). Adoption of BT in the system not only enhances trust but also the authenticity of the tea product due to consumers growing demand for sustainability (Huang et al., 2024). BT offers a robust framework to improve transparency, efficiency, and reliability among all the participants in TSC, encouraging documentation for fostering accountability, ensuring that the journey of tea leaves from farm to cup is completely traceable and trustworthy in the TSC (C.-L. Chen et al., 2023; Mangla et al., 2022; Priyadarshi, 2024). In Fig. 1., the proposed diagram of BT in TSC is mentioned.

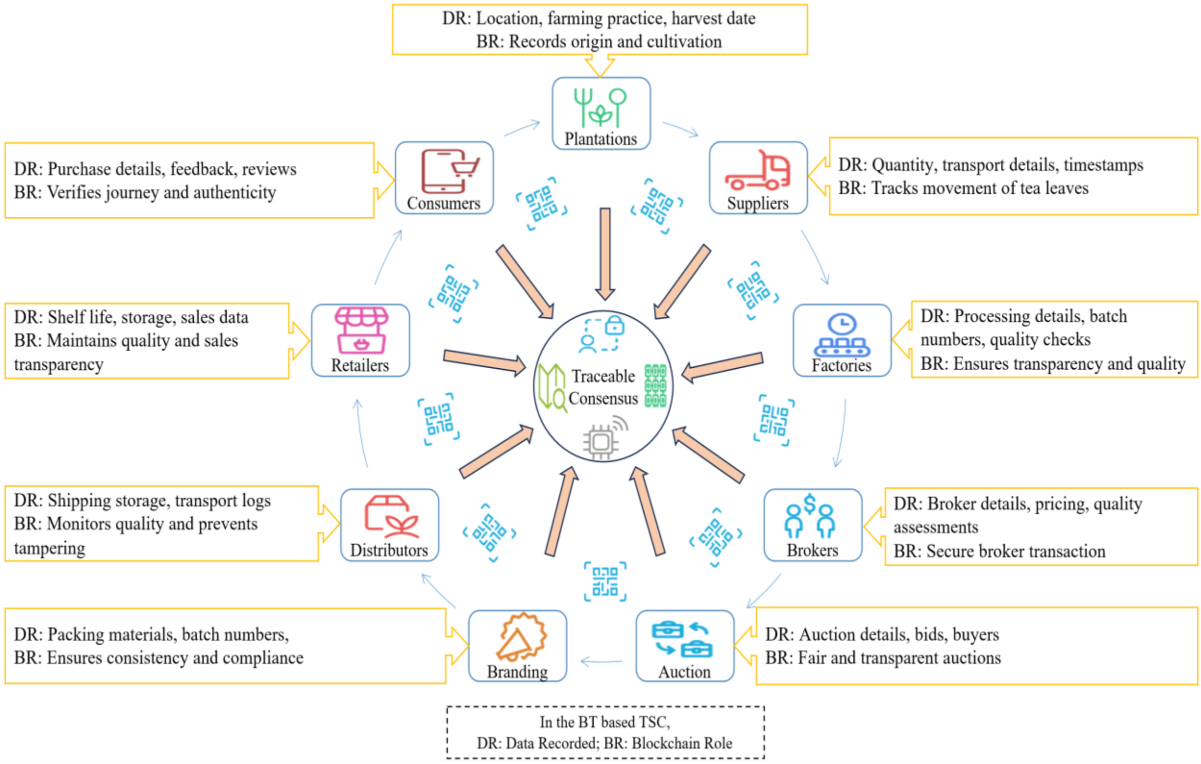

Fig.1: The proposed diagram of BT in TSC

Based on the literature review and the perception of the academic and industry experts, 12 drivers were identified for the study. Table 1 represents a detailed description of identified BT drivers (i.e., BTDs)

Table 1

Detailed description of Blockchain drivers (BTDs).

Drivers Code	BTDs	Descriptions	References
BTD 1	Transparency	BT ensures transparent transactions through a public ledger, which increases trust and accountability.	(Centobelli et al., 2022b; Omar et al., 2020; Omidian, 2024)
BTD 2	Secured-shared database	BT employs cryptographic mechanisms and distributed ledgers for ensuring data security and also preventing unauthorised alterations.	(Asamoah et al., 2024; Majumdar & Mitra, 2024; Shrimali & Patel, 2022)
BTD 3	Product provenance	BT enables end-to-end visibility by assuring product authenticity and verifiability of the raw materials' origin in the supply chains.	(Ahmed & MacCarthy, 2023; H. M. Kim & Laskowski, 2018; Konstantopoulou & Mikalef, 2024)
BTD 4	Enhance risk management	BT reduces operational risks through smart contracts, which have an automated feature that mitigates fraud risks.	(Dehshiri et al., 2024; Min, 2019; F. Zhang & Song, 2022)

BTD 5	Immutability	Once data is recorded on BT, it cannot be modified or deleted, assuring integrity and trust.	(Akanfe et al., 2024; Gunjal et al., 2024; Reyna et al., 2018)
BTD 6	Cost & time efficiency	BT minimises intermediaries, reducing processing time and transaction cost.	(Du et al., 2023; Surucu-Balci et al., 2024; Yousefi & Tosarkani, 2022)
BTD 7	Decentralised database	BT's peer-to-peer architecture eliminates central authority, providing secure and distributed data management.	(Kalajdjieski et al., 2023; M. T. Rana et al., 2024; Zaabar et al., 2021)
BTD 8	Real-time information database	BT enables real-time updates, which improve supply chain visibility and product movements in the entire system.	(Akram et al., 2024; Hader et al., 2022; Helo & Hao, 2019)
BTD 9	Smart Contract	It is a self-executing program on BT that automatically enforces and carries out agreements when pre-defined conditions are met, without requiring any intermediaries.	(Chang et al., 2019; Daraghmi et al., 2024; De Giovanni, 2020)
BTD 10	Pseudonymity & confidentiality	Blockchain ensures pseudonymity and confidentiality by masking real identities with cryptographic addresses and protects sensitive data through encryption and restricted access.	(Anjali, 2024; Chulerttiyawong & Jamalipour, 2021; Wan, 2025)
BTD 11	Traceability	BT records each transaction in a manner that is verifiable, which enables full traceability of the product across the supply chains.	(Agrawal et al., 2021; Biswas et al., 2023; Li et al., 2024)
BTD 12	Auditability	Verifiable and permanent records of transactions in the BT have the ability to verify and review each transaction history in the system. This feature supports transparent auditing processes and simplifies external and internal audits.	(R. W. Ahmad et al., 2021; Autore et al., 2024; Z. Liu & Li, 2020)

2.4. Application of ISM and DEMATEL techniques

BT possesses revolutionary capacity that can reshape the traditional supply chain, but adoption of this technology is often seen as complicated due to technical, organisational, and regulatory factors; thus, to overcome these complex issues within the system, ISM and DEMATEL methodologies have been employed (Hu et al., 2025; L. Wang et al., 2024). Öztürk, (2025) adopted a hybrid ISM-DEMATEL approach to examine how digitalisation affects social responsibility within supply chains comprehensively. K. Ahmad et al., (2024) applied hybrid ISM-DEMATEL technique to identify prominent challenges while incorporating IoT in the cold SCM. Vishwakarma et al., (2022) study integrating ISM-DEMATEL technique analysed barriers to the sustainable supply chain. In Table 2, a list of contributions of various research using ISM, DEMATEL and combined ISM-DEMATEL methodologies is shown.

Despite being beneficial, the combined ISM-DEMATEL approach is still limited in its adoption of BT in TSC. ISM and DEMATEL methodology can yield robust insights into the identified drivers (BTDs) and prioritise the most influential BTDs and their inter-relationship that would shape the adoption of BT in TSC. Previous research also illustrated that combining the ISM and DEMATEL approaches develops a hierarchical structure and prominence diagram. Hence, using these techniques in complex systems, the cause/influential-and-effect/dependent relationships within the drivers were determined very conveniently and effectively (Bagherian et al., 2024; Chuang et al., 2013). Therefore, this study adopts the hybrid ISM-DEMATEL methodology to identify the most influential BTDs of blockchain, enabling BT adoption in TSC.

Table 2

List of contributions of various researchers using ISM and DEMATEL methodologies.

S. No.	Contribution	ISM	DEMATEL	AUTHORS
1.	Formulated a model to enable the integration of sustainability practices in supply chain using Industry 4.0.	√		(Nirmal et al., 2025)
2.	Examined the incorporation of solar renewable energy products in India.	√		(R. Agarwal et al., 2023)
3.	Analysed concerns in manufacturing industries related to Industry 4.0 adoption.	√		(P. Kumar et al., 2021)
4.	Studied challenges in integrating m-commerce in SMEs.	√		(N. P. Rana et al., 2019)
5.	Studied technological drivers in Industry 4.0 to promote a transparent and sustainable SCM.		√	(Rajput, 2024)
6.	Examined aids for decision-making in humanitarian supply chain.		√	(W. Wang et al., 2024)
7.	Studied the adoption of BT on sustainable SCM.		√	(Yontar, 2023)
8.	Analysed Supplier selection in green SCM to manage carbon.		√	(Hsu et al., 2013)
9.	This research explores 11 key success factors for implementation of metaverse in the service sector.	√	√	(Chi et al., 2025)
10.	Examined how digitalisation and energy sustainability are connected.	√	√	(Zuo & Ren, 2025)
11.	Studied the effective patterns of emerging technologies in reducing supply chain vulnerability.	√	√	(Guo et al., 2024)
12.	Developed a resilient framework for the evaluation of green logistics drivers.	√	√	(Shoaib et al., 2023)

13.	Studied the sustainable concerns in the diamond industry's SCM.	√	√	(Shanker & Barve, 2021)

3. Methodology

This study adopts a hybrid Interpretive Structural Modelling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) multi-criteria decision-making (MCDM) approach. Both ISM and DEMATEL are widely recognized for their capability to analyse the causal relationships among multiple criteria. Integrating these two methodologies provides a more comprehensive framework for group decision-making by leveraging the unique strengths of each technique. Specifically, ISM facilitates the development of a hierarchical structure and conceptual model, while DEMATEL quantifies the direction and intensity of interrelationships among the identified drivers, thereby offering a deeper understanding of their causal interactions (K. Ahmad et al., 2024).Within the ISM framework, the contextual relationships expressed through the four symbols P, Q, R, and S are transformed into a binary reachability matrix using values of 1 and 0 to establish the hierarchical relationships among the blockchain technology drivers. In contrast, the DEMATEL approach employs a comparison matrix with influence scores ranging from 0 to 4, enabling the assessment of the magnitude of influence that each driver exerts on the others. This facilitates the identification of both causal (influencing) and effect (dependent) drivers based on the strength of their interactions. Figure 2 illustrates the overall research methodology adopted in this study. The methodology is organised into three major stages: data collection, ISM analysis, and DEMATEL analysis.

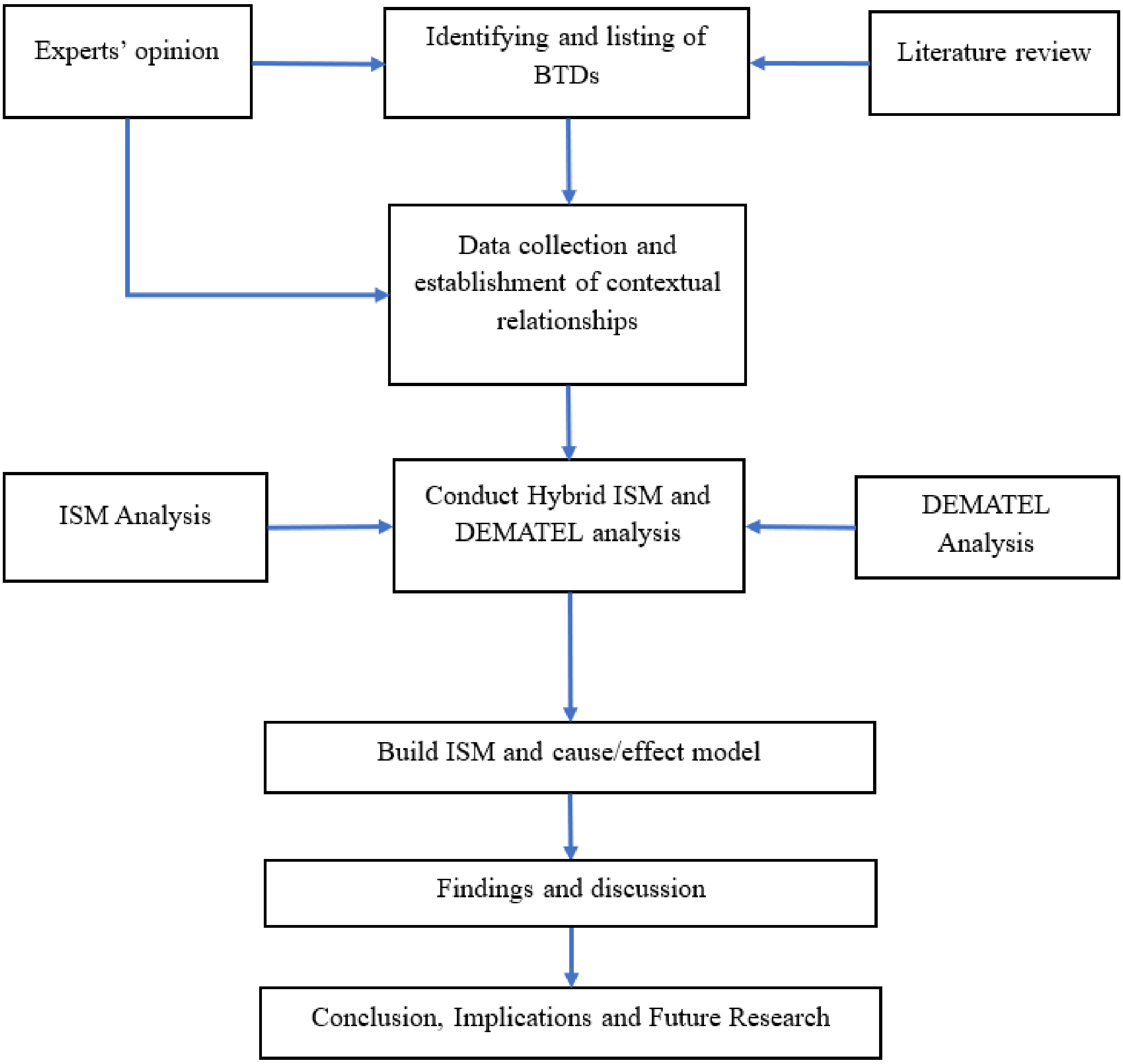

Fig.2: Proposed framework for research methodology

3.1. Data Collection

For this study, a field survey was conducted in major tea-producing states of Assam, West Bengal, Tamil Nadu, and Kerala, as well as major tea manufacturers and distributors within India, to have an in-depth insight into the traceability in existing TSC and also understand BT application in it. The research methodology uses an extensive literature review and experts' perception to identify BTDs for the development of the contextual relationship matrix of the drivers. A team of 12 experts participated in this study, which included four academicians, three blockchain integration specialists, three senior executives from the tea industry, and two scientists from the tea research institute. Each expert has a minimum of 8 years of experience in the study area.

3.2. ISM Methodology

Interpretive structural modelling (ISM) was introduced by Warfield, (1974) to systematically visualise and build structural relationships among the identified drivers based on experts' opinions within a complex structured system. ISM helps to arrange and organise direct or indirect drivers in the system to develop a hierarchical model (Sage, 1977). The different steps of the ISM approach are summarised below, as used by other researchers in their studies (Hamdi & Toumi, 2025; Hong et al., 2024; Jayant & Azhar, 2014; A. Kumar & Dixit, 2018; Kumar Sharma & Bhat, 2014; Movahedipour et al., 2017; Nirmal et al., 2023).

Step 1. Twelve drivers (criteria) are considered for the adoption of BT in TSC.

Step 2. A contextual relationship is formed based on the identified drivers in step 1 to determine particular pairs of drivers that require examination among the drivers.

Step 3. A self-structural interaction matrix (SSIM) is established for the drivers, indicating the inter-relationships between pairs of drivers using symbols P, Q, R, and S.

Step 4. The initial reachability matrix (IRM) is constructed using step 3 by converting P, Q, R, and S into binary digits '0' and '1' and checked for transitivity. In the ISM model, transitivity is a basic assumption of the contextual relation among the drivers. The principle of transitivity indicates that if driver A is related to driver B and driver B is related to driver C, then driver A is inevitably related to driver C.

Step 5. The final reachability matrix (FRM) is developed from the IRM incorporating transitivities.

Step 6. FRM is partitioned into multiple levels, and the final level partitioning is obtained.

Step 7. Based on the partitioning of all levels, a digraph is drawn, and the transitivities are removed, considering the rule of transitivity.

Step 8. Replacing the driver's code with statements, the final directed graph is converted into an ISM model.

3.3. DEMATEL methodology

Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was first designed by the Science and Human Affairs Program at the Battelle Memorial Institute in Geneva between 1972 to 1976. DEMATEL method was developed to effectively analyse complex analytical problems and understand the inter-relationships between different drivers within a system (Si et al., 2018). This methodology categorises cause and effect group factors that drive the system, and identifies drivers that are influencing and influenced by others (Jassbi et al., 2011). The DEMATEL technique is used to understand causal relationships among drivers, making decision-making and strategic planning for a complex system more efficient (Braga et al., 2021; Quezada et al., 2018; W.-W. Wu, 2008). The summarised steps of the DEMATEL method are mentioned below:

Step 1: Develop the average direct relation matrix (A):

In this step, every expert was asked to rate the direct influence among any two drivers using a scale from 0 to 4 to establish a pairwise matrix. The typical range of scale is 0 to 4, denoting: "0 = No influence, 1 = Low influence, 2 = Moderate influence, 3 = High influence, 4 = Very high influence". The expression "y_{lm}" represents the degree to which the individual expert believes driver 'l' influences driver 'm', if l = m, then y_{lm} = 0 (i.e., all the diagonal elements in the matrix are set to zero). For each expert, a non-negative q×q matrix is formulated as $Y^k = [\, y_{lm}^k \,]_{q\times q}$, ; where 'q' indicates the number of drivers, and 'k' means the number of experts such that $1 \leq k \leq N$. As a result, $Y^1, Y^2, Y^3, \ldots, Y^N$ are the matrices from N experts. Integrating all the ratings from N experts, the average direct-relation matrix A = $[a_{lm}]$ is established using Eq. 1 as presented below.

$$a_{lm} = \frac{1}{N} \sum_{k=1}^{N} y_{lm}^k \qquad (1)$$

Step 2: Compute the normalised direct-relation matrix (N):

The normalised direct relation matrix (B) is computed from Eq. 2 mentioned below:

B = A×Z,

where, $Z = \frac{1}{max_{1\leq l\leq q}\sum_{m=1}^{q} a_{lm}}$ (2)

Here, the range of the matrix B falls between 0 and 1

Step 3: Establish the total-relation matrix (T):

Applying the transition theory, the total-relation matrix (T) is obtained by adding all direct and indirect relationships among drivers using Eq. 3 shown below:

$T = [t_{lm}]_{q\times q} = B\,(I - B)^{-1}$, (3)

Here, 'I' is represented as the identity matrix.

Step 4: Formulate the degree of influence:

Now, adding rows and columns of the total relation matrix (T), vectors R_l and C_m are obtained to achieve the degree of influence through Eq. 4 and Eq. 5 as follows;

$R_l = [r_{lm}]_{q\times 1} = (\sum_{m=1}^{q} t_{lm})_{q\times 1}$ (4)

$C_m = [c_{lm}]_{1\times q} = (\sum_{l=1}^{q} t_{lm})_{1\times q}$ (5)

where, R_l is the sum of the l^{th} row in the T matrix and outlines the direct and indirect influence offered by the driver D_l to other drivers. Similarly, C_m is the sum of the m^{th} column in the matrix T and outlines the direct and indirect influence accepted by the driver D_m from other drivers. Thus, sum $(R_l + C_m)$ indicates the total effects offered and accepted by the driver D_l in the entire system, indicating the degree of importance or prominence that the driver D_l plays. In contrast, difference $(R_l - C_m)$ implies the net effect or relation that the driver D_l contribute to the system. Precisely, if $(R_l - C_m)$ is negative, then the driver D_l is a net receiver and if $(R_l - C_m)$ is positive than the driver D_l is a net cause.

Step 5: Plot digraph:

Finally, diagraph plotting is done by mapping a set of data of $(R_l + C_m)$ and $(R_l - C_m)$ to provide meaningful insights in decision-making. Experts must establish a threshold value eliminating insignificant effects, as the matrix (T) provides data on how one driver affects another. In this process, only effects greater than the threshold value are selected and plotted in the digraph. By computing the value of the elements in the matrix (T), the threshold value is calculated.

4. Hybrid ISM-DEMATEL analysis

4.1. ISM-MICMAC analysis

In this section, the ISM methodology is employed for structural modelling of the identified drivers in the context of the adoption of BT in TSC.

4.1.1. SSIM

The structural self-interaction matrix (SSIM) is formed on the consensus of the experts to establish the contextual relationship between the 12 identified pairs of drivers. Four letters, P, Q, R, and S, are assigned for the contextual relationship between a pair of drivers (l and m) in one of the four ways:

- P: Driver (D_l) influences corresponding to the driver (D_m).
- Q: Driver (D_l) is influenced by the corresponding driver (D_m).
- R: Driver (D_l) and corresponding driver (D_m) influence each other.
- S: Driver (D_l) and corresponding driver (D_m) does not have any influence.

The SSIM for the BT drivers' adoption in the TSC is developed based on contextual relationships as presented in Table 3. Explanation of letters P, Q, R, and S is mentioned in the following section:

Driver decentralised database (BTD 7) directly influences driver traceability (BTD 11). So, "P" denotes the contextual relationship between the decentralised database (BTD 7) and traceability (BTD 11).

Driver enhanced risk management (BTD 4) is influenced by driver pseudonymity & confidentiality (BTD 10). So, "Q" denotes a contextual relationship between enhanced risk management (BTD 4) and pseudonymity & confidentiality (BTD 10).

The driver secured-shared database (BTD 2) and the driver real-time information database (BTD 8) influence each other. So, “R” denotes the contextual relationship between the secured-shared database (BTD 2) and the real-time information database (BTD 8).

Driver smart contract (BTD 9) and driver auditability (BTD 12) have no relationship. So, “S” denotes no contextual relationship between smart contract (BTD 9) and auditability (BTD 12).

Table 3:

SSIM

Drivers code	BTD 1	BTD 2	BTD 3	BTD 4	BTD 5	BTD 6	BTD 7	BTD 8	BTD 9	BTD 10	BTD 11	BTD 12
BTD 1		Q	S	Q	Q	Q	Q	Q	Q	Q	P	S
BTD 2			P	P	P	P	Q	R	P	P	P	P
BTD 3				Q	Q	Q	Q	Q	Q	Q	P	Q
BTD 4					P	Q	Q	S	Q	Q	P	S
BTD 5						Q	Q	Q	Q	Q	P	S
BTD 6							S	S	Q	S	P	P
BTD 7								P	P	P	P	P
BTD 8									S	P	P	P
BTD 9										P	P	S
BTD 10											P	P
BTD 11												Q
BTD 12												

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

4.1.2. IRM and FRM:

The Initial reachability matrix (IRM) is obtained from the SSIM by converting P, Q, R, and S in each cell with binary digits (1 and 0). The following rules are used in conversion:

If “P” is plotted in the SSIM for the cell (l, m), then in the IRM, 1 is plotted in that cell (l, m) and 0 is plotted in the cell (m, l). If “Q” is plotted in the SSIM for the cell (l, m), then in the IRM, 0 is plotted in that cell (l, m) and 1 is plotted in the cell (m, l). If “R” is plotted in the SSIM for the cell (l, m), then in the IRM, 1 is plotted for both the cell (l, m) and cell (m, l). If “S” is plotted in the SSIM for the cell (l, m), then in the IRM, 0 is plotted in both the cell (l, m) and cell (m, l). Following these rules, IRM is developed and presented in Table 4.

The final reachability matrix (FRM), as shown in Table 5, is developed from the IRM incorporating transitivity, where transitivity is marked as 1*.

Table 4

IRM

Drivers code	BTD 1	BTD 2	BTD 3	BTD 4	BTD 5	BTD 6	BTD 7	BTD 8	BTD 9	BTD 10	BTD 11	BTD 12
BTD 1	1	0	1	0	0	0	0	0	0	0	1	0
BTD 2	1	1	1	1	1	1	0	1	1	1	1	1
BTD 3	1	0	1	0	0	0	0	0	0	0	1	0
BTD 4	1	0	1	1	1	0	0	0	0	0	1	0
BTD 5	1	0	1	0	1	0	0	0	0	0	1	1

BTD 6	1	0	1	1	1	1	0	0	0	1	1	1
BTD 7	1	1	1	1	1	0	1	1	1	1	1	1
BTD 8	1	1	1	0	1	0	0	1	0	1	1	1
BTD 9	1	0	1	1	1	1	0	0	1	1	1	0
BTD 10	1	0	1	1	1	1	0	0	0	1	1	1
BTD 11	0	0	0	0	0	0	0	0	0	0	1	0
BTD 12	0	0	1	0	1	0	0	0	0	0	1	1

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

Table 5

FRM

Drivers code	BTD 1	BTD 2	BTD 3	BTD 4	BTD 5	BTD 6	BTD 7	BTD 8	BTD 9	BTD 10	BTD 11	BTD 12	Driving Power
BTD 1	1	0	1	0	0	0	0	0	0	0	1	0	3
BTD 2	1	1	1	1	1	1	0	1	1	1	1	1	11
BTD 3	1	0	1	0	0	0	0	0	0	0	1	0	3
BTD 4	1	0	1	1	1	0	0	0	0	0	1	1*	6
BTD 5	1	0	1	0	1	0	0	0	0	0	1	1	5
BTD 6	1	0	1	1	1	1	0	0	0	1	1	1	8
BTD 7	1	1	1	1	1	1*	1	1	1	1	1	1	12
BTD 8	1	1	1	1*	1	1*	0	1	1*	1	1	1	11
BTD 9	1	0	1	1	1	1	0	0	1	1	1	1*	9
BTD 10	1	0	1	1	1	1	0	0	0	1	1	1	8
BTD 11	0	0	0	0	0	0	0	0	0	0	1	0	1
BTD 12	1*	0	1	0	1	0	0	0	0	0	1	1	5
Dependence Power	11	3	11	7	9	6	1	3	4	6	12	9	

1* notation plotted in the cell to incorporate transitivity.

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

4.1.3. Level partitioning

For each driver, the reachability and the antecedent set are obtained from FRM. In the ISM hierarchy, the top-level driver is identified by the reachability and intersection sets that share the same driver, preventing any other driver from reaching above their own level. Those identified top-level drivers are removed from the remaining drivers. Thus, this process is continued until the level of each driver is obtained. It can be observed that traceability (BTD 11) is at Level I. This procedure is completed in eight iterations, as summarised in Table 6.

Table 6

Final Level Partitioning

Drivers code	Reachability Set	Antecedent Set	Intersection Set	Level
BTD 1	1, 3,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12,	1, 3,	2
BTD 2	2, 8,	2, 7, 8,	2, 8,	7
BTD 3	1, 3,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12,	1, 3,	2
BTD 4	4,	2, 4, 6, 7, 8, 9, 10,	4,	4
BTD 5	5, 12,	2, 4, 5, 6, 7, 8, 9, 10, 12,	5, 12,	3
BTD 6	6, 10,	2, 6, 7, 8, 9, 10,	6, 10,	5
BTD 7	7,	7,	7,	8
BTD 8	2, 8,	2, 7, 8,	2, 8,	7
BTD 9	9,	2, 7, 8, 9,	9,	6
BTD 10	6, 10,	2, 6, 7, 8, 9, 10,	6, 10,	5
BTD 11	11,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	11,	1
BTD 12	5, 12,	2, 4, 5, 6, 7, 8, 9, 10, 12,	5, 12,	3

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

4.1.4. Formation of ISM hierarchy model:

4.1.5. Based on the FRM inputs, a digraph is developed including transitivity. After removing transitivity from the digraph, as mentioned in the research methodology, the ISM hierarchy model is developed. The final model is presented in the Fig. 3.

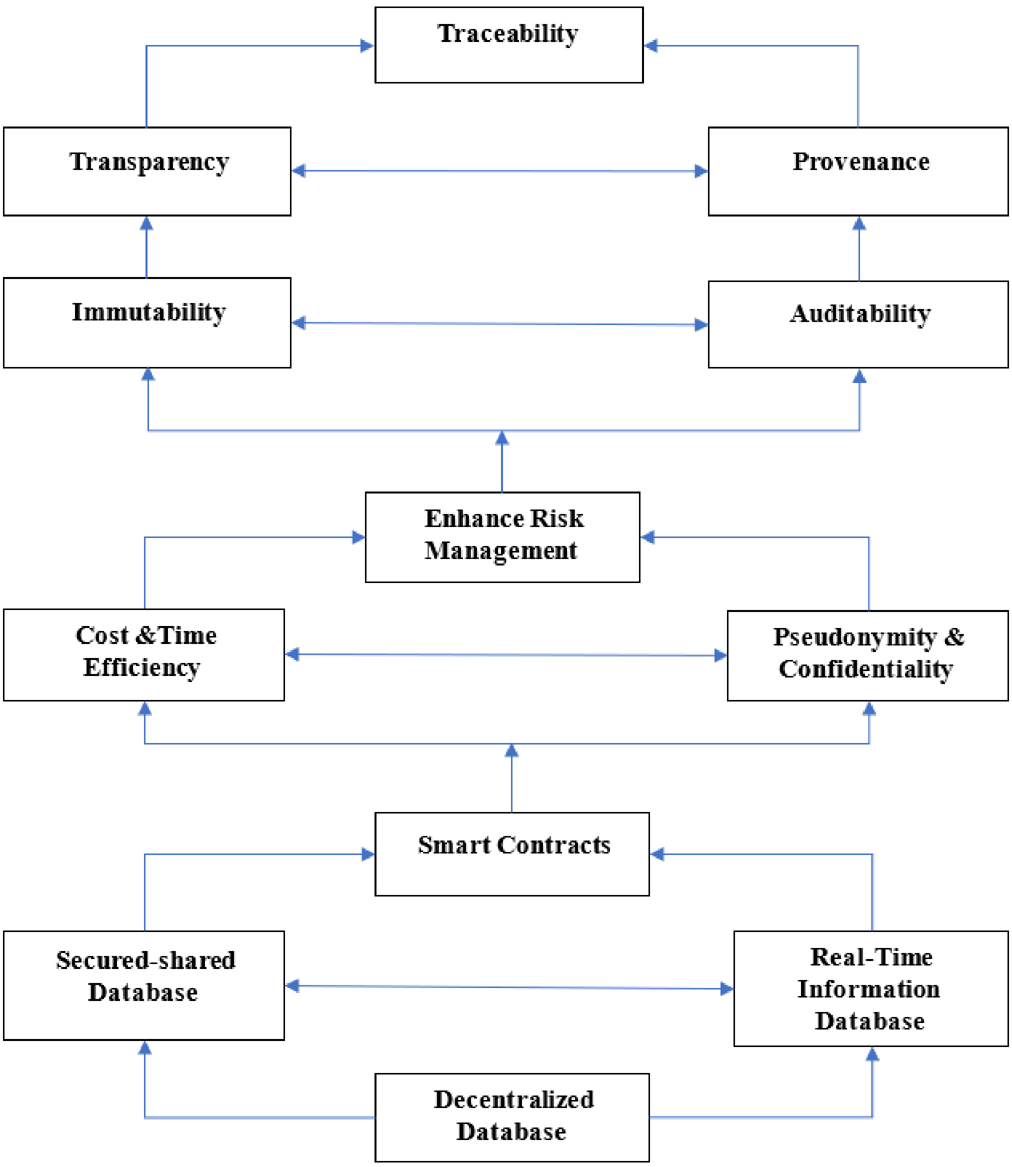

Fig.3: ISM Hierarchy Model

4.1.6. MICMAC analysis:

Abbreviation of MICMAC is Matrice d'Impacts croisés multiplication appliquée à un classement (Cross-Impact Matrix Multiplication Applied to Classification), and the principle of MICMAC is based on the multiplication properties of matrices (U. Khan & Haleem, 2015; Vaishnavi et al., 2019). The purpose of this analysis is to examine the dependence power and driving power of the identified drivers, as well as identify the influential drivers that significantly drive the system. These drivers are classified into four quadrants as presented in Fig. 4. and discussed below:

i) Autonomous drivers: The drivers mentioned in quadrant (I) have weak dependence power and drive power. The drivers represented in this quadrant are not connected to each other and do not have any influence on the system. Thus, all the identified drivers in this study plays a significant role, as there are no such drivers in this quadrant.

ii) Dependent drivers: The drivers, plotted in quadrant (II), have strong dependence power and weak driving power. Transparency (BTD 1), product provenance (BTD 3), enhanced risk management (BTD 4), Immutability (BTD 5), traceability (BTD 11), and auditability (BTD 12) are dependent drivers in our study. This analysis implies that decision-makers must consider these six drivers, as they are the principal reasons to decide for while implementing BT in TSC.

iii) Linkage drivers: The drivers mentioned in quadrant (III) have strong driving power and dependence power. These drivers are highly unstable; any intervention concerning them will influence other drivers as well as themselves. There are no unstable drivers in this study, as no driver is present in this quadrant.

iv) Driving drivers: The drivers plotted in quadrant (IV) have weak dependence power and strong driving power. Secured-shared database BTD 2, cost & time efficiency (BTD 6), decentralised database (BTD 7), real-time information database (BTD 8), smart contract (BTD 9), and pseudonymity & confidentiality (BTD 10) are independent drivers as they have strong drive power. The finding suggest that these six drivers are primary drivers that significantly influence other drivers within the system, driving BT adoption in TSC, as they are possible substrata of the system.

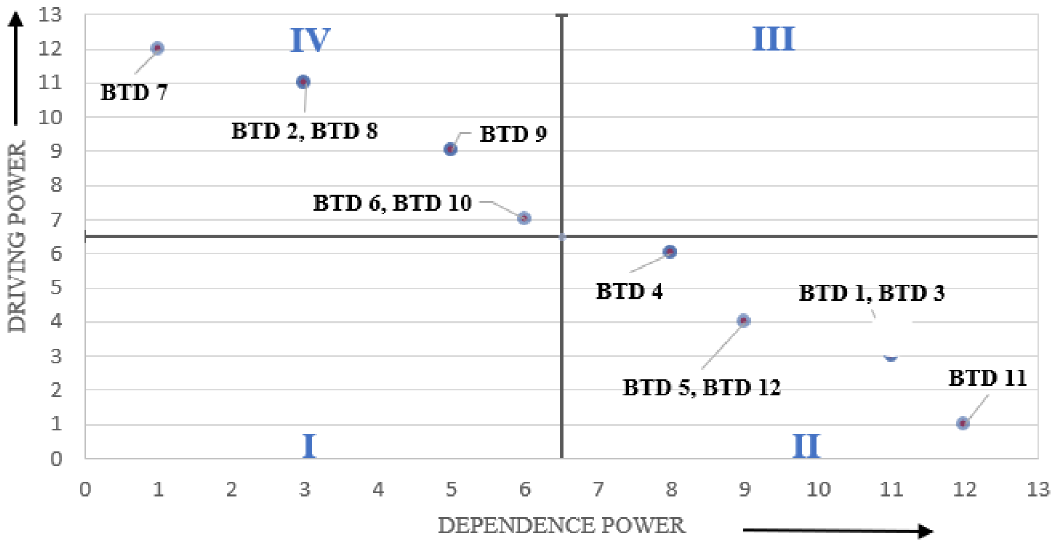

Fig.4: Representation of MICMAC analysis.

4.2. DEMATEL analysis

In this approach, experts rated the drivers on a scale ranging from 0 to 4 based on the influence of one driver over other drivers. Depending on the experts' opinions, the comparison matrix is developed in pairs. The average direct relation matrix (A) as shown in Table 7 is computed from the combined pair-wise matrix based on responses of individual expert using Eq. (1). Thereafter, the normalised direct relationship matrix (B) is formulated from Eq. (2) with a range of 0 to 1 for each driver as mentioned in Table 8. Finally, by using Eq. (3), the total relationship matrix (T) for each driver is established, as presented in Table 9. The overall degree of influence, for each critical driver selected in the study is shown in Table 10 and plotted in Figure 5, and can be classified as follows:

The prominence or important order as per the ($R_l + C_m$) values for the identified drivers are prioritised as traceability (BTD 11) > transparency (BTD 1) > product provenance (BTD 3) > Immutability (BTD 5) > auditability (BTD 12) > pseudonymity & confidentiality (BTD 10) > enhanced risk management (BTD 4) > decentralised database (BTD 7) > smart contract (BTD 9) > real-time information database (BTD 8) > cost & time efficiency (BTD 6) > secured-shared database (BTD 2). Based on the highest prominence value, traceability (BTD 11) is ranked first and identified as the most important driver, followed by transparency (BTD 1) and product provenance (BTD 3). Similarly, the cause or effect groups drivers are demonstrated by the relation values, i.e., (R_l - C_m), categorising these drivers into two groups: the net cause group for positive (R_l - C_m) values, and the net effect or receiver group for negative (R_l - C_m) values. Subsequently, the calculated threshold value for all identified drivers is 0.51 using the total relation matrix. According to the cause-and-effect or causal diagram secured-shared database (BTD 2), cost & time efficiency (BTD 6), decentralised database (BTD 7), real-time information database (BTD 8), smart contract (BTD 9), and pseudonymity & confidentiality (BTD 10) come under the cause group, where decentralised database (BTD 7) is considered the most crucial driver that has significant influence on all other drivers. On the other hand, transparency (BTD 1), product provenance (BTD 3), enhanced risk management (BTD 4), traceability (BTD 11), and auditability (B12) belong to the effect group and further indicate that traceability (BTD 11) is the highest net receiver; it does not influence other drivers but gets influenced by each driver within the system. The causal diagram is mentioned in the Fig.5. The cause group drivers should be considered directly by the decision-makers, as these drivers affect the effective implementation of BT in TSC.

Table 7

The average direct-relation matrix (A)

Drivers code	BTD 1	BTD 2	BTD 3	BTD 4	BTD 5	BTD 6	BTD 7	BTD 8	BTD 9	BTD 10	BTD 11	BTD 12
BTD 1	0	0.167	2.917	0.25	0.5	0.333	0.083	0.167	0.25	0.333	3.833	0.5
BTD 2	2.833	0	2.75	2.083	2.667	2.667	0.167	1.75	1.667	2.583	3.75	1.833
BTD 3	3.917	0.083	0	0.083	0.333	0.417	0.083	0.167	0.083	0.167	3.833	0.083
BTD 4	3.75	0.167	2.667	0	2.917	0.083	0.083	0.083	0.417	0.83	3.917	2.917
BTD 5	3.833	0.083	2.667	0.167	0	0.167	0.25	0.083	0.25	0.167	3.667	3.083
BTD 6	3.667	0.083	2.583	1.917	2.75	0	0.417	0.5	0.417	2.917	3.833	2.833
BTD 7	2.667	2.083	2.917	2.917	2.833	1.917	0	1.833	2.917	2.667	3.917	2.833
BTD 8	2.833	1.833	3.083	2.833	1.75	1.667	0.167	0	2.75	2.833	3.833	2.75
BTD 9	3.917	0.167	3.917	2.917	2.833	1.917	0.083	0.417	0	2.083	3.75	2.917
BTD 10	3.917	0.25	1.833	3.833	2.917	1.833	0.333	0.167	0.083	0	3.917	1.917
BTD 11	0.083	0.167	0.083	0.083	0.25	0.167	0.083	0.167	0.083	0.083	0	0.083
BTD 12	3.667	0.083	2.583	1.583	2.833	0.083	0.083	0.083	0.25	0.417	3.667	0

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

Table 8

The normalised direct-relation matrix (N)

Drivers code	BTD 1	BTD 2	BTD 3	BTD 4	BTD 5	BTD 6	BTD 7	BTD 8	BTD 9	BTD 10	BTD 11	BTD 12
BTD 1	0.000	0.004	0.070	0.006	0.012	0.008	0.002	0.004	0.006	0.008	0.091	0.012
BTD 2	0.068	0.000	0.066	0.050	0.064	0.064	0.004	0.042	0.040	0.062	0.089	0.044
BTD 3	0.093	0.002	0.000	0.002	0.008	0.010	0.002	0.004	0.002	0.004	0.091	0.002
BTD 4	0.089	0.004	0.064	0.000	0.070	0.002	0.002	0.002	0.010	0.020	0.093	0.070
BTD 5	0.091	0.002	0.064	0.004	0.000	0.004	0.006	0.002	0.006	0.004	0.087	0.074

BTD 6	0.087	0.002	0.062	0.046	0.066	0.000	0.010	0.012	0.010	0.070	0.091	0.068
BTD 7	0.064	0.050	0.070	0.070	0.068	0.046	0.000	0.044	0.070	0.064	0.093	0.068
BTD 8	0.068	0.044	0.074	0.068	0.042	0.040	0.004	0.000	0.066	0.068	0.091	0.066
BTD 9	0.093	0.004	0.093	0.070	0.068	0.046	0.002	0.010	0.000	0.050	0.089	0.070
BTD 10	0.093	0.006	0.044	0.091	0.070	0.044	0.008	0.004	0.002	0.000	0.093	0.046
BTD 11	0.002	0.004	0.002	0.002	0.006	0.004	0.002	0.004	0.002	0.002	0.000	0.002
BTD 12	0.087	0.002	0.062	0.038	0.068	0.002	0.002	0.002	0.006	0.010	0.087	0.000

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

Table 9

The total-relation matrix (T)

Drivers code	BTD 1	BTD 2	BTD 3	BTD 4	BTD 5	BTD 6	BTD 7	BTD 8	BTD 9	BTD 10	BTD 11	BTD 12
BTD 1	0.015	0.005	0.076	0.010	0.018	0.011	0.003	0.005	0.008	0.011	0.108	0.017
BTD 2	0.121	0.005	0.106	0.072	0.093	0.075	0.007	0.046	0.047	0.077	0.155	0.073
BTD 3	0.100	0.003	0.011	0.005	0.013	0.012	0.003	0.005	0.004	0.007	0.107	0.007
BTD 4	0.118	0.006	0.087	0.009	0.083	0.007	0.004	0.004	0.013	0.025	0.133	0.081
BTD 5	0.111	0.004	0.081	0.011	0.011	0.008	0.007	0.004	0.009	0.008	0.118	0.079
BTD 6	0.129	0.006	0.093	0.061	0.088	0.009	0.012	0.015	0.015	0.077	0.145	0.088
BTD 7	0.131	0.055	0.121	0.098	0.106	0.063	0.004	0.050	0.080	0.084	0.175	0.104
BTD 8	0.126	0.047	0.117	0.091	0.076	0.054	0.007	0.006	0.072	0.084	0.162	0.095
BTD 9	0.143	0.007	0.129	0.085	0.093	0.054	0.005	0.014	0.006	0.060	0.152	0.093
BTD 10	0.132	0.009	0.075	0.101	0.090	0.049	0.010	0.007	0.007	0.010	0.144	0.067
BTD 11	0.006	0.004	0.005	0.004	0.008	0.005	0.002	0.004	0.003	0.003	0.004	0.004
BTD 12	0.111	0.004	0.081	0.042	0.077	0.006	0.003	0.004	0.009	0.014	0.120	0.013

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD

8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

Table 10

Degree of influence

Drivers code	R_l	C_m	R_l+C_m	$R_l–C_m$	Rank
BTD 1	0.287	1.242	1.529	-0.955	2
BTD 2	0.878	0.157	1.035	0.721	12
BTD 3	0.277	0.982	1.259	-0.705	3
BTD 4	0.570	0.589	1.159	-0.019	7
BTD 5	0.451	0.755	1.206	-0.304	4
BTD 6	0.739	0.352	1.091	0.387	11
BTD 7	1.071	0.067	1.138	1.003	8
BTD 8	0.937	0.166	1.103	0.770	10
BTD 9	0.839	0.272	1.111	0.567	9
BTD 10	0.702	0.462	1.164	0.240	6
BTD 11	0.053	1.523	1.576	-1.470	1
BTD 12	0.484	0.721	1.205	-0.238	5

BTD 1: Transparency; BTD 2: Secured-Shared Database; BTD 3: Product Provenance; BTD 4: Enhanced Risk Management; BTD 5: Immutability; BTD 6: Cost & Time Efficiency; BTD 7: Decentralised Database; BTD 8: Real-Time Information Database; BTD 9: Smart Contract; BTD 10: Pseudonymity & Confidentiality; BTD 11: Traceability; BTD 12: Auditability

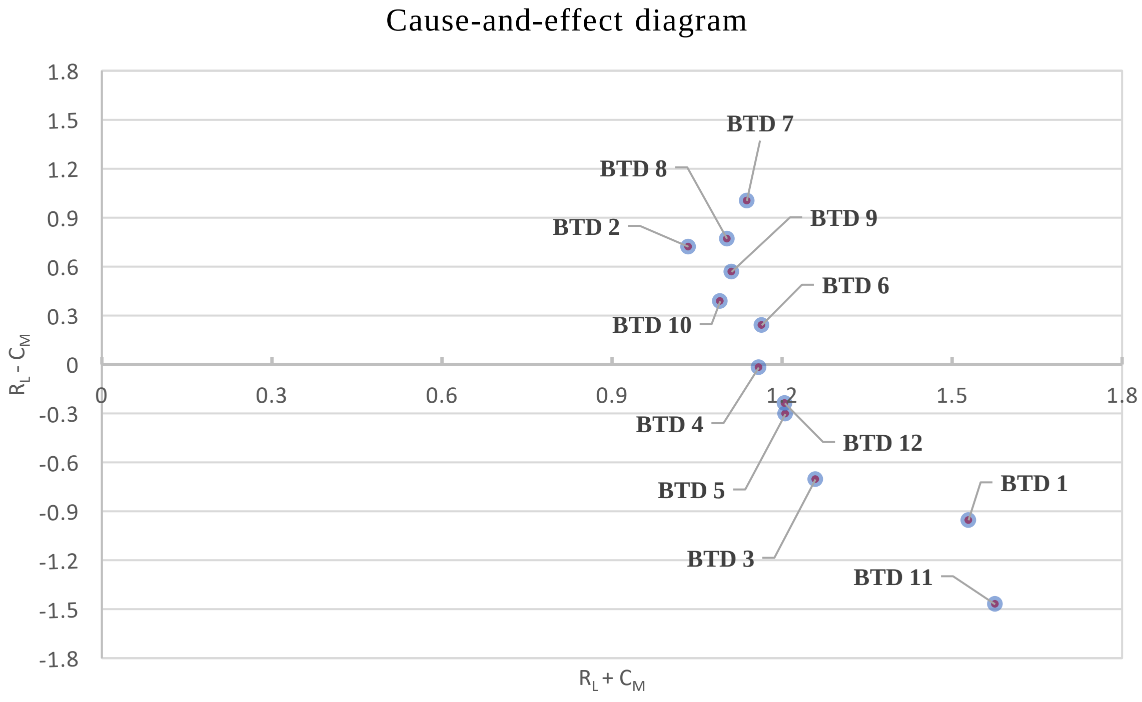

Fig. 5: Degree of influence of drivers adopting BT in TSC.

5. Discussions on the findings

This study aims to investigate the identified drivers influencing the adoption of BT in TSC. Although some studies have addressed these drivers, no study has established a structured relationship among them. This study focuses on the selection of key drivers, which are incorporated into a hierarchical framework using the ISM and DEMATEL methods. This method also develops inter-relationships among the identified drivers. From the ISM-MICMAC analysis as presented in Fig. 4, it is observed that the decentralised database (BTD 7) is the most critical driver, having the strongest drive power and weak dependence power. Thus, the decentralised database (BTD 7) is the primary driver and root cause of the system, driving the whole system, followed by the secured-shared database (BTD 2) and the real-time information database (BTD 8), which are interrelated, having strong drive and weak dependence power. These drivers focus on handling BT in a sustainable manner, as they exert influence over drivers' smart contract (BTD 9), which have strong driving power, facilitating broader system-wide interactions and are also considered influential drivers. Fig. 3 reveals that drivers cost & time efficiency (BTD 6) and pseudonymity & confidentiality (BTD 10) have moderately strong driving and dependence power and serve as a transitional node, carrying the influence of the driving group drivers to the dependent group drivers within the system. Moreover, among the dependent group drivers, traceability (BTD 11) is the most affected driver, having strong dependence and weak driving power, along with drivers' transparency (BTD 1), product provenance (BTD 3), enhanced risk management (BTD 4), Immutability (BTD 5), traceability (BTD 11), and auditability (BTD 12). Thus, the ISM-MICMAC analysis shows that each identified driver has a significant impact on the adoption of BT, as there are no autonomous or linkage drivers present.

From the DEMATEL methodology, as shown in Table 10, it is evident that, secured-shared database (BTD 2), cost & time efficiency (BTD 6), decentralised database (BTD 7), real-time information database (BTD 8), smart contract (BTD 9) and pseudonymity & confidentiality (BTD 10) are considered as the most influential cause group drivers. This highlights that secured-shared database BTD 2 and real-time information database (BTD 8) help in understanding the importance of BT integration in the tea supply chain. More importantly, the use of smart contract (BTD 9) and cost & time efficiency (BTD 6) strengthens the basic concept of BT adoption in TSC. Pseudonymity & confidentiality (BTD 10), which has a low influence, still remains a critical driver because it falls under the cause group drivers and its relative position in the system suggests that it is helpful in amplifying changes that other cause group drivers initiate.

Decentralised database (BTD 7), a cause group driver with strong driving power and weak dependence power, is identified as the highest influential driver in both DEMATEL and ISM analyses. Therefore, the driver decentralised database (BTD 7) can be considered as the underlying cause influencing the affected or dependent group drivers. Moreover, traceability (BTD 11), an effect group driver with strong dependence power and weak driving power, is the most influenced driver in the hybrid ISM-DEMATEL analysis. Therefore, to make an effective traceable TSC by adopting BT, the cause group drivers should be given priority-based consideration, as cause group drivers will naturally lead changes in the effect group drivers. In this study cause group drivers aligns with the previous studies such as secured-shared database suggesting that data in a BT network is stored in multiple nodes instead of a single central server, making it tamper-proof and hacking resistant (Cavaliere et al., 2024), real-time information database allows secure, transparent, and efficient tracking of goods and transactions from origin to delivery in the supply chain (Helo & Shamsuzzoha, 2020) and smart contract ensures automatic execution of an agreement offering visibility to all the participants eliminating the involvement of an intermediary or third party (Chang et al., 2019). This study supports the claim that pseudonymity and confidentiality in BT offer enhanced privacy and security, helping supply chain stakeholders to share information safely while protecting their sensitive business details (Barański et al., 2025). This study supports the recommendation that BT significantly enhances cost and time efficiency, leading to fast transactions, reduced operational costs, and improved management in the supply chain (Cole et al., 2019; Rejeb et al., 2019). Findings of the study also suggest decentralisation in BT enhances transparency, security, and resilience by eliminating a single point of failure, reducing intermediaries' reliance (Min, 2019). Blockchain-driven traceability plays a significant role in enhancing supply chain sustainability by promoting transparency, accountability of the stakeholders, and ensuring responsible sourcing (Centobelli et al., 2022c; Oriekhoe et al., 2024; Parmentola et al., 2022). BT provides a secure and immutable record of the product's journey, verifying sustainable practices, fair sourcing, and environmental consequences (Chaudhuri et al., 2023; J. Wu & Tran, 2018). Thus, to reduce the influence of the influencing drivers, decision-makers and policy-makers must ascertain that an effective and coherent framework is developed, taking cause group drivers into consideration. Hence, hybrid ISM-DEMATEL analysis develops the framework for the BT-based TSC system drivers and also determines the inter-dependences among these drivers.

6. Conclusion, implications and limitations

6.1. Conclusion:

Across developing nations, particularly India, the existing regulatory organisations of traditional tea supply chains are prone to corruption, error, and hacking. Currently, in TSC, tea adulteration has become a significant issue, as food labelling systems are not fully trusted by consumers, raising concerns about the authenticity, integrity, and safety of products. There is a high demand for traceability and transparency in TSC. To overcome these issues, a practical implementation of BT on TSC is employed in this study. MCDM criteria have been deliberately applied, and 12 critical drivers were identified for evaluation using the integrated ISM-DEMATEL technique. This methodology facilitates the integration of BT in TSC by establishing inter-dependency among drivers into a structured model and also categorising them into cause/influential or effect/dependence groups. This suggested methodology drives the decision-maker's attention to the dependence and causal effects of the drivers in the system, by solving MCDM problems for smooth adoption of BT in TSC in a constructive manner.

In the hierarchical structure, identifying drivers of BT adoption in TSC is very complex. The findings of the study identified that the decentralised database (BTD 7), along with the real-time information database (BTD 8) and the secured-shared database BTD 2 are the most influential and causal drivers; on the other hand, traceability (BTD 11) is the most effective dependent driver in the ISM as well as the DEMATEL approach. Cause/influential group drivers easily affect the effect/dependent group drivers, as these cause group drivers have high potential to influence the overall system. Hence, practitioners need to be more focused on these cause group drivers while implementing blockchain in the context of India.

6.2. Research implications

Based on the empirical analysis, the identified drivers were classified into two groups: either cause/influential or affected/dependent. The drivers falling under the affected or dependent group are significantly influenced by cause or influential group drivers, as they play a crucial role in the adoption of BT in TSC and warrant immediate attention from organisational decision-makers and policymakers. These cause-type drivers act as the root sources of the dependent/affected drivers. Addressing the root causes is essential, as managing them effectively can mitigate the influence of the dependent factors. Consequently, organisational leaders and policymakers must prioritise the resolution of these influential drivers to maintain consistency and prevent systemic disruptions across the supply chain.

Moreover, for organisational decision-makers, the identified drivers offer a strategic opportunity and proactively recognise and manage potential risks within the TSC. To achieve this, it is required to place social considerations at the core of decision-making processes, assuring the technical advantages of implementing BT in a manner that aligns with societal needs and expectations. From an organisational perspective, the successful integration of BT within TSC depends on designing incentive-driven mechanisms. BT integration encourages supply chain participants to collect and share authentic and trustworthy data, which is an essential component for building an effective traceability model, ensuring transparency and accountability within the system. Blockchain technology can act as a foundational technology that integrates, adapts, and collaborates with other emerging technologies within its network, thereby enabling uninterrupted improvements in the TSC. Technologies such as IoT and artificial intelligence can support the development of data-driven ASCs.

In addition, it is recommended that government bodies and stakeholders to collaborate and address challenges related to the implementation of BT in TSC, and also develop a sustainable framework. This model can also be extended to diverse sectors, such as agriculture, beverage and food supply chains. In this study, the proposed research model offers recommendations to decision-makers and policy-makers in the adoption of BT, considering cause/influential group drivers to enhance traceability within the TSC in a sustainable and environmentally friendly manner. This study also contributes to achieve both economic and social sustainability in the TSC.

6.3. Limitations and future research

Instead of the valuable contributions of this study in understanding BT integration in TSC, several limitations are also present. The hybrid ISM-DEMATEL technique used to model the inter-relationships among drivers relies heavily on experts' opinions, which, while insightful, may introduce a degree of subjectivity and bias. Moreover, the study focuses on 12 drivers identified and validated by experts solely within the Indian context. This geographic and contextual limitation may exclude key drivers that are relevant in other countries with different technological readiness, regulatory frameworks, or supply chain dynamics.

Future research should consider a broader, cross-country perspective to identify additional drivers and validate the model statistically using techniques like Structural Equation Modelling (SEM). Comparative studies across different regions can help refine the interdependencies between drivers and lead to the development of a more inclusive and globally relevant framework for BT-driven traceability in the tea supply chain.

Data availability statement

The authors confirm that the data supporting the findings of this study are available in this research article.

Disclosure statement

"The Authors report there are no competing interests to declare".

References

1. Agarwal, R., Bhadauria, A., Kaushik, H., Swami, S., & Rajwanshi, R. (2023). ISM-MICMAC-based study on key enablers in the adoption of solar renewable energy products in India. *Technology in Society*, *75*, 102375.
2. Agarwal, U., Rishiwal, V., Yadav, M., Aslhammari, M., Yadav, P., Singh, O., & Maurya, V. (2024). Exploring Blockchain and Supply Chain Integration: State-of-the-Art, Security Issues and Emerging Directions. *IEEE Access*. https://ieeexplore.ieee.org/abstract/document/10700747/
3. Agrawal, T. K., Kumar, V., Pal, R., Wang, L., & Chen, Y. (2021). Blockchain-based framework for supply chain traceability: A case example of textile and clothing industry. *Computers & Industrial Engineering*, *154*, 107130.
4. Ahmad, K., Islam, M. S., Jahin, M. A., & Mridha, M. F. (2024). Analysis of Internet of things implementation barriers in the cold supply chain: An integrated ISM-MICMAC and DEMATEL approach. *Plos One*, *19*(7), e0304118.
5. Ahmad, R. W., Hasan, H., Yaqoob, I., Salah, K., Jayaraman, R., & Omar, M. (2021). Blockchain for aerospace and defense: Opportunities and open research challenges. *Computers & Industrial Engineering*, *151*, 106982.
6. Ahmed, W. A., & MacCarthy, B. L. (2023). Blockchain-enabled supply chain traceability–How wide? How deep? *International Journal of Production Economics*, *263*, 108963.
7. Akanfe, O., Lawong, D., & Rao, H. R. (2024). Blockchain technology and privacy regulation: Reviewing frictions and synthesizing opportunities. *International Journal of Information Management*, *76*, 102753.
8. Akram, H. W., Ahmad, A., Dana, L.-P., Khan, A., & Akhtar, S. (2024). Do Trade Agreements Enhance Bilateral Trade? Focus on India and Sri Lanka. *Sustainability*, *16*(2), Article 2. https://doi.org/10.3390/su16020582
9. Al-Farsi, S., Rathore, M. M., & Bakiras, S. (2021). Security of blockchain-based supply chain management systems: Challenges and opportunities. *Applied Sciences*, *11*(12), 5585.
10. Almadadha, R. (2024). Blockchain technology in financial accounting: Enhancing transparency, security, and esg reporting. *Blockchains*, *2*(3), 312–333.
11. Anjali, V. S. (2024). Security and Privacy Considerations in Blockchain-based IoT Systems. In *Blockchain and Digital Twin Enabled IoT Networks* (pp. 201–215). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003403791-11/security-privacy-considerations-blockchain-based-iot-systems-anjali
12. Asamoah, K. O., Darko, A. P., Antwi, C. O., Sey, C., Osei, A. H., Ma, X., & Zhu, J. (2024). A probabilistic reliable linguistic model for blockchain-based student information management system assessment. *Applied Soft Computing*, *159*, 111645.
13. Attaran, M. (2022). Blockchain technology in healthcare: Challenges and opportunities. *International Journal of Healthcare Management*, *15*(1), 70–83. https://doi.org/10.1080/20479700.2020.1843887
14. Autore, D., Chen, H. A., Clarke, N., & Lin, J. (2024). Blockchain and earnings management: Evidence from the supply chain. *The British Accounting Review*, 101357.
15. Bagherian, A., Gershon, M., Kumar, S., & Mishra, M. K. (2024). Analyzing the relationship between digitalization and energy sustainability: A comprehensive ISM-MICMAC and DEMATEL approach. *Expert Systems with Applications*, *236*, 121193.
16. Balcıoğlu, Y. S., Çelik, A. A., & Altındağ, E. (2024). Integrating Blockchain Technology in Supply Chain Management: A Bibliometric Analysis of Theme Extraction via Text Mining. *Sustainability*, *16*(22), 10032.
17. Barański, S., Szymański, J., & Mora, H. (2025). Anonymous provision of privacy-sensitive services using blockchain and decentralised storage. *International Journal of Information Security*, *24*(3), 130.
18. Bhutta, M. N. M., & Ahmad, M. (2021). Secure identification, traceability and real-time tracking of agricultural food supply during transportation using internet of things. *Ieee Access*, *9*, 65660–65675.
19. Biswas, D., Jalali, H., Ansaripoor, A. H., & De Giovanni, P. (2023). Traceability vs. sustainability in supply chains: The implications of blockchain. *European Journal of Operational Research*, *305*(1), 128–147.
20. Bosona, T., & Gebresenbet, G. (2023). The Role of Blockchain Technology in Promoting Traceability Systems in Agri-Food Production and Supply Chains. *Sensors*, *23*(11), 5342. https://doi.org/10.3390/s23115342
21. Braga, I. F., Ferreira, F. A., Ferreira, J. J., Correia, R. J., Pereira, L. F., & Falcão, P. F. (2021). A DEMATEL analysis of smart city determinants. *Technology in Society*, *66*, 101687.
22. Brandín, R., & Abrishami, S. (2021). Information traceability platforms for asset data lifecycle: Blockchain-based technologies. *Smart and Sustainable Built Environment*, *10*(3), 364–386.
23. Calvão, F., & Archer, M. (2021). Digital extraction: Blockchain traceability in mineral supply chains. *Political Geography*, *87*, 102381.
24. Camel, A., Belhadi, A., Kamble, S., Tiwari, S., & Touriki, F. E. (2024). Integrating smart Green Product Platforming for carbon footprint reduction: The role of blockchain technology and stakeholders influence within the agri-food supply chain. *International Journal of Production Economics*, *272*, 109251.
25. Cavaliere, L. P. L., Rawat, S., Sidana, N., Acharjee, P. B., Kharb, L., & Podile, V. (2024). Securing Automated Systems with BT: Opportunities and Challenges. *Robotics and Automation in Industry 4.0*, 337–348.
26. Centobelli, P., Cerchione, R., Del Vecchio, P., Oropallo, E., & Secundo, G. (2022a). Blockchain technology for bridging trust, traceability and transparency in circular supply chain. *Information & Management*, *59*(7), 103508.
27. Centobelli, P., Cerchione, R., Del Vecchio, P., Oropallo, E., & Secundo, G. (2022b). Blockchain technology for bridging trust, traceability and transparency in circular supply chain. *Information & Management*, *59*(7), 103508.
28. Centobelli, P., Cerchione, R., Del Vecchio, P., Oropallo, E., & Secundo, G. (2022c). Blockchain technology for bridging trust, traceability and transparency in circular supply chain. *Information & Management*, *59*(7), 103508.
29. Chaker, B., & Damak, C. (2024). Integrating Blockchain Technology for Enhanced Transparency and Security in Supply Chains. In *Strategic Innovations for Dynamic Supply Chains* (pp. 147–169). IGI Global. https://www.igi-

global.com/chapter/integrating-blockchain-technology-for-enhanced-transparency-and-security-in-supply-chains/344330

30. Chang, S. E., Chen, Y.-C., & Lu, M.-F. (2019). Supply chain re-engineering using blockchain technology: A case of smart contract based tracking process. *Technological Forecasting and Social Change*, *144*, 1–11.
31. Channi, H. K., & Kumar, P. (2025). Automating and Streamlining Drug Payments Through Smart Contracts. In *Blockchain-Enabled Solutions for the Pharmaceutical Industry* (pp. 153–173). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781394287970.ch8
32. Chaudhuri, A., Bhatia, M. S., Kayikci, Y., Fernandes, K. J., & Fosso-Wamba, S. (2023). Improving social sustainability and reducing supply chain risks through blockchain implementation: Role of outcome and behavioural mechanisms. *Annals of Operations Research*, *327*(1), 401–433. https://doi.org/10.1007/s10479-021-04307-6
33. Chen, C.-L., Zhan, W.-B., Huang, D.-C., Liu, L.-C., Deng, Y.-Y., & Kuo, C.-G. (2023). Hyperledger fabric-based tea supply chain production data traceable scheme. *Sustainability*, *15*(18), 13738.
34. Chen, S., Liu, X., Yan, J., Hu, G., & Shi, Y. (2021). Processes, benefits, and challenges for adoption of blockchain technologies in food supply chains: A thematic analysis. *Information Systems and E-Business Management*, *19*(3), 909–935. https://doi.org/10.1007/s10257-020-00467-3
35. Chi, M., Ren, S., Xu, Y., Chen, Y., & Wu, Y. (2025). Critical success factors for metaverse implementation in the service industry: A hybrid ISM-DEMATEL approach. *Journal of Retailing and Consumer Services*, *87*, 104424. https://doi.org/10.1016/j.jretconser.2025.104424
36. Chuang, H.-M., Lin, C.-K., Chen, D.-R., & Chen, Y.-S. (2013). Evolving MCDM Applications Using Hybrid Expert-Based ISM and DEMATEL Models: An Example of Sustainable Ecotourism. *The Scientific World Journal*, *2013*(1), 751728. https://doi.org/10.1155/2013/751728
37. Chulerttiyawong, D., & Jamalipour, A. (2021). A blockchain assisted vehicular pseudonym issuance and management system for conditional privacy enhancement. *Ieee Access*, *9*, 127305–127319.
38. 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.
39. Daraghmi, E., Jayousi, S., Daraghmi, Y., Daraghmi, R., & Fouchal, H. (2024). Smart Contracts for Managing the Agricultural Supply Chain: A Practical Case Study. *Ieee Access*. https://ieeexplore.ieee.org/abstract/document/10623674/
40. De Giovanni, P. (2020). Blockchain and smart contracts in supply chain management: A game theoretic model. *International Journal of Production Economics*, *228*, 107855.
41. Dehshiri, S. J. H., Amiri, M., & Bamakan, S. M. H. (2024). Evaluating the blockchain technology strategies for reducing renewable energy development risks using a novel integrated decision framework. *Energy*, *289*, 129987.
42. Du, J., Shi, Y., Li, W., & Chen, Y. (2023). Can blockchain technology be effectively integrated into the real economy? Evidence from corporate investment efficiency. *China Journal of Accounting Research*, *16*(2), 100292.
43. Eyo-Udo, N. L., Apeh, C. E., Bristol-Alagbariya, B., Udeh, C. A., & Ewim, C. P.-M. (2025). The Evolution of Blockchain Technology in Accounting: A Review of Its Implications for Transparency and Accountability. *Account and Financial Management Journal*, *10*(1), 2456–3374.
44. 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*, *31*(8), 3769–3785. https://doi.org/10.1002/bse.3031
45. Gunjal, P. R., Jondhale, S. R., Mauri, J. L., & Agrawal, K. (2024). *Internet of Things: Theory to Practice*. CRC Press. https://doi.org/10.1201/9781003282945
46. Guo, X., Yang, Z., Sun, J., & Zhang, Y. (2024). Impact pathways of emerging ITs to mitigate supply chain vulnerability: A novel DEMATEL-ISM approach based on grounded theory. *Expert Systems with Applications*, *239*, 122398.
47. Guo, X., Zuo, Y., & Li, D. (2025). When auditing Meets Blockchain: A study on applying blockchain smart contracts in auditing. *International Journal of Accounting Information Systems*, *56*, 100730.
48. Habib, G., Sharma, S., Ibrahim, S., Ahmad, I., Qureshi, S., & Ishfaq, M. (2022). Blockchain technology: Benefits, challenges, applications, and integration of blockchain technology with cloud computing. *Future Internet*, *14*(11), 341.
49. Hader, M., Tchoffa, D., El Mhamedi, A., Ghodous, P., Dolgui, A., & Abouabdellah, A. (2022). Applying integrated Blockchain and Big Data technologies to improve supply chain traceability and information sharing in the textile sector. *Journal of Industrial Information Integration*, *28*, 100345.
50. Hamdi, I., & Toumi, S. (2025). An ISM-MICMAC approach for analyzing the relationship between blockchain adoption criteria in a pharmaceutical supply chain: Tunisian case. *Journal of Modelling in Management*, *20*(2), 495–516.
51. Harinath, D., Bandi, M., Patil, A., Murthy, M. R., & Raju, A. V. S. (2024). Enhanced Data Security and Privacy in IoT devices using Blockchain Technology and Quantum Cryptography. *Journal of Systems Engineering and Electronics (ISSN NO: 1671-1793)*, *34*(6). https://www.researchgate.net/profile/Madhu-Bandi-4/publication/387495645_Enhanced_Data_Security_and_Privacy_in_IoT_devices_using_Blockchain_Technology_and_Quantum_Cryptography/links/67706b68c1b0135465fec8dd/Enhanced-Data-Security-and-Privacy-in-IoT-devices-using-Blockchain-Technology-and-Quantum-Cryptography.pdf
52. Helo, P., & Hao, Y. (2019). Blockchains in operations and supply chains: A model and reference implementation. *Computers & Industrial Engineering*, *136*, 242–251. https://doi.org/10.1016/j.cie.2019.07.023
53. Helo, P., & Shamsuzzoha, A. H. M. (2020). Real-time supply chain—A blockchain architecture for project deliveries. *Robotics and Computer-Integrated Manufacturing*, *63*, 101909.

54. Hong, J., Quan, Y., Tong, X., & Lau, K. H. (2024). A hybrid ISM and fuzzy MICMAC approach to modeling risk analysis of imported fresh food supply chain. *Journal of Business & Industrial Marketing*, *39*(2), 124–141.
55. Hsu, C.-W., Kuo, T.-C., Chen, S.-H., & Hu, A. H. (2013). Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production*, *56*, 164–172.
56. Hu, X., Xie, J., Yan, A., Chen, Z., Li, Y., Zhai, P., & Davarpanah, A. (2025). Evaluating the potential of depleted gas reservoirs for carbon storage: A comprehensive fuzzy DEMATEL assessment of influential factors. *Fuel*, *393*, 134986.
57. Huang, B., Dai, J., & Lim, J. J. (2024). Blockchain technology as a driver for sustainability? A consumer purchase intention perspective. *International Journal of Operations & Production Management*, *ahead-of-print*(ahead-of-print). (world). https://doi.org/10.1108/IJOPM-04-2024-0340
58. Hussain, I., Shah, M., Thakur, B., & Gupta, D. (2025). Tea Trade Dynamics: Assessing India's Competitiveness in the Global Scenario using analytical tools RCA and SRCA. *South Eastern European Journal of Public Health*, *XXVI*, 506–515. https://doi.org/10.70135/seejph.vi.3598
59. Jassbi, J., Mohamadnejad, F., & Nasrollahzadeh, H. (2011). A Fuzzy DEMATEL framework for modeling cause and effect relationships of strategy map. *Expert Systems with Applications*, *38*(5), 5967–5973.
60. Jayant, A., & Azhar, M. (2014). Analysis of the barriers for implementing green supply chain management (GSCM) practices: An interpretive structural modeling (ISM) approach. *Procedia Engineering*, *97*, 2157–2166.
61. Kalajdjieski, J., Raikwar, M., Arsov, N., Velinov, G., & Gligoroski, D. (2023). Databases fit for blockchain technology: A complete overview. *Blockchain: Research and Applications*, *4*(1), 100116.
62. Khan, M. A., & Salah, K. (2018). IoT security: Review, blockchain solutions, and open challenges. *Future Generation Computer Systems*, *82*, 395–411. https://doi.org/10.1016/j.future.2017.11.022
63. Khan, S. A. R., Sheikh, A. A., Hassan, N. M., & Yu, Z. (2024). Modeling the intricate association between sustainable service quality and supply chain performance: Moderating role of blockchain technology and environmental uncertainty. *Sustainability*, *16*(11), 4808.
64. Khan, U., & Haleem, A. (2015). Improving to smart organization: An integrated ISM and fuzzy-MICMAC modelling of barriers. *Journal of Manufacturing Technology Management*, *26*(6), 807–829.
65. Kim, H. M., & Laskowski, M. (2018). Toward an ontology-driven blockchain design for supply-chain provenance. *Intelligent Systems in Accounting, Finance and Management*, *25*(1), 18–27. https://doi.org/10.1002/isaf.1424
66. Kim, S.-K., & Huh, J.-H. (2020). Blockchain of carbon trading for UN sustainable development goals. *Sustainability*, *12*(10), 4021.
67. Konstantopoulou, Z., & Mikalef, P. (2024). Enhancing Traceability in the Norwegian Fish Supply Chain: Blockchain Adoption. In R. van de Wetering, R. Helms, B. Roelens, S. Bagheri, Y. K. Dwivedi, I. O. Pappas, & M. Mäntymäki (Eds.), *Disruptive Innovation in a Digitally Connected Healthy World* (pp. 383–393). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-72234-9_32
68. Kshetri, N. (2021). Blockchain and sustainable supply chain management in developing countries. *International Journal of Information Management*, *60*, 102376. https://doi.org/10.1016/j.ijinfomgt.2021.102376
69. Kumar, A., & Dixit, G. (2018). An analysis of barriers affecting the implementation of e-waste management practices in India: A novel ISM-DEMATEL approach. *Sustainable Production and Consumption*, *14*, 36–52.
70. Kumar, P., Bhamu, J., & Sangwan, K. S. (2021). Analysis of barriers to Industry 4.0 adoption in manufacturing organizations: An ISM approach. *Procedia Cirp*, *98*, 85–90.
71. Kumar Sharma, S., & Bhat, A. (2014). Modelling supply chain agility enablers using ISM. *Journal of Modelling in Management*, *9*(2), 200–214.
72. Li, J., Wang, Z., Guan, S., & Cao, Y. (2024). ProChain: A privacy-preserving blockchain-based supply chain traceability system model. *Computers & Industrial Engineering*, *187*, 109831.
73. Liu, K., Liu, P., & Gao, S. (2024). Research on the Trusted Traceability Model of Taishan Tea Products Based on Blockchain. *Applied Sciences*, *14*(22), 10630. https://doi.org/10.3390/app142210630
74. Liu, X., Barenji, A. V., Li, Z., Montreuil, B., & Huang, G. Q. (2021). Blockchain-based smart tracking and tracing platform for drug supply chain. *Computers & Industrial Engineering*, *161*, 107669.
75. Liu, Y., Lu, Q., Yu, G., Paik, H.-Y., & Zhu, L. (2022). Defining blockchain governance principles: A comprehensive framework. *Information Systems*, *109*, 102090. https://doi.org/10.1016/j.is.2022.102090
76. Liu, Z., & Li, Z. (2020). A blockchain-based framework of cross-border e-commerce supply chain. *International Journal of Information Management*, *52*, 102059. https://doi.org/10.1016/j.ijinfomgt.2019.102059
77. Majumdar, P., & Mitra, S. (2024). Blockchain technology for society 4.0: A comprehensive review of key applications, requirement analysis, research trends, challenges and future avenues. *Cluster Computing*, 1–23.
78. Mangla, S. K., Kazançoğlu, Y., Yıldızbaşı, A., Öztürk, C., & Çalık, A. (2022). A conceptual framework for blockchain-based sustainable supply chain and evaluating implementation barriers: A case of the tea supply chain. *Business Strategy and the Environment*, *31*(8), 3693–3716. https://doi.org/10.1002/bse.3027
79. Mijwil, M. M., Aljanabi, M., Abotaleb, M., Shukur, B. S., Al Sailawi, A. S. A., Bala, I., Hiran, K. K., Doshi, R., & Dhoska, K. (2025). Exploring the Impact of Blockchain Revolution on the Healthcare Ecosystem: A Critical Review. *Mesopotamian Journal of Cybersecurity*, *5*(1), 78–89.
80. Min, H. (2019). Blockchain technology for enhancing supply chain resilience. *Business Horizons*, *62*(1), 35–45.
81. Mohanta, B. K., Panda, S. S., & Jena, D. (2018). An Overview of Smart Contract and Use Cases in Blockchain Technology. *2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, 1–4. https://doi.org/10.1109/ICCCNT.2018.8494045
82. Movahedipour, M., Zeng, J., Yang, M., & Wu, X. (2017). An ISM approach for the barrier analysis in implementing sustainable supply chain management: An empirical study. *Management Decision*, *55*(8), 1824–1850.
83. Nazir, H., & Fan, J. (2024). Revolutionizing retail: Examining the influence of blockchain-enabled IoT capabilities on sustainable firm performance. *Sustainability*, *16*(9), 3534.

84. Nirmal, D. D., Nageswara Reddy, K., Sohal, A. S., & Kumari, M. (2023). Development of a framework for adopting Industry 4.0 integrated sustainable supply chain practices: ISM–MICMAC approach. *Annals of Operations Research*, 1–69.
85. Nirmal, D. D., Nageswara Reddy, K., Sohal, A. S., & Kumari, M. (2025). Development of a framework for adopting Industry 4.0 integrated sustainable supply chain practices: ISM–MICMAC approach. *Annals of Operations Research*, *348*(3), 1387–1455.
86. Nygaard, A. (2024). Authenticity, Blockchain Technology and Green Marketing. In A. Nygaard (Ed.), *Green Marketing and Entrepreneurship* (pp. 155–165). Springer International Publishing. https://doi.org/10.1007/978-3-031-50333-7_9
87. Omar, I. A., Jayaraman, R., Salah, K., Simsekler, M. C. E., Yaqoob, I., & Ellahham, S. (2020). Ensuring protocol compliance and data transparency in clinical trials using Blockchain smart contracts. *BMC Medical Research Methodology*, *20*(1), 224. https://doi.org/10.1186/s12874-020-01109-5
88. Omidian, H. (2024). Synergizing blockchain and artificial intelligence to enhance healthcare. *Drug Discovery Today*, 104111.
89. Onu, P., Mbohwa, C., & Pradhan, A. (2024). Blockchain-Powered Traceability Solutions: Pioneering Transparency to Eradicate Counterfeit Products and Revolutionize Supply Chain Integrity. *Procedia Computer Science*, *232*, 1420–1427.
90. Oriekhoe, O. I., Oyeyemi, O. P., Bello, B. G., Omotoye, G. B., Daraojimba, A. I., & Adefemi, A. (2024). Blockchain in supply chain management: A review of efficiency, transparency, and innovation. *International Journal of Science and Research Archive*, *11*(1), 173–181.
91. Öztürk, C. (2025). Digitalization as a catalyst for social sustainability in supply chains: An ISM-fuzzy MICMAC and DEMATEL approach. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-025-06011-y
92. Pandey, V., Pant, M., & Snasel, V. (2022). Blockchain technology in food supply chains: Review and bibliometric analysis. *Technology in Society*, *69*, 101954.
93. 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. https://doi.org/10.1002/bse.2882
94. Parven, A., Meftaul, I. M., Venkateswarlu, K., & Megharaj, M. (2025). Herbicides in modern sustainable agriculture: Environmental fate, ecological implications, and human health concerns. *International Journal of Environmental Science and Technology*, *22*(2), 1181–1202. https://doi.org/10.1007/s13762-024-05818-y
95. Paul, T., Islam, N., Mondal, S., & Rakshit, S. (2022). RFID-integrated blockchain-driven circular supply chain management: A system architecture for B2B tea industry. *Industrial Marketing Management*, *101*, 238–257.
96. Paul, T., Mondal, S., Islam, N., & Rakshit, S. (2021). The impact of blockchain technology on the tea supply chain and its sustainable performance. *Technological Forecasting and Social Change*, *173*, 121163. https://doi.org/10.1016/j.techfore.2021.121163
97. Payandeh, R., Delbari, A., Fardad, F., Helmzadeh, J., Shafiee, S., & Ghatari, A. R. (2025). Unraveling the potential of blockchain technology in enhancing supply chain traceability: A systematic literature review and modeling with ISM. *Blockchain: Research and Applications*, *6*(1), 100240.
98. Pincheira, M., Vechio, M., & Giaffreda, R. (2023). Exploiting Cost-Effective IoT Devices for Trustless Agri-Food Supply Chain Management: A Practical Case Study. In A. Bouras, I. Khalil, & B. Aouni (Eds.), *Blockchain Driven Supply Chains and Enterprise Information Systems* (pp. 113–134). Springer International Publishing. https://doi.org/10.1007/978-3-030-96154-1_6
99. Pinto Varela Alberte, E., & de Oliveira Novelli, G. (2024). Potential use of blockchain technology in construction supply chain management of Brazil. *Construction Innovation*. https://www.emerald.com/insight/content/doi/10.1108/CI-08-2022-0208/full/html
100. Priyadarshi, A. (2024). Trustea India Sustainable Tea Code and Democratizing Agricultural Standards. In W. Leal Filho, T. F. Ng, U. Iyer-Raniga, A. Ng, & A. Sharifi (Eds.), *SDGs in the Asia and Pacific Region* (pp. 839–865). Springer International Publishing. https://doi.org/10.1007/978-3-031-17463-6_73
101. Quezada, L. E., López-Ospina, H. A., Palominos, P. I., & Oddershede, A. M. (2018). Identifying causal relationships in strategy maps using ANP and DEMATEL. *Computers & Industrial Engineering*, *118*, 170–179.
102. Rajput, S. (2024). Analysis of Industry 4.0 technological enablers for sustainable supply chain transparency in a fuzzy environment. *Business Strategy and the Environment*, *33*(8), 8616–8636. https://doi.org/10.1002/bse.3936
103. Raman, R., Sreenivasan, A., Ma, S., Patwardhan, A., & Nedungadi, P. (2023). Green supply chain management research trends and linkages to UN sustainable development goals. *Sustainability*, *15*(22), 15848.
104. Rana, M. T., Numan, M., Yousif, M., Hussain, T., Khan, A. Z., & Zhao, X. (2024). Enhancing sustainability in electric mobility: Exploring blockchain applications for secure EV charging and energy management. *Computers and Electrical Engineering*, *119*, 109503.
105. Rana, N. P., Barnard, D. J., Baabdullah, A. M., Rees, D., & Roderick, S. (2019). Exploring barriers of m-commerce adoption in SMEs in the UK: Developing a framework using ISM. *International Journal of Information Management*, *44*, 141–153.
106. Rani, P., Sachan, R. K., & Kukreja, S. (2024). A systematic study on blockchain technology in education: Initiatives, products, applications, benefits, challenges and research direction. *Computing*, *106*(2), 405–447. https://doi.org/10.1007/s00607-023-01228-z
107. Rani, P., Sachan, R. K., & Kukreja, S. (2025). BT-CNV: A distributed and decentralized solution for certificate notarization and verification for academia using public blockchain. *Peer-to-Peer Networking and Applications*, *18*(1), 1–26.

108. Rathnayake, B., Gunathilake, L., Edirisinghe, R., & Perera, S. (2025). EcoConstruct: A blockchain-based system for carbon trading in construction projects. *Construction Innovation*, *25*(7), 213–234. https://doi.org/10.1108/CI-08-2024-0224
109. Rejeb, A., Keogh, J. G., & Treiblmaier, H. (2019). Leveraging the internet of things and blockchain technology in supply chain management. *Future Internet*, *11*(7), 161.
110. Reyna, A., Martín, C., Chen, J., Soler, E., & Díaz, M. (2018). On blockchain and its integration with IoT. Challenges and opportunities. *Future Generation Computer Systems*, *88*, 173–190.
111. Ronoh, H. K., Omieno, K., & Odawa, J. (2025). The Capabilities of Blockchain Technology in Enhancing Supply Chain Management in the Tea Sector in Kenya. *Journal of Research and Academic Writing*, *2*(1), 24–35. https://doi.org/10.58721/jraw.v2i1.1068
112. Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, *57*(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261
113. Sage, A. P. (1977). *Methodology for large-scale systems.* https://www.sidalc.net/search/Record/dig-minciencias-co-20.500.14143-47508/Description
114. Saleh, A. M. S. (2024). Blockchain for secure and decentralized artificial intelligence in cybersecurity: A comprehensive review. *Blockchain: Research and Applications*, 100193.
115. Sancaktar, Ç., & Sayar, A. (2025). Development of a Distributed and Immutable Archive System with Blockchain Technology. In Z. Illés, C. Verma, P. J. S. Gonçalves, & Y. Singh (Eds.), *Proceedings of International Conference on Recent Innovations in Computing* (Vol. 1421, pp. 579–591). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-6034-6_39
116. Shanker, S., & Barve, A. (2021). Analysing sustainable concerns in diamond supply chain: A fuzzy ISM-MICMAC and DEMATEL approach. *International Journal of Sustainable Engineering*. (world). https://www.tandfonline.com/doi/abs/10.1080/19397038.2020.1862351
117. Shoaib, M., Zhang, S., & Ali, H. (2023). Assessment of sustainable green logistics enablers: A robust framework using fuzzy DEMATEL and ISM approach. *International Journal of Environmental Science and Technology*, *20*(10), 11407–11426. https://doi.org/10.1007/s13762-022-04709-4
118. Shrimali, B., & Patel, H. B. (2022). Blockchain state-of-the-art: Architecture, use cases, consensus, challenges and opportunities. *Journal of King Saud University-Computer and Information Sciences*, *34*(9), 6793–6807.
119. Si, S.-L., You, X.-Y., Liu, H.-C., & Zhang, P. (2018). DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. *Mathematical Problems in Engineering*, *2018*, 1–33. https://doi.org/10.1155/2018/3696457
120. Sianaki, O. A., & Peiris, S. (2022). The Impact of the Blockchain Technology on the Smart Grid Customer Domain: Toward the Achievement of the Sustainable Development Goals (SDGs) of the United Nations. In L. Barolli, F. Hussain, & T. Enokido (Eds.), *Advanced Information Networking and Applications* (Vol. 451, pp. 515–530). Springer International Publishing. https://doi.org/10.1007/978-3-030-99619-2_49
121. Singh, A. K., Kumar, V. P., Irfan, M., Mohandes, S. R., & Awan, U. (2023). Revealing the barriers of blockchain technology for supply chain transparency and sustainability in the construction industry: An application of pythagorean FAHP methods. *Sustainability*, *15*(13), 10681.
122. Sunny, J., Undralla, N., & Madhusudanan Pillai, V. (2020). Supply chain transparency through blockchain-based traceability: An overview with demonstration. *Computers & Industrial Engineering*, *150*, 106895. https://doi.org/10.1016/j.cie.2020.106895
123. Surucu-Balci, E., Iris, Ç., & Balci, G. (2024). Digital information in maritime supply chains with blockchain and cloud platforms: Supply chain capabilities, barriers, and research opportunities. *Technological Forecasting and Social Change*, *198*, 122978.
124. Tayal, A., Solanki, A., Kondal, R., Nayyar, A., Tanwar, S., & Kumar, N. (2021). Blockchain-based efficient communication for food supply chain industry: Transparency and traceability analysis for sustainable business. *International Journal of Communication Systems*, *34*(4), e4696. https://doi.org/10.1002/dac.4696
125. Thakur, A., Ranga, V., & Agarwal, R. (2025). Exploring the Transformative Impact of Blockchain Technology on Healthcare: Security, Challenges, Benefits, and Future Outlook. *Transactions on Emerging Telecommunications Technologies*, *36*(3), e70087. https://doi.org/10.1002/ett.70087
126. Thanasi-Boçe, M., & Hoxha, J. (2025). Blockchain for Sustainable Development: A Systematic Review. *Sustainability*, *17*(11), 4848.
127. Vaishnavi, V., Suresh, M., & Dutta, P. (2019). A study on the influence of factors associated with organizational readiness for change in healthcare organizations using TISM. *Benchmarking: An International Journal*, *26*(4), 1290–1313. https://doi.org/10.1108/BIJ-06-2018-0161
128. Vishwakarma, A., Dangayach, G. S., Meena, M. L., & Gupta, S. (2022). Analysing barriers of sustainable supply chain in apparel & textile sector: A hybrid ISM-MICMAC and DEMATEL approach. *Cleaner Logistics and Supply Chain*, *5*, 100073.
129. Wahab, A., Wang, J., Shojaei, A., & Ma, J. (2023). A model-based smart contracts system via blockchain technology to reduce delays and conflicts in construction management processes. *Engineering, Construction and Architectural Management*, *30*(10), 5052–5072.
130. Wan, Z. (2025). Chapter 20 - Preserving privacy in blockchains: Challenges, solutions, and future directions. In D. L. K. Chuen & R. H. Deng (Eds.), *Handbook of Blockchain, Digital Finance, and Inclusion, Volume 3* (pp. 291–305). Academic Press. https://doi.org/10.1016/B978-0-443-34717-7.00002-7
131. Wang, L., Zhang, J., Li, J., Yu, H., & Li, J. (2024). An ISM-DEMATEL analysis of blockchain adoption decision in the circular supply chain finance context. *Management Decision*, *62*(9), 2814–2835.

132. Wang, W., Chen, Y., Wang, Y., Deveci, M., Cheng, S., & Brito-Parada, P. R. (2024). A decision support framework for humanitarian supply chain management–Analysing enablers of AI-HI integration using a complex spherical fuzzy DEMATEL-MARCOS method. *Technological Forecasting and Social Change*, *206*, 123556.
133. Warfield, J. N. (1974). Developing interconnection matrices in structural modeling. *IEEE Transactions on Systems, Man, and Cybernetics*, (1), 81–87.
134. Wu, J., & Tran, N. K. (2018). Application of blockchain technology in sustainable energy systems: An overview. *Sustainability*, *10*(9), 3067.
135. Wu, W.-W. (2008). Choosing knowledge management strategies by using a combined ANP and DEMATEL approach. *Expert Systems with Applications*, *35*(3), 828–835.
136. Xu, X., Bao, X., Yi, H., Wu, J., & Han, J. (2023). A Novel Resource-Saving and Traceable Tea Production and Supply Chain Based on Blockchain and IoT. *IEEE Access*, *11*, 71873–71889. https://doi.org/10.1109/access.2023.3295210
137. Yontar, E. (2023). The role of blockchain technology in the sustainability of supply chain management: Grey based dematel implementation. *Cleaner Logistics and Supply Chain*, *8*, 100113.
138. Younis, H., Bwaliez, O. M., Al-Okaily, M., & Tanveer, M. I. (2024). Revolutionizing supply chain management: A critical meta-analysis of empowerment and constraint factors in blockchain technology adoption. *Business Process Management Journal*, *30*(5), 1472–1500.
139. Yousefi, S., & Tosarkani, B. M. (2022). An analytical approach for evaluating the impact of blockchain technology on sustainable supply chain performance. *International Journal of Production Economics*, *246*, 108429.
140. Zaabar, B., Cheikhrouhou, O., Jamil, F., Ammi, M., & Abid, M. (2021). HealthBlock: A secure blockchain-based healthcare data management system. *Computer Networks, 200*, 108500.
141. Zhang, F., & Song, W. (2022). Sustainability risk assessment of blockchain adoption in sustainable supply chain: An integrated method. *Computers & Industrial Engineering*, *171*, 108378.
142. Zhang, X., Sheng, Y., & Liu, Z. (2024). Using expertise as an intermediary: Unleashing the power of blockchain technology to drive future sustainable management using hidden champions. *Heliyon*, *10*(1). https://www.cell.com/heliyon/fulltext/S2405-8440(23)11015-2
143. Zhang, Z., Qu, T., Zhao, K., Zhang, K., Zhang, Y., Guo, W., Liu, L., & Chen, Z. (2024). Enhancing trusted synchronization in open production logistics: A platform framework integrating blockchain and digital twin under social manufacturing. *Advanced Engineering Informatics*, *61*, 102404.
144. Zuo, L., & Ren, Y. (2025). How renewable energy consumption and digitalization contribute to environmental sustainability: Evidence from One Belt One Road countries. *Journal of Environmental Management*, *380*, 124379.