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# Blockchain-driven ESG governance in innovating global supply networks: An integrated PCA–fuzzy DEMATEL approach

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## ABSTRACT

This study develops an integrated decision-support framework for blockchain-enabled Environmental, Social, and Governance (ESG) compliance in global supply networks. Multinational enterprises face complex sustainability challenges due to fragmented supplier systems, inconsistent standards, and limited traceability. Blockchain technology offers transparency, immutability, and decentralized validation, addressing critical barriers to ESG integration. Using a three-phase empirical design, the research employs the Fuzzy Delphi Method to validate 26 critical success factors (CSFs), Principal Component Analysis (PCA) to identify 12 underlying dimensions, and Fuzzy DEMATEL to model influential interrelationships among them. Results reveal that knowledge capital, ESG awareness, sustainable operations, and Resource Efficiency & Performance Optimization are key influential factors driving blockchain-enabled ESG performance, while Organizational Learning & ESG Governance, traceability, and stakeholder accountability are key dependent outcomes. These drivers also have substantial financial implications for multinational enterprises. The information asymmetry is addressed by improvements in transparency and traceability of ESG, which enhance investor confidence, increase the availability of sustainable finance instruments, and potentially lower the cost of capital and ESG-related risk premiums. The framework, based on this, provides insight into the role of blockchain-enabled ESG governance: not only it ensures that a firm meets its sustainability standards, but it also generates long-term firm value. The study contributes to theory by integrating multivariate and influential modeling to explain the systemic dynamics of technology-driven sustainability governance. Managerially, it provides actionable insights to prioritize blockchain investments and enhance ESG transparency across global supply networks.

## 1. Introduction

Besides operational transparency, ESG governance facilitated by blockchain has direct consequences for firm-level financial performance (Abdelwahed et al., 2025). Stronger traceability and more robust ESG reporting will reduce information asymmetry between

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firms and investors, lowering the cost of capital, increasing access to credit, and boosting firm valuation. Blockchain-authenticated ESG compliance prevents regulatory fines, reputational loss, and supply-disruption costs, and at the same time enhances investor confidence and access to sustainable finance products such as green bonds and ESG-linked loans. Therefore, it is essential to explain the influential forces of blockchain-based ESG governance not only to attain compliance with the sustainability compliances but also to create long-term financial value.

Multinational companies must contend with challenges associated with compliance with global supply chain standards and ESG requirements. Supply chains span multiple geographic boundaries and thousands of suppliers, making it difficult to track sustainability activities. The globalization of trade has compounded supply chain risks (Tamayo-Torres et al., 2019), as evidenced by the Volkswagen emissions case and labor rights violations in developing countries. Yang et al. (2024) found that the peer network strongly influences ESG performance. Compliance with regulatory requirements is difficult to monitor because reporting frameworks lack standardization, and real-time monitoring. Also, Nasrollahi et al. (2021) discussed that environmental drivers necessary for monitoring processes are complex and require more sophisticated monitoring mechanisms. Regulatory fines, brand damage, and consumer boycotts linked to non-observance of ESG standards are risky and difficult to control using traditional means. Besides compliance issues, ESG governance has begun to influence firm-level financial performance. ESG risk is now included in valuation models and credit evaluations by institutional investors, lenders, and credit rating agencies. The verification of ESG data using blockchain can reduce uncertainty around sustainability disclosures, minimize perceived risk, increase access to green finance instruments, including sustainability-linked loans, and improve firm valuation. Munir et al. (2022) also noted that the issue of supply chain sustainability can be addressed through blockchain, which provides greater clarity and automates compliance testing via smart contracts. This technology enables real-time tracking and validation of ESG metrics, ensuring that sustainability reports do not contain data integrity issues. In calculating carbon footprints, Shekarian et al. (2022) observed that blockchain and IoT devices can be used together to monitor the environmental impact of products throughout product lifecycle. ESG compliance regulations can be implemented automatically using smart contracts on the blockchain, eliminating the manual auditing process and enabling active sustainability management. Nonetheless, successful blockchain deployment can be evaluated in terms of energy consumption, scalability, and system integration, as Mbanye and Muchenje (2025) suggested.

The multi-stakeholder approach to ESG compliance does not rely on hierarchical supply chain governance but rather on a collaborative one, in which all the interests of the multiple members of the network are considered. In this approach, the collaboration of manufacturers, suppliers, customers, regulators, civil society organizations, and even communities, which can provide alternative insights into sustainability challenges, can be considered (Gurawska, 2020). Based on the findings of Siems et al. (2023), effective stakeholder engagement must be anchored on strategic partnerships that considers economic, environmental, and social objectives across networks. The theoretical background is grounded in stakeholder theory and relational perspectives, in which the success of stakeholder networks is defined by the quality of the relationships rather than economic indicators. Soundararajan et al. (2019) showed the advantages of multi-stakeholder efforts to improve supply chain governance through deliberative capacity enhancement. The synergies arising from integrating blockchain technology include building trust among stakeholders, joint decision-making, and monitoring. Chae et al. (2025) demonstrated the benefits of dispersed supplier networks by leveraging local knowledge to address region-specific ESG risks.

This study develops and validates a multi-stakeholder model of pivotal success factors for implementing blockchain-enabled ESG compliance in global supply chains. Fuzzy-Delphi method is used to confirm the identified critical success factors. Then, principal component analysis is used to group the identified CSFs into coherent dimensions, and fuzzy-DEMATEL is used to indicate causation between the dimensions. This study focuses on developing theoretical contributions to management research on technology-driven sustainability and providing recommendations to supply chain practitioners. It will also provide an effective decision-support system by integrating quantitative grouping and influential modeling. Compared to other studies that focus solely on the adoption of blockchain or ESG compliance, this study would make a contribution to the field of financial economics by uncovering the determinants of causal governance that affect value creation at the firm level. The presented framework provides a systematic framework for assessing the effects of digital sustainability governance on financing costs, risk exposure, and investor perceptions among multinational companies. Therefore, the research objectives are mentioned as follows:

RO1: To identify critical success factors (CSF) and extract underlying factor groups that represent key dimensions of blockchain-enabled ESG compliance.

RO2: To determine the cause-and-effect relationships among the extracted CSF dimensions and establish a directional influence map.

RO3: To develop actionable recommendations and a decision-support framework for managers to prioritize blockchain investments and stakeholder initiatives based on the causal influence of the CSFs dimensions.

This study is relevant to management research because it used quantitative analysis to examine multifaceted, technology-related sustainability problems. It bridges the gap between the descriptive identification of CSFs and prescriptive decision-making by uncovering dependencies among relevant factors. The combined methods of PCA, Delphi and DEMATEL, were used to assess supply chain governance from a stakeholder perspective and to provide an example for developing a model that can be applied in other domains as well. In practice, it provides executives with a prioritized blueprint for using blockchain to enhance strategic investment and ESG goals, and to develop robust, transparent supply chains.

## 2. Theoretical background

This section consists of ESG compliances in global supply chain networks, blockchain technology in supply chain, collaborative ESG governance and research gaps.

### 2.1. ESG compliance in global supply networks

ESG compliance in global supply chains is the convergence of environmental stewardship, social responsibility, and governance excellence, which has dramatically transformed how organizations manage supply chains in the contemporary business environment (Truant et al., 2023; Singh et al., 2024). As stated by (Kocmanová and Šimberová, 2014; Tamayo-Torres et al., 2019), the concept of ESG compliance includes three interdependent considerations; environmental aspects, including carbon emissions, resource consumption, waste management, and biodiversity protection; social aspects, including labor rights, human rights, community impact, and diversity initiatives; and governance aspects, including corporate ethics, transparency, accountability, and stakeholder engagement. Compliance is not the only feature of ESG implementation, as active sustainability policies can generate long-term value for all parties without causing negative externalities associated with operations in the global supply chain (Gündoğdu et al., 2023). Current trends in global supply chains reveal a significant gap in the maturity of ESG implementation; even among organizations that have adopted comprehensive sustainability paradigm. Usually, organizations have lower compliance rates due to resource constraints, insufficient knowledge, or the inability to achieve seamless collaboration among stakeholders (Mooneeapen et al., 2022; Ahmad et al., 2024).

Yang et al. (2024) demonstrates that the impact of conformity on ESG performance diffuses throughout the entire supply chain and has a positive impact on the suppliers. Lokuwaduge and De Silva (2020) mentioned that the regulatory environment concerning ESG compliance is changing rapidly, and jurisdictions, including the European Union, the United Kingdom, and Asian markets, are implementing stricter disclosure policies. The pressure on the supply chain stakeholders has been very sharp, with investors, customers, employees, and civil society organizations setting expectations for their companies to pursue full ESG integration rather than merely superficial sustainability work, creating both opportunities and pressures for supply chain transformation (Whitelock, 2019).

### 2.2. Blockchain technology in supply chain

The characteristics and structure of blockchain technology can facilitate effective supply chain management practices by leveraging a distributed ledger system for secure, transparent, and immutable logging of transactions across complex networked systems (Sindiramutty et al., 2024). Blockchain technology is a chain of blocks containing transaction data, where each block is connected to previous one in a cryptographic manner (Bashar et al., 2022). Existing applications of blockchain technology in supply chain management span every industry, such as food safety traceability, pharmaceutical authentication, luxury goods verification, and sustainable sourcing verification (Saber et al., 2018). Also, Shekarian et al. (2022) used the example of Industrial Internet of Things devices with blockchain to record environmental metrics, showing how blockchain would enable tracking all environmental parameters to measure sustainability throughout the product lifecycle and to calculate carbon footprints.

Mugurusi and Ahishakiye (2022) proposed that the advantages of blockchain for ESG compliance include increased transparency through verifiable audit trails. However, Karakas et al. (2021) discussed the drawbacks of blockchain adoption, including significant energy consumption challenges, particularly with the proof-of-work consensus mechanism; scalability issues due to high-volume supply chain transactions; integration challenges with existing enterprise resource planning systems; and regulatory risks. According to Munir et al. (2022), when implementing blockchain, one should adopt an economic, environmental, and social lens to ensure meeting sustainability compliances. While Soori et al. (2024) highlighted the need of energy-efficient consensus mechanisms and layer-two scaling solutions that help in addressing traditional blockchain limitations. It results in making technology more feasible for large-scale blockchain applications in supply chains, aiming to achieve ESG compliance and sustainability.

### 2.3. Collaborative ESG governance

Multi-stakeholder theory in the management context provides a conceptual perspective on how organizations can effectively engage various stakeholder groups within collaborative governance systems (Siems et al., 2023; Aaltonen et al., 2024). The theoretical framework relies on stakeholder theory, which assumes that the success of organizations is predetermined by the management of relationships with all stakeholders that may influence or be influenced by organizational activities (Gurzawska, 2020). Also, Macdonald et al. (2018) stated that the multistakeholder strategies recognize that current sustainability issues are complex and multi-dimensional, requiring diverse expertise, resources, and perspectives that cannot be found within a single organization. Hence, collaborative governance is not only beneficial but also necessary to address global ESG compliance crises in the supply chains. The relationship between stakeholders in sustainable supply chain management is not merely an ordinary economic relationship, as presented by Siems et al. (2023), but one that involves knowledge sharing, risk identification, and catalyzes innovation.

Pandey et al. (2024) outlined a list of 21 essential success factors for technical capabilities, organizational readiness, and stakeholder involvement for supply chain resilience and sustainability. Shardeo et al. (2020) and Mishra et al. (2023) discussed the use of CSFs during the adoption of blockchain by identifying and prioritizing challenges, which can influence the success of technology adoption, such as the needs of the technical infrastructure, change management requirements of the organization, the ways of engaging stakeholders, and the performance review mechanisms. Yadav and Singh (2020) used factor analysis and fuzzy

decision-making models to identify and rank CSFs for adopting blockchain technology in sustainable supply chains, providing viable models for organizations that intend to use blockchain-powered ESG-compliance systems. Collectively, Çaldağ & Gökalg (2020) stated that multi-stakeholder approaches with CSF can create successful models that incorporate various stakeholder perceptions in blockchain execution plans and ESG compliance projects. All identified CSFs are explained and summarized in Table 1, in line with the existing empirical and conceptual literature. Financially, blockchain-based ESG governance may be seen as a signaling and information-checking system that lowers uncertainty about sustainability reporting. Investors value ESG performance as they assess perceived risk and, more importantly, the believability of reporting, and predict the likelihood of future regulatory or reputational shocks. The critical success factors, such as ethical data management, automated compliance systems, and traceability, can improve the reliability of disclosed information and, in turn, reduce information asymmetry between companies and shareholders. As a result, the blockchain-supported ESG performance impacts risk premiums, valuation, and investor confidence in international capital markets.

**Table 1**  
Identified CSFs.

| CSF                              | Reference                                                                      | Description                                                                                                                 |
|----------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| <b>System Robustness</b>         | Yadav and Singh (2020); Zhang et al. (2022); Pandey et al. (2024)              | Ensures technical reliability and resilience of blockchain systems to support sustainable and uninterrupted ESG operations. |
| <b>Data Transparency</b>         | Venkatesh et al. (2020); Elhidaoui et al. (2022); Kayikci et al. (2022)        | Promotes open visibility and traceability of ESG information for credible sustainability reporting.                         |
| <b>Trust &amp; Reliability</b>   | Liu et al. (2018); Kouhizadeh et al. (2020); Chaudhuri et al. (2023)           | Builds stakeholder confidence through immutable records and verified ESG data authenticity.                                 |
| <b>Smart Contracts</b>           | Christidis and Devetsikiotis (2016); Munir et al. (2022); Najjar et al. (2023) | Automates ESG compliance enforcement and performance validation without human bias.                                         |
| <b>Traceability</b>              | Hastig and Sodhi (2020); Kshetri (2021); Rejeb et al. (2021)                   | Enables end-to-end product and process tracking for verifiable environmental and social accountability.                     |
| <b>Cost Optimization</b>         | Singh et al. (2024); Mishra et al. (2023)                                      | Balances blockchain investment and operational efficiency to enhance economic and environmental sustainability.             |
| <b>Stakeholder Engagement</b>    | Gurzawska (2020); Siems et al. (2023); Soundararajan et al. (2019)             | Encourages inclusive participation of all supply chain actors in shared ESG governance.                                     |
| <b>Regulatory Compliance</b>     | Tamayo-Torres et al. (2019); Nasrollahi et al. (2021); Shen et al. (2025)      | Aligns blockchain operations with global ESG standards and jurisdictional sustainability mandates.                          |
| <b>Data Quality</b>              | Huang et al. (2022); Yontar (2023); Al Amin et al. (2025)                      | Ensures integrity, accuracy, and reliability of ESG data for transparent blockchain reporting.                              |
| <b>Interoperability</b>          | Vern et al. (2025); Shekarian et al. (2022)                                    | Integrates diverse blockchain and enterprise systems to streamline ESG information exchange.                                |
| <b>Scalability</b>               | Mbanye and Muchenje (2025); Bhatt and Emdad (2025); Zhu et al. (2025)          | Supports expansion of blockchain-enabled ESG systems without compromising performance or efficiency.                        |
| <b>Privacy Protection</b>        | Mugurusi and Ahishakiye (2022)                                                 | Safeguards sensitive data while maintaining transparency for ESG verification and audits.                                   |
| <b>Tokenization</b>              | Dutta et al. (2020); Elhidaoui et al. (2022); Kayikci et al. (2022)            | Creates incentive mechanisms for sustainability achievements through digital ESG-linked tokens.                             |
| <b>Green Practices</b>           | Elhidaoui et al. (2022); Li and Liu (2023); Yang et al. (2024)                 | Embeds eco-friendly principles into blockchain operations for reduced carbon and resource impact.                           |
| <b>Organizational Management</b> | Elhidaoui et al. (2022); Marttinen et al. (2024)                               | Strengthens leadership and governance structures to drive ESG-aligned blockchain initiatives.                               |
| <b>Knowledge Management</b>      | Elhidaoui et al. (2022); Hu and Zhao (2025); Farinha and de Fátima Pina (2025) | Facilitates ESG learning, sharing, and innovation within blockchain-based supply networks.                                  |
| <b>Collaborative Logistics</b>   | Cao et al. (2024); Bernards et al. (2024)                                      | Coordinates logistics for shared resource use and emission reduction across the network.                                    |
| <b>Performance Monitoring</b>    | Zhang et al. (2022); Pandey et al. (2024)                                      | Enables real-time ESG metric tracking and corrective action through blockchain analytics.                                   |
| <b>Risk Management</b>           | Chaudhuri et al. (2023); Mishra et al. (2023); Schuster and Mossig (2025)      | Enhances foresight and control over ESG-related risks through transparent blockchain insights.                              |
| <b>Innovation Culture</b>        | Gurzawska (2020); Chae et al. (2025); Plaček et al. (2024)                     | Fosters creativity and adaptation in developing blockchain-based sustainability solutions.                                  |
| <b>Supplier Development</b>      | Liu et al. (2018); Jossierand et al. (2018)                                    | Builds supplier capacity for blockchain adoption and consistent ESG compliance.                                             |
| <b>Digital Infrastructure</b>    | Hu and Zhao (2025); Farinha and de Fátima Pina (2025)                          | Provides the foundational technological backbone for blockchain-driven ESG systems.                                         |
| <b>Change Management</b>         | Alvarez et al. (2010); Fougère and Solitander (2020)                           | Ensures smooth organizational transition and stakeholder buy-in during blockchain-ESG integration.                          |
| <b>Certification Systems</b>     | Siems et al. (2023); Schuster and Mossig (2025)                                | Validates ESG and blockchain standards through third-party audits and accreditation.                                        |
| <b>Continuous Improvement</b>    | Kayikci et al. (2022); Pandey et al. (2024)                                    | Drives ongoing enhancement of blockchain and ESG processes based on feedback loops.                                         |
| <b>Global Integration</b>        | Bernards et al. (2024); Chae et al. (2025)                                     | Harmonizes ESG compliance efforts across multinational blockchain-enabled supply networks.                                  |

## 2.4. Research gaps

Even though it is widely believed that blockchain technology is supposed to improve transparency, traceability, and accountability in supply chains, the topic and its implementation have been widely studied, yet there are evident gaps in the literature at the intersection point between blockchain and ESG governance. [Yadav and Singh \(2020\)](#) and [Elhidaoui et al. \(2022\)](#) both limited their studies to identifying the critical factors in the adoption of blockchain but failed to examine how these factors may be causally linked, a weakness given the interaction between these factors in producing ESG outcomes. On the same note, other works such as [Munir et al. \(2022\)](#) and [Soori et al. \(2024\)](#) have also examined the technical benefits of blockchain use, but they have not taken into account a multi-stakeholder perspective, which is needed to understand global supply networks. In addition, [Gurzawska \(2020\)](#) and [Siems et al. \(2023\)](#) studied collaborative ESG governance but did not link it to technological enablers, such as blockchain, which could facilitate stakeholder engagement and compliance verification. [Pandey et al. \(2024\)](#) and [Zhang et al. \(2022\)](#) examined frameworks for sustainability enabled by blockchain technology, but did not develop decision-support models to address the priority strategies managers should implement. In addition, [Bhatt and Emdad \(2025\)](#) highlighted the potential sustainability benefits of blockchain but neglected potential issues related to scale and energy efficiency. Therefore, this study addresses this gap in the literature with an integrated data-driven approach and presents a new systemic methodology and framework for stakeholders to identify and analyze the causal relationships among blockchain-enabled factors for ESG compliance. Though research in the fields of ESG and blockchain has been growing rapidly, there has been little research into the implementation of governance mechanisms derived from these technologies into the financial decision-making processes of multinational enterprises. Interestingly, little previous research explains the organizational or technological drivers of ESG credibility. This is the gap this study have filled by creating a causal decision-support model that relates blockchain-enabled ESG governance to mechanisms relevant to financial economics. Moreover, the existing literature rarely describes how ESG governance facilitated by blockchain can affect financial performance at the firm level, including the cost of capital, investor relations, and enterprise value. This study provides a basis for future research to establish the relationship between digital sustainability governance and financial performance indicators by identifying causal determinants of ESG transparency and traceability.

## 3. Research methodology & data analysis

The research methodology and data analysis are explained as follows:

The Fuzzy Delphi Method (FDM) was implemented in phase one to refine and validate the original pool of twenty-six CSFs associated with blockchain-enabled ESG governance. We invited a panel of 15 experts to evaluate the importance of CSFs by rating their relevance on a five-point scale, ranging from very low to very high. The expert details are mentioned in [Table 2](#). The heterogeneity of the experts from different functional areas, i.e., technical, managerial, and governance roles, avoids the issue of homogeneity bias and the issue of groupthink. Independent, anonymous evaluations of expert responses were conducted to ensure they were not influenced by other respondents, thereby reducing anchoring bias and dominance concerns. A total of 2 iterative fuzzy-Delphi processes were conducted, allowing experts to reexamine their responses based on aggregate feedback. It helps reach consensus and minimize extreme, inconsistent judgments.

Next, their evaluations were transformed into triangular fuzzy numbers (TFNs) and defuzzified, using the centroid approach to produce crisp values. An agreement was reached, as all twenty-six CSFs exceeded 0.6 (the acceptable threshold), underscoring that the experts agreed on all the identified CSFs. In phase two of the study, we developed and administered a structured survey, which was sent to 486 respondents; 257 completed it, yielding a response rate of 52.88%. The respondents were practitioners, sustainability managers, and researchers from industry sectors. The data collected from the survey responses were used to perform a PCA to determine latent constructs and reduce the data's dimensions, while capturing the essential underlying patterns of the study. The sample (as shown in [Table 3](#)) consisted predominantly of male respondents (70.82%) compared with female respondents (29.18%). Regarding age

**Table 2**  
Expert details for fuzzy-Delphi & Fuzzy-DEMATEL analysis.

| Expert Code | Designation                                                    | Experience | Qualification          |
|-------------|----------------------------------------------------------------|------------|------------------------|
| T1          | Chief Sustainability Officer (CSO)                             | 15.4       | BTECH + MBA            |
| T2          | Chief Blockchain Officer                                       | 24.7       | BTECH                  |
| T3          | Head of ESG Strategy                                           | 15.9       | BTECH + MBA            |
| T4          | Director – Blockchain Solutions                                | 23.5       | PhD (Computer Science) |
| T5          | ESG Technology Integration Director                            | 21.2       | BTECH + MBA            |
| T6          | Vice President – Sustainable Supply Chain                      | 24.1       | BTECH + MBA            |
| T7          | Blockchain Program Manager – ESG Systems                       | 22.1       | BTECH                  |
| T8          | ESG Compliance and Digital Governance Manager                  | 18.4       | BTECH + MBA            |
| T9          | Senior Manager – Blockchain-Enabled Supply Networks            | 16.3       | BTECH + MBA            |
| T10         | Director – Digital Risk and ESG Assurance                      | 16.7       | BTECH + MTECH          |
| T11         | Head of Sustainable Innovation and Distributed Ledger Projects | 17.2       | BTECH + MTECH          |
| T12         | ESG Reporting and Blockchain Implementation Lead               | 18.9       | BTECH + MBA            |
| T13         | Global Supply Chain Transparency Director                      | 19.3       | BTECH + MBA            |
| T14         | Sustainability Transformation Lead (Blockchain Initiatives)    | 20.6       | BTECH                  |
| T15         | ESG Data Governance and Blockchain Operations Manager          | 21.8       | PhD (Sustainability)   |

**Table 3**  
Survey respondents for PCA.

| Parameter                             | Sub-parameter     | Frequency | Percentage |
|---------------------------------------|-------------------|-----------|------------|
| <b>Profile of Respondents</b>         |                   |           |            |
| <b>Gender</b>                         | Male              | 182       | 70.82      |
|                                       | Female            | 75        | 29.18      |
| <b>Age (in years)</b>                 | 30-40             | 26        | 10.12      |
|                                       | 41-50             | 97        | 37.74      |
|                                       | 51-60             | 87        | 33.85      |
|                                       | >60               | 47        | 18.29      |
|                                       | Bachelor          | 189       | 73.54      |
| <b>Education Level</b>                | Master            | 57        | 22.18      |
|                                       | Doctorate         | 11        | 4.28       |
| <b>Firms characteristics</b>          |                   |           |            |
| <b>Turnover (in billion \$)</b>       | 05-10             | 20        | 7.782      |
|                                       | 11-15             | 95        | 36.96      |
|                                       | 16-20             | 58        | 22.57      |
|                                       | >20               | 84        | 32.68      |
| <b>Number of employees</b>            | 01-10             | 42        | 16.34      |
|                                       | 101-200           | 65        | 25.29      |
|                                       | 201-300           | 42        | 16.34      |
|                                       | >300              | 108       | 42.02      |
| <b>Years of Establishment (years)</b> | <5                | 35        | 13.62      |
|                                       | 05-10             | 47        | 18.29      |
|                                       | 11-20             | 81        | 31.52      |
|                                       | >20               | 94        | 36.58      |
| <b>Industry Type</b>                  | Metals and Mining | 38        | 14.79      |
|                                       | FMCG              | 92        | 35.8       |
|                                       | Automobiles       | 87        | 33.85      |
|                                       | Oil & Gas         | 40        | 15.56      |

structure, the highest percentage (37.74 percent) was found in the 41-50 years category, followed by 33.85 percent in the 51-60 years category, 18.29 percent in the above 60 years category, and 10.12 percent in the 30-40 years category. Most of the respondents had bachelor's degrees (73.54 percent), 22.18 percent had master's, and 4.28 percent had doctoral degrees. Organizational features revealed a strong representation of large organizations: 42.02 percent had a workforce over 300, and 32.68 percent had turnover over USD 20 billion. The FMCG, automotive, metals and mining, and oil and gas companies were the dominant industry participants (35.8%, 33.85%, 14.79%, and 15.56%, respectively). Overall, the quantitative characteristics of the sample indicate a mature, industry-relevant sample with significant management experience, which enhances the strength and generalizability of the empirical results.

The final step was a Fuzzy DEMATEL assessment to investigate causal relationships among the first-order factors based on PCA results. As part of phase one, those same 15 experts engaged in pairwise influence ratings using linguistic variables, which were then converted into fuzzy numbers. Since the presented research uses fuzzy Delphi and Fuzzy DEMATEL approaches to compute results, the evaluations can be driven by individual experiences, cognitive heuristics, industry-specific exposure, and company background. To overcome these subjectivities, experts were selected based on threshold experience, required qualifications, and proven track records of blockchain adoption in improving ESG metrics. Moreover, fuzzy Delphi helps overcome ambiguities and uncertainties in complex problem-solving, leading to a common consensus and thereby minimizing extreme or inconsistent judgments. This study involved three phases, which are explained below:

### 3.1. Phase I: Fuzzy Delphi Method (FDM)

In the first phase of the study, the FDM was applied to validate and refine the 26 CSFs identified as affecting blockchain-enabled ESG governance. In total, 15 experts, practitioners in environmental sustainability through blockchain technology, contributed to this round of evaluation. Each expert rated CSFs in this round using a five-point linguistic scale ranging from 'Very Low Importance' to 'Very High Importance' (see Table 4 for TFN conversion). Aggregated fuzzy values were defuzzified using a centroid method to get crisp scores. Any CSFs that scored above a defuzzified score of 0.60 were included for the next phase of the process (Ishikawa et al., 1993;

**Table 4**  
Triangular Linguistic scale.

| Linguistic Term | Triangular Fuzzy Number (TFN) | Interpretation                                                         |
|-----------------|-------------------------------|------------------------------------------------------------------------|
| Very Low (VL)   | (0.0, 0.0, 0.25)              | Factor has no observable influence on others                           |
| Low (L)         | (0.0, 0.25, 0.5)              | Factor has minor relevance                                             |
| Medium (M)      | (0.25, 0.5, 0.75)             | Factor is moderately relevant                                          |
| High (H)        | (0.5, 0.75, 1.0)              | Factor is highly relevant to ESG-blockchain linkage                    |
| Very High (VH)  | (0.75, 1.0, 1.0)              | Factor is critically important for blockchain-based ESG implementation |

Hsu et al., 2010; Cheng and Lin, 2002). These CSFs were evaluated by the group of experts as an aggregate for the multivariate and causal study in Phase 2. This approach was a useful way to establish consensus, as validated by experts, by including only the group-verified CSFs to enhance construct validity and methodological rigor for the subsequent multivariate and causal study.

### 3.2. Phase-II PCA analysis

PCA helps extract dominant patterns through complementary scores & loading schematics (Wold et al., 1987). It is a well-known dimension-reduction technique that retains variations in the data set (Ringnér, 2008). It is used in a variety of applications, including supply chain resilience (Radhakrishnan et al., 2026); marketing analytics (Contreras-Peña et al., 2026); circular economy perspectives (Li et al., 2025), and supply chain carbon finance indexing (Patro et al., 2025). The scree plot of eigenvalues is mentioned in Fig. 1.

### 3.3. Phase III: Fuzzy DEMATEL

The third phase of the research study employed the Fuzzy DEMATEL method to analyze causal relationships among the identified factor groups derived from the PCA. The Fuzzy DEMATEL approach is a robust analytical framework that helps translate complex, uncertain expert judgment into a quantitative cause-and-effect relationship, indicating that the Fuzzy DEMATEL method is suitable for multi-criteria decision-making (Liou et al., 2007; Wu and Lee, 2007). The analysis was conducted by following the standard calculus procedure, which is described below:

Step 1: A group of fifteen domain experts who shared similar characteristics was asked to evaluate the interrelationship among the determined CSFs. Each expert evaluated the influence of one CSF upon another using the linguistic terms ranging from Very low influence (VL) to Very high influence (VH). Referring to Table 4, these linguistic evaluations were transformed into TFNs. The fuzzy direct-relation matrix ( $\tilde{Y} = [\tilde{y}_{ij}]$ ) is thus created, where each element  $\tilde{y}_{ij}$  represents the fuzzy influence of factor  $i$  on factor  $j$ .

Step 2: To analyze the fuzzy matrix quantitatively, it is defuzzified into a crisp decision matrix by converting fuzzy values into crisp scores.

Let  $\tilde{y}_{ij} = (\alpha_k, \beta_k, \gamma_k)$  be a TFN; then:  $L = \min(\alpha_k)$ ,  $R = \max(\gamma_k)$

$$Y_{ak} = \frac{\alpha_k - L}{\Delta}; Y_{\beta k} = \frac{\beta_k - L}{\Delta}; Y_{\gamma k} = \frac{\gamma_k - L}{\Delta} \quad (1)$$

The left and right normalized scores are:

$$Y_k^{left} = \frac{Y_{\beta k}}{1 + Y_{\beta k} - Y_{ak}}; Y_k^{right} = \frac{Y_{\gamma k}}{1 + Y_{\gamma k} - Y_{\beta k}} \quad (2)$$

The total normalized crisp value is obtained as:

$$Y_k^{crisp} = \frac{(Y_k^{left} * (1 - Y_k^{left}) + Y_k^{right} * Y_k^{right})}{1 + Y_k^{left} - Y_k^{right}} \quad (3)$$

and the final crisp score for each pairwise comparison:

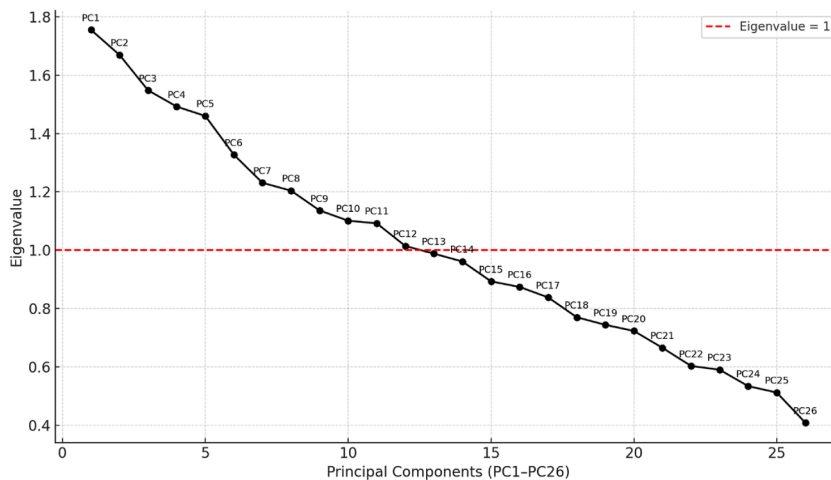


Fig. 1. Scree plot of Eigen values.

$$\omega_{ij}^n = L + Y_k^{crisp} * \Delta \quad (4)$$

Finally, the average opinion of all experts is derived as:

$$\omega_{ij}^n = \frac{\omega_{ij}^1 + \omega_{ij}^2 + \omega_{ij}^3 + \dots + \omega_{ij}^n}{\text{Total Experts}} \quad (5)$$

Step 3: The initial direct influence matrix  $C = [c_{ij}]$  is the mean of all crisp matrices provided by experts:

$$C_{ij} = \frac{\sum E_{ij}}{\text{number of Experts matrices}} \quad (6)$$

It is then normalized to form the Direct Normalized Influence Matrix (DNIM) using:

$$\lambda = \min_{ij} \left( \frac{1}{\max_i \sum C_{ij}} \text{ or } \frac{1}{\max_j C_{ij}} \right) \quad (7)$$

Step 4: The Total Influence Relation Matrix (TIRM) incorporates both direct and indirect effects of factors and is calculated as:

$$T = D(I - D)^{-1} \quad (8)$$

where  $I$  is the identity matrix of the same dimension as  $D$ . The matrix  $T$  captures the complete influence flow within the system.

Step 5: For each factor  $i$ , the sum of rows ( $R_i$ ) and sum of columns ( $C_i$ ) in matrix  $T$  are computed as:

$$R_i = \sum_j t_{ij} \quad \text{and} \quad C_i = \sum_j t_{ij} \quad (9)$$

$R_i + C_i$  represents the prominence, indicating the overall importance of factor  $i$ , and  $R_i - C_i$  represents the net effect, identifying whether the factor is a cause (positive) or an effect (negative) critical success factor. Factors with  $R_i - C_i > 0$  are causal, while those with  $R_i - C_i < 0$  are effect factors.

#### 4. Result analysis

The result of fuzzy-Delphi is shown in Table 5. A total of two rounds with experts were conducted. It is followed by principal component analysis (PCA) as shown in Table 6. Moreover, Table 7 shows the grouping of observed variables into principal factors after varimax rotation. Table 8 develops an aggregated crisp decision matrix using expert opinion. Then, as per standard operating procedures, the normalized direct-influence matrix (NDIM) for blockchain-ESG factors and the total influence relation matrix (TIRM) for

**Table 5**  
Fuzzy Delphi result.

| CSF                       | L    | M    | U    | Defuzzified Score | Decision |
|---------------------------|------|------|------|-------------------|----------|
| System Robustness         | 0.72 | 0.86 | 0.95 | 0.84              | Accepted |
| Data Transparency         | 0.7  | 0.88 | 0.96 | 0.85              | Accepted |
| Trust & Reliability       | 0.68 | 0.84 | 0.94 | 0.82              | Accepted |
| Smart Contracts           | 0.69 | 0.83 | 0.91 | 0.81              | Accepted |
| Traceability              | 0.71 | 0.87 | 0.94 | 0.84              | Accepted |
| Cost Optimization         | 0.66 | 0.82 | 0.92 | 0.8               | Accepted |
| Stakeholder Engagement    | 0.68 | 0.85 | 0.93 | 0.82              | Accepted |
| Regulatory Compliance     | 0.73 | 0.88 | 0.97 | 0.86              | Accepted |
| Data Quality              | 0.64 | 0.79 | 0.89 | 0.77              | Accepted |
| Interoperability          | 0.67 | 0.82 | 0.9  | 0.8               | Accepted |
| Scalability               | 0.61 | 0.77 | 0.88 | 0.75              | Accepted |
| Privacy Protection        | 0.64 | 0.79 | 0.87 | 0.77              | Accepted |
| Tokenization              | 0.69 | 0.83 | 0.92 | 0.81              | Accepted |
| Green Practices           | 0.72 | 0.86 | 0.95 | 0.84              | Accepted |
| Organizational Management | 0.66 | 0.82 | 0.9  | 0.79              | Accepted |
| Knowledge Management      | 0.63 | 0.8  | 0.88 | 0.77              | Accepted |
| Collaborative Logistics   | 0.68 | 0.84 | 0.92 | 0.81              | Accepted |
| Performance Monitoring    | 0.7  | 0.85 | 0.93 | 0.83              | Accepted |
| Risk Management           | 0.74 | 0.89 | 0.96 | 0.86              | Accepted |
| Innovation Culture        | 0.66 | 0.81 | 0.89 | 0.79              | Accepted |
| Supplier Development      | 0.65 | 0.8  | 0.89 | 0.78              | Accepted |
| Digital Infrastructure    | 0.69 | 0.84 | 0.93 | 0.82              | Accepted |
| Change Management         | 0.63 | 0.78 | 0.88 | 0.76              | Accepted |
| Certification Systems     | 0.7  | 0.86 | 0.93 | 0.83              | Accepted |
| Continuous Improvement    | 0.68 | 0.83 | 0.91 | 0.81              | Accepted |
| Global Integration        | 0.72 | 0.87 | 0.94 | 0.84              | Accepted |

**Table 6**  
CSFs Eigen values.

| Principal Component | Eigenvalue | Variability (%) | Cumulative (%) |
|---------------------|------------|-----------------|----------------|
| PC1                 | 1.755      | 6.715           | 6.715          |
| PC2                 | 1.669      | 6.388           | 13.103         |
| PC3                 | 1.548      | 5.925           | 19.029         |
| PC4                 | 1.492      | 5.709           | 24.737         |
| PC5                 | 1.460      | 5.589           | 30.326         |
| PC6                 | 1.327      | 5.078           | 35.404         |
| PC7                 | 1.231      | 4.710           | 40.114         |
| PC8                 | 1.204      | 4.606           | 44.719         |
| PC9                 | 1.136      | 4.349           | 49.068         |
| PC10                | 1.101      | 4.214           | 53.282         |
| PC11                | 1.092      | 4.177           | 57.460         |
| PC12                | 1.014      | 3.880           | 61.340         |
| PC13                | 0.988      | 3.780           | 65.121         |
| PC14                | 0.961      | 3.677           | 68.798         |
| PC15                | 0.893      | 3.416           | 72.214         |
| PC16                | 0.874      | 3.344           | 75.558         |
| PC17                | 0.838      | 3.205           | 78.763         |
| PC18                | 0.770      | 2.947           | 81.710         |
| PC19                | 0.744      | 2.846           | 84.556         |
| PC20                | 0.723      | 2.768           | 87.324         |
| PC21                | 0.665      | 2.547           | 89.871         |
| PC22                | 0.603      | 2.307           | 92.178         |
| PC23                | 0.590      | 2.258           | 94.435         |
| PC24                | 0.534      | 2.043           | 96.479         |
| PC25                | 0.512      | 1.959           | 98.438         |
| PC26                | 0.408      | 1.562           | 100.000        |

**Table 7**  
Descriptions of principal factors influencing blockchain-enabled ESG performance.

| PF   | Label                                            | CSFs grouped                                                  | ESG Compliance Linkage                                                                                                                                                   |
|------|--------------------------------------------------|---------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| PF1  | Organizational Learning & ESG Governance         | Knowledge Management, Risk Management                         | Supports continuous knowledge development, facilitate organization to develop adaptive capabilities and effective risk management                                        |
| PF2  | Data Integrity & ESG Reporting                   | Data Quality, Data Transparency                               | Provides transparent, accurate data trails for ESG reporting, improving trust among regulators and stakeholders.                                                         |
| PF3  | Secure & Accountable Systems                     | Trust & Reliability, Continuous Improvement                   | Ensures secure, tamper-proof records that enhance accountability and auditability for ESG disclosures.                                                                   |
| PF4  | Adaptive System Governance                       | Change Management, System Robustness, Digital Infrastructure  | Ability of organization to dynamically adapt governance structures & decision-making.                                                                                    |
| PF5  | Resource Efficiency & Performance Optimization   | Cost Optimization, Performance Monitoring                     | Supports resource efficiency and cost optimization, directly reducing environmental footprint and improving governance metrics.                                          |
| PF6  | Sustainable Operations & Green Innovation        | Green Practices, Innovation Culture                           | Aligns blockchain use with environmental goals, ensuring energy-efficient and sustainable supply practices.                                                              |
| PF7  | Global ESG Integration                           | Global Integration, Interoperability                          | Facilitates global harmonization of ESG practices and cross-border sustainability compliance.                                                                            |
| PF8  | Knowledge Capital & ESG Awareness                | Organizational Management, Scalability                        | Promotes internal capacity building and ESG knowledge sharing for global supply chain governance.                                                                        |
| PF9  | Ethical Data Management                          | Tokenization, Privacy Protection                              | Ensures ethical data management using immutable and decentralized ledgers, facilitate the organizations to enhance accountability, results in trustworthy ESG reporting. |
| PF10 | Automated ESG Compliance Systems                 | Smart Contracts, Regulatory Compliance, Certification Systems | Facilitates real-time tracking of ESG metrics and integrate data from supply chains                                                                                      |
| PF11 | Sustainable Supplier Collaboration               | Supplier Development, Collaborative Logistics                 | Strengthens ESG compliance via supplier development and collaborative logistics for sustainable sourcing.                                                                |
| PF12 | Global Traceability & Stakeholder Accountability | Traceability, Stakeholder Engagement                          | Enhances visibility, transparency and traceability across global supply chain networks                                                                                   |

blockchain-enabled ESG network are shown in [Tables 9 and 10](#), respectively. Finally, cause-and-effect relationships are shown in [Table 11](#) and [Fig. 2](#).

The professional panel used in the fuzzy Delphi and DEMATEL steps consisted of fifteen experienced professionals with a high level of knowledge about blockchain-based ESG governance in multinational supply chains. Based on the data provided in [Table 2](#), the panel included Chief Sustainability Officers, Blockchain Directors, ESG Strategy Heads, and Digital Governance Managers who had an experience of approximately fifteen to twenty-five years and a variety of qualifications, including engineering, management, and doctoral programs. This diverse and highly experienced team ensured that validation of key success elements was grounded in both

**Table 8**

Aggregated crisp decision matrix derived from expert responses.

| PF   | PF1   | PF2   | PF3   | PF4   | PF5   | PF6   | PF7   | PF8   | PF9   | PF10  | PF11  | PF12  |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| PF1  | 0.000 | 0.467 | 0.417 | 0.600 | 0.417 | 0.367 | 0.467 | 0.333 | 0.400 | 0.450 | 0.300 | 0.650 |
| PF2  | 0.600 | 0.000 | 0.367 | 0.533 | 0.233 | 0.550 | 0.650 | 0.500 | 0.550 | 0.500 | 0.417 | 0.600 |
| PF3  | 0.567 | 0.450 | 0.000 | 0.417 | 0.550 | 0.367 | 0.450 | 0.517 | 0.500 | 0.400 | 0.500 | 0.600 |
| PF4  | 0.333 | 0.500 | 0.467 | 0.000 | 0.467 | 0.550 | 0.467 | 0.367 | 0.417 | 0.650 | 0.283 | 0.467 |
| PF5  | 0.400 | 0.550 | 0.400 | 0.367 | 0.000 | 0.500 | 0.450 | 0.467 | 0.367 | 0.567 | 0.700 | 0.500 |
| PF6  | 0.583 | 0.300 | 0.467 | 0.467 | 0.500 | 0.000 | 0.633 | 0.633 | 0.733 | 0.400 | 0.517 | 0.633 |
| PF7  | 0.417 | 0.550 | 0.600 | 0.500 | 0.450 | 0.483 | 0.000 | 0.317 | 0.550 | 0.500 | 0.550 | 0.500 |
| PF8  | 0.500 | 0.567 | 0.500 | 0.350 | 0.550 | 0.417 | 0.467 | 0.000 | 0.450 | 0.550 | 0.500 | 0.483 |
| PF9  | 0.650 | 0.600 | 0.550 | 0.500 | 0.367 | 0.550 | 0.500 | 0.517 | 0.000 | 0.600 | 0.500 | 0.567 |
| PF10 | 0.517 | 0.500 | 0.417 | 0.383 | 0.550 | 0.600 | 0.517 | 0.467 | 0.667 | 0.000 | 0.467 | 0.550 |
| PF11 | 0.350 | 0.550 | 0.500 | 0.600 | 0.550 | 0.500 | 0.317 | 0.333 | 0.533 | 0.583 | 0.000 | 0.400 |
| PF12 | 0.450 | 0.467 | 0.500 | 0.600 | 0.467 | 0.650 | 0.367 | 0.467 | 0.600 | 0.350 | 0.550 | 0.000 |

**Table 9**

Normalized direct-influence matrix (NDIM) for blockchain-ESG factors.

| PF   | PF1   | PF2   | PF3   | PF4   | PF5   | PF6   | PF7   | PF8   | PF9   | PF10  | PF11  | PF12  |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| PF1  | 0.000 | 0.079 | 0.071 | 0.102 | 0.071 | 0.062 | 0.079 | 0.056 | 0.068 | 0.076 | 0.051 | 0.110 |
| PF2  | 0.102 | 0.000 | 0.062 | 0.090 | 0.039 | 0.093 | 0.110 | 0.085 | 0.093 | 0.085 | 0.071 | 0.102 |
| PF3  | 0.096 | 0.076 | 0.000 | 0.071 | 0.093 | 0.062 | 0.076 | 0.088 | 0.085 | 0.068 | 0.085 | 0.102 |
| PF4  | 0.056 | 0.085 | 0.079 | 0.000 | 0.079 | 0.093 | 0.079 | 0.062 | 0.071 | 0.110 | 0.048 | 0.079 |
| PF5  | 0.068 | 0.093 | 0.068 | 0.062 | 0.000 | 0.085 | 0.076 | 0.079 | 0.062 | 0.096 | 0.119 | 0.085 |
| PF6  | 0.099 | 0.051 | 0.079 | 0.079 | 0.085 | 0.000 | 0.107 | 0.107 | 0.124 | 0.068 | 0.088 | 0.107 |
| PF7  | 0.071 | 0.093 | 0.102 | 0.085 | 0.076 | 0.082 | 0.000 | 0.054 | 0.093 | 0.085 | 0.093 | 0.085 |
| PF8  | 0.085 | 0.096 | 0.085 | 0.059 | 0.093 | 0.071 | 0.079 | 0.000 | 0.076 | 0.093 | 0.085 | 0.082 |
| PF9  | 0.110 | 0.102 | 0.093 | 0.085 | 0.062 | 0.093 | 0.085 | 0.088 | 0.000 | 0.102 | 0.085 | 0.096 |
| PF10 | 0.088 | 0.085 | 0.071 | 0.065 | 0.093 | 0.102 | 0.088 | 0.079 | 0.113 | 0.000 | 0.079 | 0.093 |
| PF11 | 0.059 | 0.093 | 0.085 | 0.102 | 0.093 | 0.085 | 0.054 | 0.056 | 0.090 | 0.099 | 0.000 | 0.068 |
| PF12 | 0.076 | 0.079 | 0.085 | 0.102 | 0.079 | 0.110 | 0.062 | 0.079 | 0.102 | 0.059 | 0.093 | 0.000 |

**Table 10**

Total influence relation matrix (TIRM) for blockchain-enabled ESG network.

| PF   | PF1   | PF2   | PF3   | PF4   | PF5   | PF6   | PF7   | PF8   | PF9   | PF10  | PF11  | PF12  |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| PF1  | 0.753 | 0.840 | 0.794 | 0.841 | 0.780 | 0.836 | 0.814 | 0.748 | 0.870 | 0.843 | 0.788 | 0.927 |
| PF2  | 0.939 | 0.861 | 0.877 | 0.924 | 0.841 | 0.958 | 0.933 | 0.858 | 0.992 | 0.945 | 0.895 | 1.022 |
| PF3  | 0.904 | 0.903 | 0.789 | 0.877 | 0.860 | 0.901 | 0.874 | 0.833 | 0.951 | 0.901 | 0.881 | 0.990 |
| PF4  | 0.828 | 0.865 | 0.820 | 0.766 | 0.806 | 0.883 | 0.835 | 0.773 | 0.895 | 0.892 | 0.806 | 0.923 |
| PF5  | 0.876 | 0.913 | 0.849 | 0.866 | 0.771 | 0.917 | 0.870 | 0.823 | 0.930 | 0.922 | 0.906 | 0.970 |
| PF6  | 0.988 | 0.964 | 0.942 | 0.965 | 0.930 | 0.925 | 0.979 | 0.925 | 1.072 | 0.984 | 0.963 | 1.083 |
| PF7  | 0.901 | 0.935 | 0.899 | 0.907 | 0.862 | 0.936 | 0.821 | 0.821 | 0.979 | 0.934 | 0.905 | 0.995 |
| PF8  | 0.900 | 0.925 | 0.872 | 0.872 | 0.864 | 0.913 | 0.882 | 0.757 | 0.950 | 0.928 | 0.885 | 0.978 |
| PF9  | 1.002 | 1.010 | 0.956 | 0.974 | 0.914 | 1.015 | 0.966 | 0.912 | 0.966 | 1.016 | 0.962 | 1.079 |
| PF10 | 0.950 | 0.962 | 0.905 | 0.923 | 0.908 | 0.988 | 0.935 | 0.874 | 1.032 | 0.890 | 0.927 | 1.039 |
| PF11 | 0.863 | 0.906 | 0.857 | 0.892 | 0.850 | 0.910 | 0.846 | 0.798 | 0.946 | 0.918 | 0.792 | 0.949 |
| PF12 | 0.913 | 0.930 | 0.892 | 0.928 | 0.871 | 0.967 | 0.887 | 0.850 | 0.994 | 0.920 | 0.911 | 0.925 |

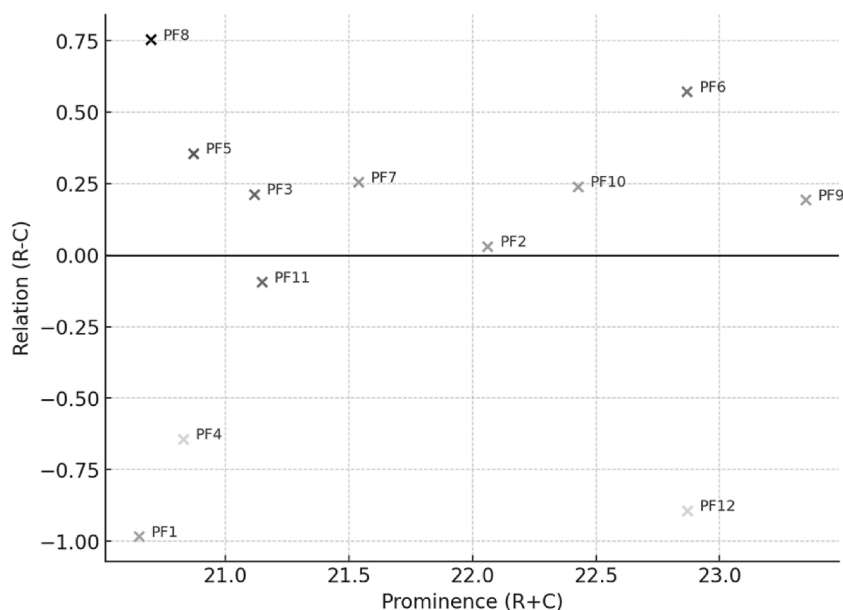
technological expertise and sustainable governance practices, thereby enhancing the credibility and relevance of the resulting PCA and causal modeling results.

To interpret the twelve major factors, each was traced to its constituent critical success factors, as shown in [Table 7](#). For example, PF8 Knowledge Capital and ESG Awareness, which is based on the CSF Knowledge Management, indicates that blockchain adoption based on ESG hinges on the organization's learning capacity. Likewise, PF10, Automated ESG Compliance Systems, consolidates Smart Contracts, Regulatory Compliance, and Certification Systems, thereby highlighting the applicability of programmable governance structures for verifiable ESG reporting. PF12, Global Traceability and Stakeholder Accountability, is an amalgamation of Traceability and Stakeholder Engagement that addresses the interaction between technical transparency tools and collaborative governance to deliver accountability outcomes. The PCA outcomes not only provide a statistically dimensionally reduced representation of the data but also offer a theoretically grounded account of the interplay among specific organizational, technological, and governance capabilities in driving blockchain-based ESG performance.

**Table 11**

Causal prominence and influence strength for key ESG success factors.

| PF   | R (Given) | C (Received) | R + C (Prominence) | R–C (Relation) | Group  |
|------|-----------|--------------|--------------------|----------------|--------|
| PF1  | 9.8331    | 10.8164      | 20.6496            | –0.9833        | Effect |
| PF2  | 11.0458   | 11.015       | 22.0608            | 0.0307         | Cause  |
| PF3  | 10.6651   | 10.4518      | 21.117             | 0.2133         | Cause  |
| PF4  | 10.093    | 10.7366      | 20.8296            | –0.6436        | Effect |
| PF5  | 10.6131   | 10.2572      | 20.8703            | 0.3558         | Cause  |
| PF6  | 11.7199   | 11.1483      | 22.8682            | 0.5716         | Cause  |
| PF7  | 10.8964   | 10.6413      | 21.5376            | 0.2551         | Cause  |
| PF8  | 10.7257   | 9.9717       | 20.6975            | 0.754          | Cause  |
| PF9  | 11.7709   | 11.5777      | 23.3486            | 0.1933         | Cause  |
| PF10 | 11.3331   | 11.0933      | 22.4265            | 0.2398         | Cause  |
| PF11 | 10.5271   | 10.6207      | 21.1478            | –0.0936        | Effect |
| PF12 | 10.9881   | 11.8813      | 22.8694            | –0.8932        | Effect |

**Fig. 2.** Causal effect map of blockchain-driven ESG compliance factors.

## 5. Discussion & implications

The study explored factors influencing blockchain-driven ESG compliance in supply chain management. A total of 26 factors were identified from the scholarly literature and further categorized into 12 key factors using principal component analysis. Then, the fuzzy-DEMATEL technique was applied to bifurcate the principal factors into cause-and-effect categories. The value (R+C) signifies prominence, while the (R-C) value explains the relationship, as shown in Table 11. Cause-category elements, such as Ethical Data Management (PF9), Automated ESG Compliance Systems (PF10), and Knowledge Capital and ESG Awareness (PF8), increase the credibility, comparability, and transparency of the ESG information. Blockchain-empowered ESG governance serves as an engine that transforms ESG reporting from discretionary disclosure to verifiable data and, in the process, affects asset pricing by reducing perceived risk, increasing investor confidence, and enhancing access to sustainable finance markets. Both stakeholder theory and network governance theory are empirically validated by the causal structure revealed by the Fuzzy DEMATEL analysis. Knowledge capital and ESG awareness (PF8), Ethical Data Management (PF9), and Automated ESG Compliance Systems (PF10) are cause-category factors that mitigate information asymmetry and ensure coordinated decision-making among the various supply-chain actors. The stakeholder theory argues that transparency and common knowledge would promote trust and co-operation, thereby improving sustainability performance. The fact that traceability and stakeholder accountability are observed to be dependent outcomes reveals that accountability is not created in a vacuum but rather the result of prior investments in knowledge sharing, ethical data systems, and collaborative governance structures. This observation supports relational and network views, which postulate that sustainability performance is a product of systemic relationships among stakeholders rather than firm efforts in isolation. At the same time, the overwhelming presence of technology-based governance tools implies a hypothetical extrapolation, suggesting that blockchain can institutionalize trust through programmable verification rather than relying solely on relational norms.

In financial economics, the innovativeness of the integrated Fuzzy-Delphi-PCA-Fuzzy DEMATEL framework lies in its ability to go beyond identifying ESG factors and to analyze their causal relationships. Traditional ESG literature often treats sustainability practices as an aggregate measure, without analyzing how the mechanisms underlying sustainability affect investor perception or firm value. This research offers an understanding of the role of blockchain-enabled governance in reducing uncertainty in ESG disclosure, stabilizing cash flows, and improving valuation outcomes for enterprises.

### 5.1. Cause category

Through research analysis, it was found that the majority of the principal factors (8 in total) fall under the cause category. It includes Data Integrity & ESG Reporting (PF2), Secure & Accountable Systems (PF3), Resource Efficiency & Performance Optimization (PF5), Sustainable Operations & Green Innovation (PF6), Global ESG Integration (PF7), Knowledge Capital & ESG Awareness (PF8), Ethical Data Management (PF9), Automated ESG Compliance Systems (PF10). Cause category factors can also be termed triggering or influential factors, with strong driving power and significant impact on other factors. From a financial and economic perspective, the causal factors identified in this study are the channels through which blockchain-facilitated ESG governance creates enterprise value. Knowledge capital, ethical data governance, and automated compliance systems improve the integrity of ESG disclosure, thereby limiting information asymmetry and the agency problem between companies and their shareholders. As the finance literature shows, credible ESG reporting is associated with lower financing costs, higher market values, and lower downside risk. In global supply chains, sustainability information verified via blockchain can simultaneously mitigate disruption losses, compliance fines, and reputational losses, thereby stabilizing cash flows and increasing cash-adjusted returns. In this way, the causal architecture outlined herein provides a mechanism-level explanation of how digital ESG governance enhances financial resilience and long-term shareholder value in multinational enterprises. Out of all these factors mentioned above, Knowledge Capital & ESG Awareness (PF8) has the highest (R-C) value of 0.754. It implies that organizational learning and knowledge management lay the foundation for achieving blockchain-enabled ESG practices. Moreover, if an organization invests in training and educational programs to raise awareness of ESG and implement best practices, it automatically affects the effectiveness of other factors. Hou et al. (2025) discussed similar results and stated the importance of environmental awareness for enhancing supply chain sustainability. Another study by Khan et al. (2025) discussed the importance of raising awareness to reduce wasteful production and consumption, make sustainable investments, and effectively implement sustainable practices.

The second-highest category factor is Sustainable Operations & Green Innovation (PF6), with an R-C value of 0.5716 and a prominence value of 22.868. A few research studies discussed that blockchain operations are energy-intensive. Alzoubi and Mishra (2023) discussed the requirement of green blockchain; the authors assessed 23 networks that consume less power and generate less carbon dioxide. The third highest cause category factor is Resource Efficiency & Performance Optimization (PF5), having (R-C) and prominence value as 0.3558 and 20.870, respectively. Effectively managing resources and improving logistics practices helps minimize costs and streamline operations, ultimately resulting in cost savings. A study by Nguyen et al. (2025) found that blockchain practices are positively associated with ESG performance, with enterprise risk management mediating this relationship. Global ESG Integration (PF7) is reported as the fourth significant cause factor, with a prominence value of 21.537 & (R-C) value of 0.2551. Khan et al. (2025) examined global financial integration as a moderator and found a significant positive relationship between blockchain technology adoption and ESG performance.

### 5.2. Effect category

This category implies that they are heavily dependent on factors within the cause category. The results indicate that four factors, namely Organizational Learning & ESG Governance (PF1), Adaptive System Governance (PF4), Sustainable Supplier Collaboration (PF11), and Global Traceability & Stakeholder Accountability (PF12), fall under the effect category. Among all these, Organizational Learning & ESG Governance (PF1) ranked first, having the least (R-C) value of (−0.9833). It implies that learning is not the starting point; rather, it is achieved through well-orchestrated planning and execution of other causal factors, including investment in knowledge development (PF8), ethical data management (PF9), and sustainable operations and green innovations (PF6). A study by Li et al. (2025) reported similar results, applying organizational learning theory to adopt blockchain to achieve sustainable performance. The second important category of enablers is Global Traceability & Stakeholder Accountability (PF12). Interoperable blockchain mechanisms, globally harmonized ESG reporting, and automated compliance frameworks bring system transparency.

### 5.3. Implications

The study presented has various implications which are discussed as follows:

## 6. Implications for technology providers

- **Prioritize knowledge development and ESG awareness:** As knowledge capital & ESG governance are among the most triggering factors, organizations must invest heavily in training programs to develop advanced skill sets and technical competencies among employees at different organizational levels. It will help build thorough conceptual knowledge of ESG standards and blockchain practices among top officials, operators, and junior employees.

- **Strengthen Data Integrity and Secure Infrastructures:** Organizations must develop robust IT infrastructure to ensure precision, transparency, and immutability of ESG information. To reinforce these characteristics, blockchain-integrated ESG systems must be upgraded with robust consensus algorithms and cybersecurity measures to prevent unauthorized access to organizations' confidential data. Companies should not only consider blockchain-based ESG governance as a compliance artifact, but also as part of their financial strategy. Confirmed ESG transparency can increase credit ratings, attract sustainability-sensitive investors, and reduce the cost of capital by improving disclosure quality. By integrating blockchain-based ESG monitoring, multinational companies are better positioned to tap into global markets for sustainable finance and avoid losses from supply-chain disruptions or regulatory penalties.
- **Leverage Automation and Global Integration:** Managers must automate ESG compliance and advance global integration using blockchain; this can be a game-changer, helping organizations save time and build transparency and trust across supply chain linkages. For instance, emission norms and sustainability compliance requirements can be encoded into smart contracts that trigger alerts when compliance thresholds are violated. Also, global integration ensures that the homogeneous ESG protocols are adhered to across distinct countries.

## 7. Implications for policymakers/government

- **Ethical Data Management:** Adopting blockchain inherently requires ethical data management. Policymakers must use standard data governance rules and regulations, including GDPR, and adopt anonymization or pseudonymization methodologies. Moreover, sharing a data ethics charter to properly document blockchain-integrated ESG practices among suppliers will help establish benchmarks and enhance legitimacy.
- **Incentivize Digital ESG Infrastructure:** The government can develop strategic plans to offer tax incentives to firms that take the initiative or excel at implementing blockchain-based ESG governance practices.
- **Develop a standardized blockchain-ESG certification and Audit Framework:** Policymakers must establish national or international certification programs for organizations adopting blockchain-enabled ESG reporting mechanisms. The International Sustainability Standards Board (ISSB) can develop guidelines for adopting technology for ESG data assurance and traceability.

## 8. Conclusion, limitations and scope for future work

The study provides a systematic decision-making framework for analyzing and adopting blockchain-enabled ESG governance in global supply chain networks. A deeper analysis of investing resources in blockchain-enabled ESG practices helps build organizational knowledge. It also helps improve disclosure quality, strengthen stakeholder trust, and increase investors' confidence. Also, blockchain-enabled sustainable operations practices help reduce transaction and verification costs, stabilize cash flows, improve risk-adjusted returns, decrease operational volatility, and enhance supply chain performance and resilience. Another significant advantage of data integrity is that it helps reduce reputational risks and tail risks. The results also offer a theoretical understanding of how financial markets could integrate ESG information through blockchain adoption. Blockchain-enhanced governance reduces information asymmetry by enhancing the credibility and auditability of sustainability disclosures and improving signaling to investors about a firm's risk profile over a long-term horizon. It implies that ESG systems based on blockchains can affect firm valuation and the cost of capital by increasing investor confidence and precision in evaluating ESG-related risks. In the context of international financial economics, blockchain-based ESG governance is a plausible approach to enhancing firm value by increasing transparency, reducing information asymmetry, and strengthening stakeholder trust. Blockchain-enabled ESG systems can lower financing costs, increase the credibility of disclosures, and enhance the financial stability of multinational enterprises. It will help organizations to operate in a complicated global market environment and sustain in the long term. The study's contribution is not limited to supply chain sustainability, as it provides a systematic method for analyzing digital ESG governance from a financial economics perspective. With a focus on causal ESG drivers that affect disclosure credibility and risk perception, the research provides avenues for future empirical studies to integrate blockchain-enabled ESG practices with firm valuation, the cost of capital, and investor behavior in global capital markets. By assessing 12 key principal factors and developing dyadic relationships, it examined how these factors interact to ensure ESG compliance. Therefore, the research results significantly add to the scholarly literature and offer managerial implications for developing transparent, resilient, sustainable, and globally aligned supply chains through blockchain-enabled ESG compliance. Triangulation was conducted, and the results were compared with secondary sources, i.e., high-repute publications such as McKinsey, Bain & Company, and Gartner. Our results are very well aligned with those reported in the literature. Also, the results obtained were confirmed by area experts working in blockchain integration to achieve ESG metrics.

Although the proposed study is centered on blockchain integration for ESG practices, it also has implications for modern finance theory, such as agency theory and information asymmetry. As in agency theory, conflict usually occurs among managers, also called agents, due to a lack of information transparency and opportunistic behavior. Likewise, ESG disclosures are quite susceptible to criticism for greenwashing; which intensifies agency issues, as sustainable parameters are usually complex and difficult to estimate and verify. Financial instruments such as green bonds and sustainability-linked loans can pose information asymmetry issues. Investors usually lack reliable mechanisms to verify whether funds are allocated to sustainable projects; therefore, future work can be done in this direction.

Like other studies, the present study has some limitations. First, to develop a causal relationship, fuzzy modeling assessments relied on expert opinions, which can lead to subjectivity and bias. The proposed results reflect perceived structural relationships based on experts' opinions rather than empirical causal analysis. Therefore, to overcome these issues, panel data analysis and longitudinal

studies can be conducted, and dyadic relationships can be examined. Since the proposed research involves cross-sectional data, blockchain adoption in ESG governance is evolving continuously and dynamically; as such, using a cross-sectional design may limit the ability to capture temporal changes and learning effects across dynamic global supply chains. India is a developing economy with evolving ESG compliance, varying intensity of digital capabilities, firms' priorities, and heterogeneous supply chains. So, the proposed results can be context-specific; therefore, direct generalization might not hold. In the present study, factors related to blockchain-integrated ESG governance were analyzed. However, in future studies, blockchain can be integrated with other smart technologies, such as IoT, AI, and digital twins, and the synergetic effects examined. Moreover, to explore the impact of cultural and regulatory dimensions on blockchain-enabled ESG practices across supply chain networks, cross-country studies can be conducted.

## Ethics statement

Ethics approval was obtained from the Ethics Committee of IMS Ghaziabad, India. In addition, we have taken the participants' permission and consent to participate in this study.

## CRedit authorship contribution statement

**Srikant Gupta:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Pranav Kumar:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Naveen Virmani:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Sandeep Jagtap:** Conceptualization, Formal analysis, Resources, Software.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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