Blockchain-Enabled Green Supply Chain Collaboration and Eco-Innovation Performance: Evidence from Polluting Manufacturing Firms

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Abstract:

Amid tightening environmental regulation and growing industrial sustainability demands, this study examines how blockchain technology adoption intensity (BTAI) generates superior eco-innovation performance (EIP) among pollution-intensive manufacturing firms. Grounded in dynamic capabilities theory and stakeholder theory, we conceptualize green supply chain collaboration (GSCC) as the critical mechanism through which blockchain-structured digital resources are converted into systemic eco-innovation outcomes. Using survey data from 389 senior managers in pollution-intensive Chinese manufacturing firms, we test a moderated mediation model. Results reveal that GSCC fully mediates the positive relationship between BTAI and EIP. Supply chain partner commitment (SPC) amplifies the enabling effect of BTAI on GSCC, whereas operational complexity (OC) attenuates it. Sustainability learning capability (SLC) positively moderates the GSCC–EIP relationship, directing integrated resources toward green innovation outcomes. These findings enrich dynamic capabilities theory in digital-ecological contexts and offer actionable guidance for practitioners seeking to leverage blockchain as a sustainability transformation tool.

Keywords: *blockchain technology adoption; eco-innovation performance; green supply chain collaboration; dynamic capabilities; polluting manufacturing; sustainability*

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1. Introduction

The imperative for sustainable industrial development has never been more acute. Manufacturing sectors worldwide — particularly those designated as pollution-intensive, including metal processing, chemical manufacturing, and energy-intensive industries — face mounting institutional pressure to reduce their ecological footprints. The seminal insight that environmental regulation and competitive advantage can be mutually reinforcing rather than contradictory fundamentally reshaped how scholars and practitioners approach sustainability strategy (Porter & van der Linde, 1995). In China, which remains the world's largest manufacturing economy, government mandates such as the 14th Five-Year Plan for Ecological Civilization and the dual carbon targets further compel polluting firms to rethink their operational logic.

The broader trajectory of green supply chain management scholarship has documented how institutional pressures drive environmental strategy adoption across manufacturing contexts (Sarkis et al., 2011). Eco-innovation — defined as the development and deployment of products, processes, and organizational practices that measurably reduce environmental harm — has emerged as a strategic imperative rather than a compliance exercise (Rennings, 2000). Evidence from listed Chinese companies confirms that green innovation investments generate measurable improvements in long-term firm performance, especially in sectors facing intense regulatory scrutiny (Zhang et al., 2019).

Despite its importance, eco-innovation is inherently resource-intensive, demanding sophisticated knowledge coordination across organizational boundaries, real-time visibility into material and energy flows, and collaborative green capability development with supply chain partners. Research has confirmed that the resource demands of proactive environmental strategies are substantial, though they can be offset by cost advantages when appropriate complementary organizational assets are in place (Klassen & McLaughlin, 1996). Blockchain technology — whose current state of the art and core research challenges have been systematically mapped — offers a promising digital infrastructure for addressing these coordination demands (Lu, 2019).

Empirical work has established that blockchain's smart contract functionality and immutable audit trails reduce opportunistic behavior and lower coordination costs among supply chain partners (Saberi et al., 2019). Beyond transactional efficiency, blockchain has been recognized as a key enabler for achieving supply chain management objectives related to quality assurance, information security, and environmental performance (Kshetri, 2018). However, prior research has largely treated blockchain as a direct antecedent of environmental outcomes, leaving substantially underspecified the mechanisms through which blockchain-structured digital resources are transformed — via interorganizational collaboration — into advanced eco-innovation capabilities (Nandi et al., 2021).

This study addresses that gap by proposing and empirically testing a moderated mediation model in which GSCC serves as the central mechanism linking BTAI to EIP. The theoretical framework draws on dynamic capabilities theory to explain how blockchain enables firms to sense and integrate ecological resources across supply chain networks (Teece et al., 1997). The framework also incorporates stakeholder theory (Freeman, 1984) to foreground the relational dimension of sustainability co-creation. The realization of eco-innovation from these integrated resources is contingent upon three boundary conditions: supply chain partner commitment (SPC), operational complexity (OC), and sustainability learning capability (SLC). Proactive engagement with these contextual factors is a hallmark of firms with sophisticated environmental strategies (Buysse & Verbeke, 2003).

See: https://inatgi.in/index.php/jbgi/index for more information. https://doi.org/10.63646/jbgi.2025.030302

Our study contributes to the literature in three ways. First, it identifies GSCC as the critical mediating mechanism linking BTAI to EIP, extending dynamic capabilities theory into the domain of digital sustainability. Second, it reconciles mixed empirical evidence on blockchain's environmental effects by identifying actionable boundary conditions. Third, it provides context-specific guidance for polluting manufacturing firms in emerging economies. The remainder of the paper is organized as follows. Section 2 reviews the theoretical foundations and develops five research hypotheses. Section 3 describes the research methodology. Section 4 presents the empirical results. Section 5 discusses theoretical and managerial implications, and Section 6 concludes with limitations and future research directions.

2. Theoretical Background and Hypotheses

2.1 Dynamic Capabilities Theory and Stakeholder Theory

Dynamic capabilities theory (DCT) provides the primary theoretical lens for this study. Eisenhardt & Martin (2000) conceptualized dynamic capabilities as the organizational processes through which firms integrate, reconfigure, gain, and release resources to match and even create market change. Building on this foundation, Teece (2007) articulated three specific higher-order processes — sensing environmental opportunities, seizing resources to capture identified value, and reconfiguring asset bases to sustain competitive advantage — that collectively constitute a firm's dynamic capability profile. Applied to environmental management, these processes increasingly operate through digital coordination mechanisms as firms scan supply chain ecosystems for green resource opportunities and deploy collaborative technologies to build sustainability capabilities.

Resource-based logic establishes that superior performance derives from rare, inimitable organizational capabilities rather than from technology adoption per se (Barney, 1991). This foundational insight motivates our focus on GSCC as the dynamic capability through which blockchain resources are converted into eco-innovation outcomes. Recent work examining blockchain applications in Industry 4.0 manufacturing contexts has confirmed that blockchain generates value primarily by enabling firms to bundle and leverage digitally structured resources across organizational boundaries (Chen et al., 2024).

Stakeholder theory (Donaldson & Preston, 1995) complements DCT by foregrounding the relational dimension of sustainability. It posits that firms create superior long-term value by proactively managing the interests and expectations of key stakeholder groups — including suppliers, customers, regulators, and communities. The relational view of competitive advantage further establishes that interorganizational value is co-created through long-term supplier partnerships and collaborative innovation arrangements (Dyer & Singh, 1998). In supply chain sustainability contexts, eco-innovation thus emerges not from isolated firm-level decisions but from the co-creation of green capabilities with partners who share environmental objectives.

Figure 1 presents the conceptual research model integrating these theoretical perspectives. BTAI functions as the initiating digital resource that reconfigures supply chain information flows and coordination mechanisms. GSCC serves as the dynamic capability through which these reconfigured resources are bundled into eco-innovation outcomes. SPC, OC, and SLC represent contingent conditions shaping the effectiveness of this resource-to-capability transformation process.

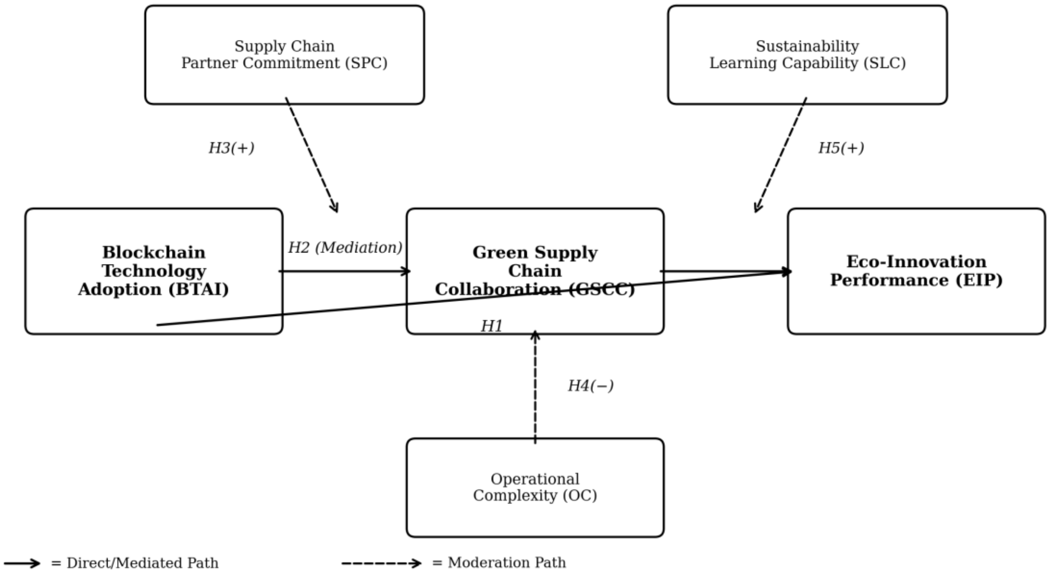

Figure 1. Conceptual Research Model: Blockchain-Enabled Green Supply Chain Collaboration and Eco-Innovation Performance.

2.2 Blockchain Technology Adoption Intensity and Eco-Innovation Performance

Blockchain technology adoption intensity (BTAI) captures the depth and breadth with which a firm embeds blockchain capabilities — including distributed ledger management, smart contract deployment, and tokenized incentive mechanisms — into its supply chain operations. A systematic review of blockchain implementation across diverse information systems demonstrates that deep blockchain adoption enhances information quality, coordination efficiency, and process transparency across organizational boundaries (Lu, 2022). These systemic improvements create a fertile digital infrastructure for eco-innovation by enabling firms to precisely monitor and manage environmental resource flows throughout the supply chain.

From a sensing perspective, blockchain enables real-time, verifiable monitoring of environmental data across supply networks — including carbon emission records, energy consumption data, and green material certifications (Hastig & Sodhi, 2020). This environmental visibility allows firms to identify eco-innovation opportunities that would otherwise remain hidden within opaque supply chains. Beyond traceability, blockchain also creates new possibilities for embedding environmental compliance directly into supply chain IoT infrastructure, automating the capture of green performance data at every transaction node (Xu et al., 2021).

From a seizing perspective, blockchain's smart contract functionality automates environmental compliance and programmatically incentivizes green supplier behavior, reducing the transaction costs of procuring and deploying green resources (Charoenwong et al., 2024). Blockchain also protects intellectual property and green certification by providing tamper-proof records that safeguard eco-innovation investment returns (Luo et al., 2023). The indirect pathway from blockchain adoption to environmental performance is further reinforced by its capacity to reshape supply chain knowledge networks and patterns of cross-boundary collaborative R&D (Li et al., 2018). Accordingly, we propose:

H1: Blockchain technology adoption intensity is positively associated with eco-innovation performance.

2.3 The Mediating Role of Green Supply Chain Collaboration

While the direct BTAI–EIP link is theoretically plausible, we argue that GSCC constitutes the primary pathway through which blockchain resources are converted into eco-innovation outcomes. GSCC refers to the coordinated, long-term engagement among supply chain partners to jointly develop, share, and deploy environmentally superior knowledge, technologies, and practices (Vachon & Klassen, 2008). Unlike conventional supply chain integration, GSCC is explicitly oriented toward sustainability objectives. Meta-analytic evidence confirms that supply chain integration mediates the relationship between technology investments and firm-level innovation outcomes, establishing it as a key mechanism in the technology-to-performance chain (Leuschner et al., 2013).

Dynamic capabilities theory suggests that advanced innovation capabilities emerge from the orchestration of complementary resources across organizational boundaries (Teece et al., 1997). BTAI structures digital resources — including supplier environmental performance data, lifecycle assessment information, and real-time material flow records — that are necessary but insufficient for eco-innovation. GSCC bundles these structured digital resources with the tacit green knowledge held by supply chain partners, creating the combined capability required for eco-innovation outcomes. Blockchain governance mechanisms reduce opportunistic behavior and enable the deeper interorganizational collaboration required for this bundling to occur (Lumineau et al., 2021).

Blockchain's role as a foundation for supply chain finance and coordination is further highlighted by research demonstrating how large language models integrated with blockchain infrastructure enable new forms of supply chain partner collaboration (Yang et al., 2025). From a stakeholder perspective, GSCC also serves as the relational mechanism through which blockchain-mediated transparency aligns partner interests around shared sustainability objectives. Research on business model design and operational performance confirms that supply chain integration is the critical link between digital strategies and operational sustainability improvements (Liu et al., 2021).

Integrating contractual and relational governance mechanisms amplifies the performance benefits of supply chain digitalization by ensuring that structured blockchain data flows translate into genuine collaborative green action (Zhou et al., 2023). Systematic analyses of blockchain's operational implications further confirm its particular value in enabling cross-partner information sharing that underpins collaborative sustainability outcomes (Cole et al., 2019). Accordingly:

H2: Green supply chain collaboration mediates the positive relationship between blockchain technology adoption intensity and eco-innovation performance.

2.4 The Moderating Role of Supply Chain Partner Commitment (H3)

Supply chain partner commitment (SPC) reflects the degree to which supply chain members are pledged to maintaining and investing in the collaborative relationship over the long term, including willingness to share sensitive environmental information and co-invest in green capability development (Anderson & Weitz, 1992). SPC functions as a relational governance mechanism that shapes the depth of resource sharing enabled by blockchain platforms. When partner commitment is high, firms are more willing to utilize the full data visibility afforded by BTAI — including green technology patents and real-time operational data — without fear of opportunistic exploitation. A study of blockchain adoption determinants among small and medium-sized enterprises confirmed that pre-existing relationship quality is a critical predictor of blockchain adoption depth and collaborative outcomes (Iranmanesh et al., 2023).

Systematic reviews of blockchain adoption in supply chains identify interorganizational trust and commitment as critical determinants of the collaborative depth achieved through shared blockchain platforms (Wang et al., 2019). When partner commitment is low, substantial BTAI investments cannot overcome the reluctance of supply chain actors to expose sensitive environmental data, limiting the depth of blockchain-enabled integration. Research on supply chain trust further demonstrates that calculative and relational trust jointly shape the performance benefits that partners derive from digital sharing arrangements (Poppo et al., 2016).

Evidence from circular supply chain research demonstrates that blockchain's ability to build trust and traceability across network nodes is the key mechanism through which it facilitates collaborative sustainability outcomes (Centobelli et al., 2022). By enabling firms to extract the full relational value of shared blockchain data, partner commitment transforms digital transparency into deeper eco-innovation capability. A complementary literature stream confirms that blockchain's value in supply chains is realized primarily through the relational mechanisms it activates rather than through the technology architecture alone (Chang & Chen, 2020). Accordingly:

H3: Supply chain partner commitment positively moderates the relationship between BTAI and GSCC, such that the positive effect of BTAI on GSCC is stronger when SPC is high.

2.5 The Moderating Role of Operational Complexity (H4)

Operational complexity (OC) describes the degree to which interorganizational tasks involve multifaceted, nonroutine, and difficult-to-standardize work processes (Daft & Macintosh, 1981). Blockchain's core value lies in managing well-defined, codifiable transactions through programmable smart contracts. However, when the operational environment is characterized by high complexity — involving bespoke customization, multi-tier coordination, or rapidly shifting environmental standards — the codification requirements of blockchain conflict with the inherent ambiguity of complex interorganizational tasks. The constraining effect of task complexity on interorganizational governance mechanisms has been empirically documented in the context of multilateral strategic alliances (Li et al., 2017).

Under high operational complexity, supply chain actors must rely on informal, flexible coordination mechanisms — such as face-to-face communication and relational contracting — that are difficult to capture or automate through blockchain protocols (Ziolkowski et al., 2020). A systematic review of blockchain applications across supply chains, transport, and logistics corroborates this finding, establishing operational complexity as a key contextual moderator of blockchain's collaborative effectiveness (Pournader et al., 2020). The technical architecture requirements for blockchain-based supply chain transparency are also substantially more demanding in complex operational settings, further attenuating blockchain's collaborative returns (Venkatesh et al., 2020). Therefore:

H4: Operational complexity negatively moderates the relationship between BTAI and GSCC, such that the positive effect of BTAI on GSCC is weaker when OC is high.

2.6 The Moderating Role of Sustainability Learning Capability (H5)

Sustainability learning capability (SLC) captures an organization's ability to systematically acquire, absorb, and apply knowledge related to sustainable development objectives through formal and informal learning mechanisms. Deliberate organizational learning processes represent a meta-level capability that enables firms to continuously update their operational routines and strategic orientations in response to evolving environmental demands (Zollo & Winter, 2002). When SLC is strong, the integrated resources achieved through GSCC are channeled toward green product development, clean technology adoption, and circular economy implementation, ensuring that supply chain-derived green knowledge is codified and applied systematically to eco-innovation.

Sustainability learning has been empirically linked to superior green innovation performance in digitally enabled supply chain contexts (Halbusi et al., 2024). Firms with strong sustainability learning orientations possess both the motivation and organizational capacity to direct integrated knowledge toward environmental problem-solving. Research on blockchain applications in organizational auditing and internal control demonstrates that the performance value of blockchain-enabled information systems depends critically on organizations' capacity to absorb and act upon the insights generated by blockchain data flows (Wu et al., 2025).

Bibliometric analyses of blockchain technology research trajectories confirm that blockchain's value for sustainability outcomes is realized only when firms develop complementary learning and sense-making capabilities (Zheng & Lu, 2022). At the supply chain level, a shared sustainability learning orientation across partner organizations amplifies the green innovation value generated through collaborative integration. Research integrating big data analytics and green supply chain processes further demonstrates that digital sustainability tools generate superior environmental performance when coupled with organizational learning mechanisms oriented toward sustainability objectives (Benzidia et al., 2021). Accordingly:

H5: Sustainability learning capability positively moderates the relationship between GSCC and EIP, such that the positive effect of GSCC on EIP is stronger when SLC is high.

3. Research Methodology

3.1 Sample and Data Collection

This study targets senior managers in pollution-intensive manufacturing firms operating in China. We focused on sectors designated as high-pollution by China's Ministry of Ecology and Environment, including metal smelting and processing, chemical manufacturing, plastics and rubber, and power generation. China provides an appropriate empirical context because its manufacturing sector accounts for a disproportionate share of global industrial pollution, and the country's environmental governance agenda has compelled firms in these sectors to actively seek technological and collaborative sustainability solutions. The strategic importance of circular economy practices in managing supply chain sustainability has been extensively documented in this context (Govindan & Hasanagic, 2018).

Questionnaires were initially developed in English and subsequently translated into Mandarin Chinese using a back-translation procedure, following the protocol recommended by Brislin (1980). Prior to the main survey, semi-structured interviews were conducted with eight senior executives — including Chief Operations Officers and Vice Presidents of Supply Chain — to assess face validity and item clarity. A pilot study involving 35 manufacturing firms produced minor item refinements. The main survey was distributed through the Credamo professional survey platform, which screens respondents by industry, job title, and minimum work experience. Survey-based research on blockchain adoption has similarly employed online survey platforms targeting experienced supply chain professionals (Queiroz & Wamba, 2019).

Data collection commenced in July 2024 and concluded after 75 days. A total of 501 questionnaires were distributed, of which 412 were returned (response rate: 82.2%). After excluding 23 incomplete responses, the final usable sample comprised 389 firms. Non-response bias was assessed by comparing early and late respondents across all key variables; independent-samples t-tests revealed no significant differences ($p > .05$), indicating that non-response bias is not a material concern (Armstrong & Overton, 1977). Table 1 provides the full sample profile.

Table 1. Sample Characteristics (N = 389)

Characteristic	Category	n	%
Industry Sector	Metal Smelting & Processing	98	25.2
	Chemical Manufacturing	112	28.8
	Plastics & Rubber	67	17.2
	Power Generation & Supply	58	14.9
	Mining & Quarrying	54	13.9
Respondent Position	CEO / President	82	21.1
	Vice President / Director	201	51.7
	Senior Manager	106	27.2
Firm Size (Employees)	200–399	154	39.6
	400–799	143	36.8

	800–1,999	72	18.5
	≥ 2,000	20	5.1
Blockchain Adoption Tenure	1–2 years	118	30.3
	3–5 years	189	48.6
	> 5 years	82	21.1

3.2 Measurement of Variables

All constructs were measured on seven-point Likert scales (1 = strongly disagree, 7 = strongly agree) using established scales adapted from prior literature. Blockchain technology adoption intensity (BTAI; 4 items) was adapted from the foundational blockchain adoption scale developed by Dubey et al. (2020), capturing the extent to which blockchain is embedded in supply chain operations, coordination, transaction settlement, and environmental traceability. The BTAI items were further refined using the supply chain transparency and blockchain agility dimensions validated by Iranmanesh et al. (2023). Green supply chain collaboration (GSCC; 5 items) was adapted from Vachon & Klassen (2008), reflecting joint green planning, the co-development of environmentally superior products and processes, and collaborative environmental problem-solving with key supply chain partners.

Eco-innovation performance (EIP; 4 items) was adapted from the measurement scale developed by Chen et al. (2006), assessing green product development, clean process innovation, and circular economy practices. The validation of green supply chain management measures typically requires items that capture both the product design and process improvement dimensions of environmental innovation (Zhu et al., 2008). Supply chain partner commitment (SPC; 4 items) was adapted from Anderson & Weitz (1992), measuring mutual dedication and the willingness to invest in the collaborative relationship over the long term.

Operational complexity (OC; 4 items) was adapted from the foundational measurement framework of Daft & Macintosh (1981), capturing task nonroutineness, multidisciplinarity, and output standardization difficulty. Sustainability learning capability (SLC; 3 items) was adapted from Halbusi et al. (2024), assessing organizational emphasis on acquiring, sharing, and applying sustainability-related knowledge through digital platforms. Additional SLC items were informed by the green supply chain learning framework validated by Benzidia et al. (2021). Large-scale empirical studies of blockchain adoption and supply chain performance have validated similar survey-based measurement approaches (Wamba et al., 2020). Firm size, firm age, and industry type were included as control variables in all regression models.

Research on green supply chain management has increasingly relied on perceptual Likert-scale measures from senior managers, an approach that has been validated for constructs reflecting organizational orientations and relational qualities (Green et al., 2012). Items measuring supply chain integration and collaboration were further anchored using the operational performance context developed by Kim & Schoenherr (2018) to ensure measurement relevance for manufacturing settings.

3.3 Common Method Bias

Because all constructs were collected from the same respondent at a single point in time, common method bias (CMB) was addressed through both procedural and statistical means. Procedurally, respondent anonymity was guaranteed, varied scale anchors were employed, and key dependent variables were placed in a separate section of the questionnaire, following the best practices established by Podsakoff et al. (2003). Statistically, Harman's single-factor test was applied: an unrotated exploratory factor analysis of all items produced a first factor explaining 24.8% of total variance, well below the 50% threshold. A common method factor was additionally introduced into the confirmatory factor analysis; its inclusion did not significantly improve model fit (ΔCFI = .006).

The suitability of these approaches for supply chain survey research has been extensively documented (Hair et al., 2019).

4. Data Analysis and Results

4.1 Measurement Model Assessment

Confirmatory factor analysis (CFA) was conducted using AMOS 26.0. The six-factor measurement model demonstrated good fit to the data: $\chi^2/df = 1.847$, RMSEA = 0.031, CFI = 0.942, TLI = 0.937, NFI = 0.921, IFI = 0.943. All standardized factor loadings exceeded 0.70, and all item-to-construct t-values were significant at $p < .001$. Table 2 presents the complete measurement model results, including factor loadings, Cronbach's alpha (α), composite reliability (CR), and average variance extracted (AVE). All α values exceeded 0.70 and all CR values exceeded 0.80, indicating strong construct reliability. The AVE threshold of 0.50 provides evidence of convergent validity (Fornell & Larcker, 1981).

Discriminant validity was assessed using the Fornell-Larcker criterion: the square root of each construct's AVE exceeded its correlations with all other constructs. We additionally examined the heterotrait-monotrait (HTMT) ratio; no value exceeded the conservative threshold of 0.85 (Henseler et al., 2015). Table 3 presents the descriptive statistics, inter-construct correlations, and square roots of AVE values on the diagonal. The pattern of correlations is consistent with the theoretical model: BTAI is significantly and positively correlated with both GSCC ($r = 0.278$, $p < .01$) and EIP ($r = 0.241$, $p < .01$), and GSCC is significantly correlated with EIP ($r = 0.312$, $p < .01$), supporting the plausibility of the moderated mediation structure.

Table 2. Measurement Model Results: Factor Loadings, Reliability, and Validity

Construct / Item	Loading	α	CR	AVE
Blockchain Technology Adoption Intensity (BTAI)		**0.824**	**0.871**	**0.629**
BTAI1: We use blockchain for supply chain operational monitoring	**0.784**			
BTAI2: We use blockchain for cross-partner coordination and scheduling	**0.791**			
BTAI3: We use blockchain for transaction settlement and verification	**0.812**			
BTAI4: We use blockchain for environmental data traceability	**0.798**			
Green Supply Chain Collaboration (GSCC)		**0.849**	**0.889**	**0.617**
GSCC1: We jointly plan environmental improvement goals with key partners	**0.776**			
GSCC2: We co-develop green products and processes with key partners	**0.803**			
GSCC3: We share environmental performance data openly with partners	**0.814**			
GSCC4: We collaboratively resolve environmental compliance challenges	**0.778**			
GSCC5: We engage partners in sustainable logistics and packaging decisions	**0.766**			
Eco-Innovation Performance (EIP)		**0.812**	**0.863**	**0.613**
EIP1: Our supply chain selects products that minimize environmental impact	**0.793**			
EIP2: We adopt clean production technologies across our supply chain	**0.786**			
EIP3: We implement circular material and waste recycling systems	**0.779**			
EIP4: We continuously reduce energy consumption in supply chain operations	**0.771**			
Supply Chain Partner Commitment (SPC)		**0.807**	**0.856**	**0.598**
SPC1: Our partners are dedicated to maintaining our long-term collaboration	**0.776**			

SPC2: Partners invest resources to sustain our green collaboration	**0.774**			
SPC3: Partners prioritize this relationship for mutual environmental benefit	**0.784**			
SPC4: Partners accept short-term sacrifices for long-term green objectives	**0.761**			
Operational Complexity (OC)		**0.798**	**0.850**	**0.587**
OC1: Our supply chain tasks require extensive multidisciplinary expertise	**0.758**			
OC2: Collaboration outcomes are difficult to quantify with standard metrics	**0.771**			
OC3: Interorganizational tasks require intensive coordination of personnel	**0.776**			
OC4: Task specifications change frequently, requiring constant renegotiation	**0.763**			
Sustainability Learning Capability (SLC)		**0.816**	**0.861**	**0.673**
SLC1: Our firm systematically acquires sustainability knowledge digitally	**0.809**			
SLC2: We share green lessons learned across supply chain partners	**0.833**			
SLC3: We apply digital sustainability insights to guide eco-innovation	**0.814**			
Model Fit: χ^2/df = 1.847; RMSEA = 0.031; CFI = 0.942; TLI = 0.937; NFI = 0.921; IFI = 0.943				

Table 3. Descriptive Statistics and Interconstruct Correlations (N = 389)

Variable	M	SD	1	2	3	4	5	6
1. BTAI	5.521	0.721	(0.793)					
2. GSCC	5.843	0.648	0.278**	(0.785)				
3. EIP	5.389	0.794	0.241**	0.312**	(0.783)			
4. SPC	5.976	0.583	0.203**	0.198**	0.156*	(0.773)		
5. OC	4.812	0.947	−0.117*	0.104*	0.041	0.097	(0.766)	
6. SLC	5.711	0.862	0.089	0.143*	0.247**	0.132*	0.025	(0.820)

Note. *Diagonal elements (in parentheses) are the square roots of AVE. M = mean; SD = standard deviation. *p < .05; **p < .01.*

4.2 Main Effect and Mediation Analysis

Structural equation modeling (SEM) was conducted using AMOS 26.0. Mediation effects were estimated via bootstrapping with 5,000 resamples, following the analytical procedures recommended by Aiken & West (1991). The structural model yielded good fit: χ^2/df = 1.893, RMSEA = 0.033, CFI = 0.938, TLI = 0.932, NFI = 0.917. Results are summarized in Table 4. Consistent with H1, BTAI exhibited a significant positive direct effect on EIP ($\beta = 0.163$, $p < .001$). This finding extends prior research documenting that blockchain adoption creates environmental value beyond its traditional applications in supply chain transparency (Kouhizadeh & Sarkis, 2018).

In support of H2, BTAI was positively associated with GSCC ($\beta = 0.241$, $p < .001$), and GSCC in turn positively predicted EIP ($\beta = 0.198$, $p < .001$). When GSCC was included in the model, the direct BTAI–EIP path became non-significant ($\beta = 0.048$, $p = .312$), indicating full mediation. The bootstrapped indirect effect of BTAI on EIP through GSCC was significant ($\beta = 0.182$, 95% CI [0.127, 0.244]). This full mediation pattern is consistent with the dynamic capabilities perspective that superior innovation outcomes emerge from collaborative capability development rather than from isolated technology adoption (Eisenhardt & Martin, 2000). Empirical research on blockchain adoption dynamics further corroborates this finding, showing that the positive supply chain performance effects of blockchain are strongest under conditions of deep collaborative adoption (Wamba et al., 2020).

4.3 Moderation Analysis

All variables involved in interaction terms were mean-centered prior to computing product terms. Moderation results are presented in Table 4. Consistent with H3, the BTAI × SPC interaction was positively significant ($\beta = 0.317$, $p < .001$), indicating that partner commitment amplifies blockchain's enabling effect on green supply chain collaboration. This result accords with the broader finding that digital supply chain tools generate superior collaborative outcomes in relational contexts characterized by high levels of interpartner commitment (Büyüközkan & Göçer, 2018). The interaction pattern further confirms that supply chain integration is most effective when supported by robust collaborative relationships across supply chain participants (Cao & Zhang, 2011).

Consistent with H4, the BTAI × OC interaction was significantly negative ($\beta = -0.138$, $p < .01$), confirming that operational complexity attenuates the BTAI–GSCC relationship. This finding corroborates the broader observation that blockchain's governance mechanisms perform suboptimally in complex, nonroutine interorganizational task environments where codification demands exceed organizational capacity (Manupati et al., 2020). The SLC × GSCC interaction coefficient was positive and significant ($\beta = 0.226$, $p < .001$), supporting H5: sustainability learning capability significantly strengthens the translation of green supply chain collaboration into eco-innovation performance. This moderation effect reflects the reconfiguring dimension of dynamic capabilities, whereby learning orientations direct integrated resources toward strategic environmental objectives. Research has established the business case for proactive green innovation strategies and confirmed that organizational learning capabilities enable firms to fully realize the value of collaborative resource integration (Ambec & Lanoie, 2008).

Figure 2 illustrates the moderating effect of SPC on the BTAI–GSCC relationship. As depicted, the positive slope connecting BTAI to GSCC is substantially steeper under conditions of high partner commitment, while firms with low partner commitment derive significantly less collaborative benefit from blockchain investment. This interaction pattern is consistent with stakeholder theory's prediction that relational governance quality determines whether digital transparency is converted into genuine collaborative green capability. The differential slopes confirm that investment in partner relationships should be treated as a strategic complement to blockchain technology deployment (Shen et al., 2022).

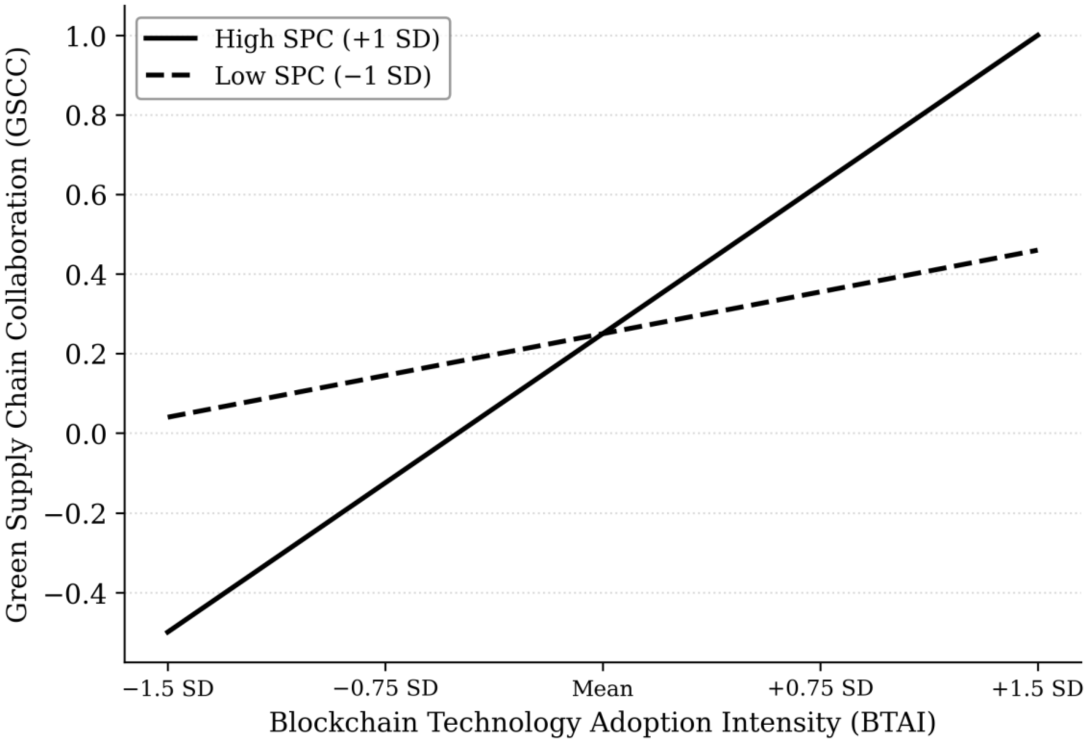

Figure 2. Moderating Effect of Supply Chain Partner Commitment (SPC) on the Relationship Between Blockchain Technology Adoption Intensity (BTAI) and Green Supply Chain Collaboration (GSCC).

Table 4. Structural Model Results and Hypothesis Testing (N = 389)

Path / Interaction	**β**	**SE**	**t**	**p**	**Supported?**
Direct Effects					
H1: BTAI → EIP (direct only)	0.163	0.041	3.976	< .001	Yes (non-sig. with mediator)
BTAI → GSCC	0.241	0.038	6.342	< .001	—
GSCC → EIP	0.198	0.043	4.605	< .001	—
BTAI → EIP (with GSCC included)	0.048	0.047	1.021	.312	—
Mediation (H2)					
Indirect: BTAI → GSCC → EIP	0.182	0.029	—	< .001	Yes 95% CI [0.127, 0.244]
Moderation on GSCC					

H3: BTAI × SPC → GSCC	0.317	0.052	6.096	< .001	Yes
H4: BTAI × OC → GSCC	−0.138	0.048	−2.875	.004	Yes
Moderation on EIP					
H5: GSCC × SLC → EIP 0.226 0.059 3.831 < .001 Yes					
Model Fit					
R² (GSCC = 0.573; EIP = 0.601) F: 54.72*** (GSCC) / 62.38*** (EIP)					

Note. *β = standardized coefficient; SE = standard error; bootstrapped 95% CI for indirect effect (H2). ***p < .001; **p < .01; *p < .05.*

5. Discussion

5.1 Theoretical Contributions

This study makes three principal contributions to the academic literature. First, by empirically establishing GSCC as a full mediator of the BTAI–EIP relationship, the study provides a theoretically grounded account of how blockchain adoption generates eco-innovation outcomes. The dominant prior literature stream has treated blockchain as a direct driver of environmental performance (Saberi et al., 2019), leaving the intervening organizational mechanisms underspecified. Our findings demonstrate that blockchain enhances eco-innovation primarily by enabling firms to develop richer, more deeply integrated green collaborative capabilities with supply chain partners. A comprehensive review of green supply chain management research documents that collaborative practices, rather than individual firm actions, are the primary drivers of environmental performance improvements (Tseng et al., 2019).

Second, the study extends dynamic capabilities theory into the intersection of digital transformation and ecological sustainability. Prior DCT applications have examined either technology management or environmental management in isolation; few have systematically mapped the sensing-seizing-reconfiguring framework onto blockchain-enabled green capability formation at the supply chain level. Meta-analytic evidence confirms that environmentally sustainable supply chain management practices generate measurable firm performance improvements, underscoring the theoretical and practical value of this digital-ecological integration (Golicic & Smith, 2013).

Third, by identifying SPC and OC as boundary conditions on the BTAI–GSCC relationship, the study reconciles the mixed empirical evidence on blockchain's environmental effects. Some prior studies have confirmed positive blockchain–sustainability relationships (Kouhizadeh & Sarkis, 2018). Other studies, however, have reported failure cases and null effects from blockchain adoption (Najati, 2025). Recent operational analyses of blockchain technology providers further highlight that centralized decision-making and limited partner engagement are primary factors undermining blockchain's collaborative potential (Zhan et al., 2025). Our contingency analysis clarifies that these divergent findings reflect differences in the relational and structural deployment contexts of blockchain. These boundary condition insights align with the broader finding that institutional and relational context significantly shapes environmental strategy outcomes (Berrone et al., 2013).

5.2 Managerial Implications

The findings carry several actionable implications for managers in pollution-intensive manufacturing firms. First, the full mediation result indicates that blockchain investment is necessary but not sufficient for eco-innovation improvement. Managers should use blockchain platforms as infrastructure for environmental co-design, collaborative R&D, and joint sustainability goal-setting, rather than as mere auditing or tracing tools. Research on green product innovation confirms the competitive value of these investments when systematically implemented across the supply chain (Lin et al., 2013).

Second, the positive moderating effect of SPC underscores the strategic importance of relational investment alongside technological investment. Firms should prioritize building partner commitment — through long-term contracting, joint sustainability training, and shared green performance incentives — as a precondition for maximizing blockchain's collaborative value. Research confirms that proactive firms that manage stakeholder relationships strategically achieve superior environmental outcomes compared with those that respond reactively to external pressure (Buysse & Verbeke, 2003).

Third, the negative moderation of OC implies that firms facing highly complex interorganizational environments should moderate their expectations of blockchain's short-term collaborative benefits. Before deploying blockchain, such firms may benefit from simplifying supply chain structures, standardizing product specifications, and using process mapping tools to reduce encoding complexity. Supply chain risk management literature suggests that structural simplification improves coordination capacity (Tang & Musa, 2011).

Finally, the positive moderation of SLC affirms that eco-innovation outcomes from supply chain collaboration are substantially enhanced when firms invest systematically in sustainability learning. Managers are encouraged to establish formal green knowledge management systems, cross-functional sustainability learning communities, and digital platforms for sharing ecological best practices across supply networks. Green innovation strategies that incorporate explicit learning mechanisms deliver superior environmental and business performance outcomes (Soewarno et al., 2019).

6. Conclusion and Limitations

This study investigated the mechanisms through which blockchain technology adoption intensity promotes eco-innovation performance among pollution-intensive manufacturing firms. Drawing on dynamic capabilities theory and stakeholder theory, and testing a moderated mediation model with survey data from 389 Chinese manufacturing enterprises, we established that green supply chain collaboration fully mediates the positive effect of BTAI on EIP. Supply chain partner commitment amplifies, while operational complexity attenuates, the enabling effect of BTAI on GSCC. Sustainability learning capability strengthens the conversion of GSCC into eco-innovation performance. These findings advance the theoretical understanding of digital sustainability and provide actionable guidance for pollution-intensive firms seeking to leverage blockchain as a green transformation tool. The well-established business case for proactive environmental management provides further motivation for firms to pursue this integrated digital-sustainability strategy (Christmann, 2000).

Several limitations should be acknowledged. First, the cross-sectional survey design precludes definitive causal inference. Future research employing longitudinal panel data or quasi-experimental designs would substantially strengthen causal conclusions. Second, the sample is confined to Chinese manufacturing firms, which may limit generalizability. Replication in South Asian, Southeast Asian, or Latin American emerging market contexts would enhance external validity. Third, this study relied on perceptual measures of green collaboration and eco-innovation; future research might incorporate objective secondary data — such as patent registries or emission databases — to supplement self-reported measures. Fourth, alternative mediating and moderating pathways — including the role of manufacturing operations integration and supply chain configuration (Swink et al., 2007) — merit further investigation alongside replications in other institutional contexts. Understanding how regulatory carbon pricing schemes shape the eco-innovation strategies of polluting firms offers a particularly promising avenue for future work (Yenipazarli, 2019).

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