Digital Transformation and Green Innovation Efficiency: Empirical Evidence on Blockchain-Enabled Supply Chain Integration

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Abstract

The accelerating integration of blockchain technology into manufacturing supply chains has prompted intensifying scholarly and managerial interest in how digital ledger capabilities translate into sustainable performance outcomes. Drawing on the resource orchestration perspective and the dynamic capabilities view, this study empirically examines the mechanism through which blockchain technology application (BTA) enhances green innovation efficiency (GIE) in Malaysian manufacturing firms operating under heightened environmental regulatory pressure. We propose that supply chain integration (SCI) functions as a network-level bundling mechanism that converts structured digital resources into systemic green innovation capabilities, while supply chain trust, task complexity and a green digital learning orientation serve as boundary conditions that shape the strength of the transformation. Survey data were collected from 401 senior managers of Malaysian manufacturers distributed across seven heavily-regulated industry sub-sectors. Structural equation modelling and bias-corrected bootstrap analysis show that SCI fully mediates the positive relationship between BTA and GIE (indirect $\beta = 0.045$, 95% CI [0.020, 0.073]); supply chain trust positively moderates the BTA→SCI pathway while task complexity attenuates it; and a green digital learning orientation amplifies the SCI→GIE pathway. Heterogeneity analysis demonstrates that the indirect benefit of BTA is substantially larger for large firms and high-pollution sectors. The findings advance digital transformation theory by unpacking the systemic mechanism linking blockchain infrastructure to environmentally-oriented innovation outcomes and inform practitioners about the organisational and relational conditions under which blockchain investment translates into genuine sustainability performance.

Keywords: Blockchain technology application; Green innovation efficiency; Supply chain integration; Digital transformation; Resource orchestration; Malaysian manufacturing; Bootstrap mediation analysis

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1. Introduction

Digital transformation has moved from a peripheral technology investment agenda to a central strategic concern for manufacturing firms navigating intensifying environmental regulation, compressed innovation cycles and volatile global supply networks. Governments across both developed and emerging economies have progressively tightened emission caps, mandated end-of-life product stewardship and imposed carbon-intensity disclosure requirements, while investors and downstream buyers increasingly condition capital allocation and procurement decisions on verifiable environmental performance (Ahmed and Rasheed, 2023; Sulaiman et al., 2024; Wang and Chiou, 2024). The consequence for manufacturers, particularly those operating in energy- and material-intensive sub-sectors, is a structural shift in which sustainable competitiveness now depends on the firm's ability to generate environmentally-oriented innovation at scale and in a credibly auditable manner.

Within this shifting institutional landscape, blockchain technology has emerged as a candidate digital infrastructure with distinctive affordances for sustainability governance (Kouhizadeh et al., 2022; Saberi et al., 2019). Blockchain's immutable ledger, cryptographic authentication and programmable smart contracts enable supply chain participants to record, verify and automate claims about provenance, emissions intensity and environmental compliance in ways that are difficult to achieve through traditional enterprise resource planning or electronic data interchange systems (Cole et al., 2019; Treiblmaier, 2018). Industry reports estimate that more than 40% of Malaysian large manufacturers have either piloted or adopted blockchain-based traceability modules since 2020, a rate that exceeds the ASEAN regional average and that reflects the country's prioritisation of digital transformation in the Twelfth Malaysia Plan and the National Fourth Industrial Revolution Policy (Ministry of Economy Malaysia, 2023). Despite these policy signals and rising adoption rates, the empirical question of whether and through what mechanisms blockchain technology application (BTA) actually produces green innovation outcomes remains unresolved.

The existing scholarly literature on BTA and sustainability has generated a substantial body of descriptive and conceptual contributions but comparatively few rigorous empirical tests of the underlying causal mechanisms (Centobelli et al., 2022; Dutta et al., 2020; Queiroz et al., 2020). Conceptual work has argued that blockchain's verification and coordination properties should support sustainability through enhanced transparency, reduced opportunism and improved compliance monitoring, yet empirical tests have generated mixed and sometimes contradictory findings (Tiwari et al., 2024; Xu et al., 2021). Several studies report positive direct effects of BTA on environmental or green performance (Bai and Sarkis, 2020; Kshetri, 2018), while others identify negative or insignificant effects attributed to high implementation costs, coordination frictions and unresolved governance questions (Clohessy and Acton, 2019; Schmidt and Wagner, 2019). This empirical heterogeneity strongly suggests that the relationship between BTA and green outcomes is not a simple direct one; rather, it is mediated by organisational and inter-

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organisational processes and contingent upon structural and cultural conditions that have not yet been systematically modelled.

The present study addresses this theoretical and empirical gap by developing and testing a moderated mediation model in which supply chain integration (SCI) carries the effect of BTA on green innovation efficiency (GIE). Our theoretical foundation combines the resource orchestration perspective (Sirmon et al., 2011) with the dynamic capabilities view (Teece et al., 1997) and the emerging digital-sustainable business model literature (Gregori and Holzmann, 2020). The core argument is that blockchain technology functions as a digital infrastructure that structures dispersed supply-chain resources into a machine-readable, verifiable resource pool; that supply chain integration operates as the bundling mechanism through which these structured resources are recombined into cross-organisational innovation capabilities; and that the resulting capabilities are leveraged for green innovation under specific cultural and relational conditions. We identify supply chain trust as a relational governance mechanism that intensifies the BTA-to-SCI transformation, task complexity as a structural friction that attenuates it, and green digital learning orientation as a cognitive amplifier of the SCI-to-GIE capability-leveraging process.

This study makes four contributions. First, it opens the 'black box' between BTA and GIE by providing direct empirical evidence that the relationship is fully mediated by supply chain integration, thereby reconciling the mixed findings reported in prior studies that tested only the direct path. Second, it advances the resource orchestration perspective by demonstrating how digital infrastructures accomplish the structuring stage of resource orchestration and how inter-organisational integration accomplishes the bundling stage, with context-specific moderators governing each stage's effectiveness. Third, it provides empirical evidence from Malaysian manufacturing — a rapidly digitalising emerging economy with stringent post-2020 environmental regulation — that complements the existing Chinese-centric empirical base and extends external validity across the broader ASEAN context (Halim et al., 2024). Fourth, it offers granular heterogeneity analysis showing that BTA's mediated benefit for GIE is substantially larger among large firms and high-pollution sectors, which has concrete implications for policy prioritisation and corporate digital investment allocation.

The remainder of the paper proceeds as follows. Section 2 reviews the theoretical foundations and empirical literature on digital transformation, blockchain, green innovation and supply chain integration. Section 3 develops the conceptual framework and derives testable hypotheses. Section 4 describes the research design, sample, measurement and analytical approach. Section 5 reports the empirical results, including structural equation modelling estimates, bootstrap mediation analysis, moderation testing and heterogeneity analysis. Section 6 discusses the theoretical contributions and managerial implications, and Section 7 concludes with limitations and directions for future research.

2. Literature Review

2.1 Digital Transformation and Sustainable Competitiveness

Digital transformation refers to the organisational change enabled and enacted by the integration of digital technologies into business processes, products and operating models (Vial, 2019; Verhoef et al., 2021). The construct encompasses far more than the mere installation of information systems: it denotes a reconfiguration of value propositions, resource allocations and organisational structures in response to the pervasive availability of digital infrastructures (Warner and Wäger, 2019). A substantial body of recent work argues that digital transformation has become particularly consequential for sustainable competitiveness, because digital technologies simultaneously reduce the transaction costs of cross-organisational coordination and generate new data streams that render environmental performance auditable at unprecedented levels of granularity (Del Giudice et al., 2022; Nambisan et al., 2019).

The sustainability-oriented digital transformation literature has converged around three recurring mechanisms. The first is information-based disintermediation, whereby digital infrastructures reduce the need for intermediate actors whose role was to translate between fragmented information silos (Matt et al., 2015). The second is algorithmic amplification, whereby machine learning and decision-support systems enable firms to extract actionable insights from previously opaque operational data (Bag et al., 2020). The third is programmable coordination, whereby automated rule execution replaces discretionary managerial intervention in routine environmental compliance, enforcement and reporting activities (Gregori and Holzmann, 2020). Each of these three mechanisms depends on the existence of a shared, trusted digital substrate, and this is precisely where blockchain technology enters the sustainable-competitiveness narrative.

2.2 Blockchain Technology in Manufacturing Supply Chains

Blockchain technology is a class of distributed ledger technology whose combination of cryptographic authentication, consensus-based validation and tamper-resistant append-only recording has generated sustained scholarly interest across operations management, information systems and sustainability research (Kshetri, 2018; Saberi et al., 2019; Wang et al., 2019). From the perspective of manufacturing supply chains, the distinctive affordances of blockchain fall into three broad categories. First, blockchain supports end-to-end traceability by creating a cryptographically-verifiable record of every material transformation and transfer of custody along a supply chain (Kamble et al., 2020; Kouhizadeh and Sarkis, 2018). Second, blockchain enables authenticated information sharing across organisational boundaries without requiring a trusted intermediary, which has important implications for the scope and depth of inter-firm coordination (Cole et al., 2019). Third, through smart contracts, blockchain permits programmable automation of contractual execution, which reduces monitoring costs and accelerates the settlement of multi-party exchanges (Treiblmaier, 2018).

Empirical studies of blockchain adoption in manufacturing supply chains have accumulated rapidly since 2018 but remain mixed in their conclusions regarding performance outcomes. Several studies document positive associations between blockchain deployment and environmental or operational improvement, particularly in contexts characterised by high provenance uncertainty or extensive regulatory disclosure requirements (Bai and Sarkis, 2020; Dutta et al., 2020). Other studies, however, identify implementation failures, cost overruns and modest or negative performance effects, attributing these outcomes to the technology's high energy consumption, coordination complexity and unresolved governance questions (Clohessy and Acton, 2019; Schmidt and Wagner, 2019). A systematic review by Tiwari et al. (2024) concluded that most existing empirical tests have focused on the direct relationship between blockchain adoption and outcome variables, neglecting the organisational and inter-organisational mechanisms that plausibly mediate this relationship. The present study responds to this gap by

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examining supply chain integration as the central mediating mechanism.

2.3 Green Innovation Efficiency: Concept and Drivers

Green innovation — also referred to as eco-innovation or environmental innovation — designates the development and commercialisation of products, processes or business models that reduce environmental burden relative to relevant baselines (Chen, 2008; Rennings, 2000). Early conceptualisations emphasised the dual nature of green innovation as both a response to environmental regulation and a source of competitive advantage (Porter and van der Linde, 1995; Horbach et al., 2012). The construct has since been disaggregated into green product innovation, green process innovation and green organisational innovation, each of which carries distinctive antecedents and performance consequences (Cai and Li, 2018; Xie et al., 2019).

The efficiency dimension of green innovation — which is the focus of the present study — captures the ratio of environmental improvement to innovation input, typically measured through survey indicators that combine perceived effectiveness, resource intensity and output quality (Hojnik and Ruzzier, 2016; de Medeiros et al., 2014). Focusing on efficiency rather than volume is theoretically motivated by the observation that mere accumulation of green innovation activities — through R&D spending or patent counts — is only weakly correlated with sustainable competitive advantage unless the inputs are efficiently transformed into deployable, market-relevant capabilities (Lin et al., 2013; Zhu et al., 2013). Empirical work has identified a range of efficiency drivers including internal organisational learning, external stakeholder pressure, regulatory stringency and complementary asset endowments (Sarkis and Zhu, 2018; Zhu, Sarkis and Lai, 2012). Among the inter-organisational drivers, supply chain integration has attracted growing attention as a potentially high-leverage mechanism, yet the mediating role of integration between digital infrastructure and green innovation efficiency has not been systematically modelled or tested.

2.4 Supply Chain Integration as a Resource-Bundling Mechanism

Supply chain integration (SCI) denotes the strategic collaboration and synchronisation of a focal firm with its upstream suppliers and downstream customers in respect of information flows, physical flows, financial flows and strategic planning (Flynn et al., 2010; Frohlich and Westbrook, 2001). Classical treatments of SCI have distinguished between internal integration (within a single firm), supplier integration (with upstream partners) and customer integration (with downstream partners), and a large body of evidence supports the contingent performance consequences of each dimension (Vickery et al., 2003; Wong et al., 2011; Zhao et al., 2011). More recent work has extended the SCI construct to digital and platform contexts, in which the integration is mediated by shared information systems and algorithmic coordination mechanisms (Jitpaiboon et al., 2013; Bag et al., 2020).

From a resource orchestration perspective, supply chain integration plays a specific and important role: it functions as the bundling mechanism through which structured but dispersed resources are recombined into firm- and network-level capabilities (Sirmon et al., 2011). When the structuring stage is accomplished by a digital infrastructure such as a blockchain ledger, integration determines whether the resulting data resources are merely stored or actively recombined with tacit knowledge, human expertise and physical assets into deployable innovation capabilities. This mechanism-oriented view of SCI provides the theoretical basis for the mediation hypothesis developed in the next section. It also motivates the examination of contingent conditions — specifically supply chain trust, task complexity and green digital learning orientation — that are known to shape the effectiveness of integration processes in prior empirical work (Panayides and Lun, 2009; Zaheer, McEvily and Perrone, 1998).

3. Conceptual Framework and Hypotheses

3.1 Resource Orchestration Foundations

The resource-based view and its dynamic capabilities extension argue that sustainable competitive advantage flows not from resource possession per se but from the firm's ability to acquire, develop and deploy resources in ways that are valuable, rare, inimitable and non-substitutable (Barney, 1991; Teece, Pisano and Shuen, 1997). The resource orchestration perspective sharpens this argument by articulating three distinct managerial processes — structuring, bundling and leveraging — that jointly determine whether available resources are actually transformed into capability-based competitive advantage (Sirmon, Hitt and Ireland, 2007; Sirmon et al., 2011). Structuring involves the acquisition, accumulation and divestment of resources required for the firm's resource portfolio. Bundling involves integrating disparate resources into routines and capabilities. Leveraging involves deploying capabilities in the pursuit of specific market opportunities. Each stage is contingent on organisational, relational and cognitive conditions that the firm can only partly control (Helfat and Peteraf, 2015; Eisenhardt and Martin, 2000).

In the present context, we posit a specific instantiation of this general framework. Blockchain technology application (BTA) is the digital infrastructure through which dispersed supply-chain resources — material provenance data, emissions records, logistics timestamps, environmental certifications — are structured into a coherent, machine-readable resource pool. Supply chain integration (SCI) is the inter-organisational bundling mechanism through which these structured resources are recombined with tacit knowledge, human expertise and physical assets into deployable innovation capabilities. Green innovation efficiency (GIE) is the capability outcome produced when these recombined resources are leveraged toward environmentally-oriented innovation. The moderating variables — supply chain trust, task complexity and green digital learning orientation — govern the effectiveness of the structuring-to-bundling and bundling-to-leveraging transitions, respectively.

3.2 Direct Effect of BTA on Green Innovation Efficiency

The direct effect of BTA on GIE is theorised through three mechanisms. First, blockchain's immutable and timestamped records provide the raw data required for life-cycle carbon accounting, material provenance verification and closed-loop recycling validation, all of which are foundational inputs to environmentally informed product and process innovation (Kouhizadeh and Sarkis, 2018). Second, blockchain's programmability through smart contracts enables the automation of routine compliance activities, freeing scarce managerial attention for substantive innovation work (Lim et al., 2021). Third, blockchain's authentication and non-repudiation properties reduce the cost of credible environmental claim-making, which strengthens the firm's ability to appropriate value from its green innovations through differentiation and premium pricing (Centobelli et al., 2022).

These three mechanisms operate at the level of the focal firm and do not strictly require cross-firm coordination to produce incremental benefits. Accordingly, we hypothesise a positive direct effect:

H1: Blockchain technology application has a positive direct effect on green innovation efficiency.

3.3 Mediating Role of Supply Chain Integration

Although the direct mechanisms just outlined are plausible, they capture only a fraction of blockchain's potential contribution to green innovation efficiency. The larger part of blockchain's value, we contend, arises from its ability to transform inter-organisational coordination — which is the domain in which supply chain integration operates. When BTA is deployed, the resulting trusted information substrate significantly reduces the friction associated with information sharing, quality verification and joint decision-making across organisational boundaries. This, in turn, enables deeper integration of physical, informational and financial flows among supply chain partners (Bag et al., 2020; Kamble et al., 2020). Empirically, recent work has documented that blockchain adoption is associated with measurable increases in cross-organisational information exchange frequency, joint planning depth and collaborative problem-solving (Cole et al., 2019; Dutta et al., 2020).

Supply chain integration, in turn, has long been identified as a central driver of innovation performance generally and green innovation specifically. Integrated supply chains provide firms with access to complementary knowledge, shared sensing of environmental demand signals, and collective learning opportunities that are unattainable by isolated firms (Flynn et al., 2010; Wong et al., 2011). In the green innovation context, integration enables the closed-loop recycling coordination, joint eco-design workshops and collaborative environmental auditing that characterise high-performing sustainable supply chains (Zhu, Sarkis and Lai, 2012; Xie et al., 2019). We therefore hypothesise:

H2a: Blockchain technology application has a positive effect on supply chain integration.

H2b: Supply chain integration has a positive effect on green innovation efficiency, and supply chain integration mediates the relationship between blockchain technology application and green innovation efficiency.

3.4 Moderating Role of Supply Chain Trust

The conversion of blockchain's information-infrastructure benefits into actual integration depth is contingent on the relational governance climate between supply chain partners. Supply chain trust — the expectation that a partner will behave competently and with benevolent intent — has been shown in a long line of prior research to reduce transaction costs, lower monitoring expenditure and enable deeper information sharing (Dyer and Chu, 2003; Mayer, Davis and Schoorman, 1995; Zaheer et al., 1998). In the blockchain context, trust plays a particularly important role because the technology's default configuration exposes all authorised participants to the entirety of the shared ledger, including potentially sensitive operational metrics (Lim et al., 2021). Firms that trust their counterparts are more willing to accept this exposure, to enrol their sensitive data streams onto the shared ledger and to commit to joint optimisation routines that could not be supported by arms-length contractual arrangements (Panayides and Lun, 2009). We therefore hypothesise:

H3: Supply chain trust positively moderates the relationship between blockchain technology application and supply chain integration, such that the relationship is stronger when trust is higher.

3.5 Moderating Role of Task Complexity

A second contingent condition that shapes the BTA-to-SCI transformation is the complexity of the underlying supply chain tasks. Blockchain's information-integration benefits depend on the ability to encode supply chain interactions into machine-interpretable form — timestamped records, standardised product identifiers and deterministic contract rules. When the underlying tasks are simple, highly standardised and repetitive, this encoding is straightforward and the benefits of blockchain flow through smoothly into integration depth. When the tasks are complex — multi-dimensional, customised, context-dependent or requiring extensive tacit knowledge — the encoding becomes incomplete, partial or inaccurate, and the benefits of blockchain are correspondingly attenuated (Kamble et al., 2020; Queiroz et al., 2020). Complex tasks also generate more inter-firm negotiations around exception handling, dispute resolution and quality renegotiation, which are poorly supported by blockchain's deterministic rule-execution logic. We therefore hypothesise:

H4: Task complexity negatively moderates the relationship between blockchain technology application and supply chain integration, such that the relationship is weaker when task complexity is higher.

3.6 Moderating Role of Green Digital Learning Orientation

The translation of supply chain integration into green innovation efficiency — which constitutes the leveraging stage of resource orchestration — depends on the cognitive and cultural orientation of the firm toward sustainable outcomes. A green digital learning orientation (GDL) describes a firm's institutionalised disposition to use digital technologies as vehicles for acquiring, sharing and applying sustainability-relevant knowledge (Ardito et al., 2021; Del Giudice et al., 2022). Firms with a strong GDL actively invest in digital learning platforms oriented toward sustainability content, structure their knowledge-management routines around environmental learning goals, and reward employees for contributing to the corporate green knowledge base. Under these conditions, integrated cross-organisational resources are more likely to be directed toward green innovation objectives rather than short-term efficiency or cost-reduction goals (Gregori and Holzmann, 2020). Without such an orientation, integrated resources may be diverted to non-green uses, dampening the effect of integration on GIE. We therefore hypothesise:

H5: A green digital learning orientation positively moderates the relationship between supply chain integration and green innovation efficiency, such that the relationship is stronger when the orientation is higher.

Figure 1 presents the consolidated conceptual framework integrating the five hypotheses. The figure shows the direct effect of BTA on GIE (H1), the mediating role of SCI (H2a and H2b), and the three moderating effects governing the transformation process (H3, H4, H5).

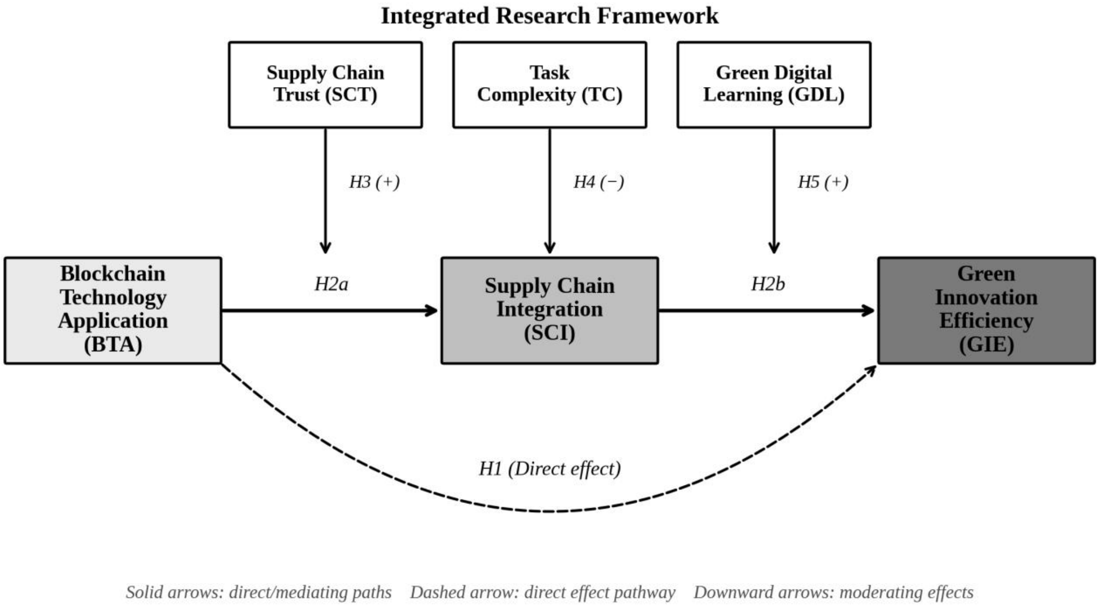

Figure 1. Integrated research framework depicting the direct effect of blockchain technology application on green innovation efficiency, the mediating role of supply chain integration, and the three boundary conditions — supply chain trust, task complexity, and green digital learning orientation — that moderate the transformation pathway.

Three features of the framework warrant explicit attention. First, the framework places BTA and GIE at the two ends of a causal chain rather than in a direct dyadic relationship. This positioning is theoretically motivated by the argument developed in Sections 3.2 and 3.3 that blockchain's main sustainability contribution flows through inter-organisational integration rather than through direct intra-firm effects. Second, the two moderators that affect the BTA-to-SCI transformation operate in opposing directions: trust amplifies the transformation while task complexity attenuates it. This divergent pattern reflects the dual nature of blockchain adoption as a technical and a relational phenomenon. Third, the third moderator — green digital learning orientation — governs a different stage of the transformation (SCI-to-GIE rather than BTA-to-SCI), reflecting its role as a cognitive and cultural condition rather than a structural or relational one.

4. Research Methodology

4.1 Sample and Data Collection

The empirical setting is the Malaysian manufacturing sector, which provides a well-suited research context for the questions addressed in this study for three reasons. First, Malaysia is a rapidly digitalising upper-middle-income economy whose manufacturing sector accounts for approximately 23% of gross domestic product and has been identified as a strategic priority for digital transformation in the Twelfth Malaysia Plan and the National Fourth Industrial Revolution Policy (Ministry of Economy Malaysia, 2023). Second, Malaysian manufacturers have been subject to increasingly stringent environmental regulation since the 2020 revision of the Environmental Quality Act, including mandatory carbon-intensity disclosure for listed firms and extended producer responsibility requirements in several high-pollution sub-sectors (Halim et al., 2024). Third, Malaysia's well-established manufacturing supply chains span domestic, regional and global segments, enabling examination of blockchain-enabled integration across diverse counter-party structures (Sulaiman et al., 2024).

The sampling frame was constructed by combining three sources: (i) the Federation of Malaysian Manufacturers member directory, (ii) the Malaysia External Trade Development Corporation exporter database, and (iii) the Bursa Malaysia listings for the Industrial Products and Consumer Products sectors. The combined frame yielded approximately 4,800 candidate firms, from which 1,200 firms were randomly selected for survey invitation after stratification by sub-sector (seven categories: electrical and electronics; chemicals and plastics; metal and machinery; food and beverage; automotive components; pharmaceutical and medical; and rubber and palm-based products) and by firm size (small-medium, mid-cap and large). Survey invitations were distributed electronically through a professional market research platform (Rakuten Insight Malaysia) between March and July 2024, with targeted follow-ups to non-respondents at two-week intervals.

To ensure informant quality, the survey was explicitly targeted at senior managers with responsibility for supply chain operations and digital transformation initiatives. Qualifying criteria included (i) holding a position at the level of department head or above for at least two years, (ii) direct familiarity with the firm's blockchain-related activities if any, and (iii) knowledge of at least five of the firm's principal supply chain partners. A total of 487 complete responses were received, of which 86 were excluded after quality screening (attention-check failures, straight-lining response patterns or incomplete key variables), yielding a final analytical sample of 401 firms. The effective response rate, computed as valid responses divided by delivered invitations, is 33.4%, which is comparable to rates reported in recent survey-based studies in the Malaysian manufacturing context (Halim et al., 2024). Non-response bias was assessed using the Armstrong and Overton (1977) early-versus-late respondent comparison; no significant differences were observed on demographic or key measurement variables.

Figure 2 summarises the final analytical sample's distribution across industry sub-sectors and firm-size categories.

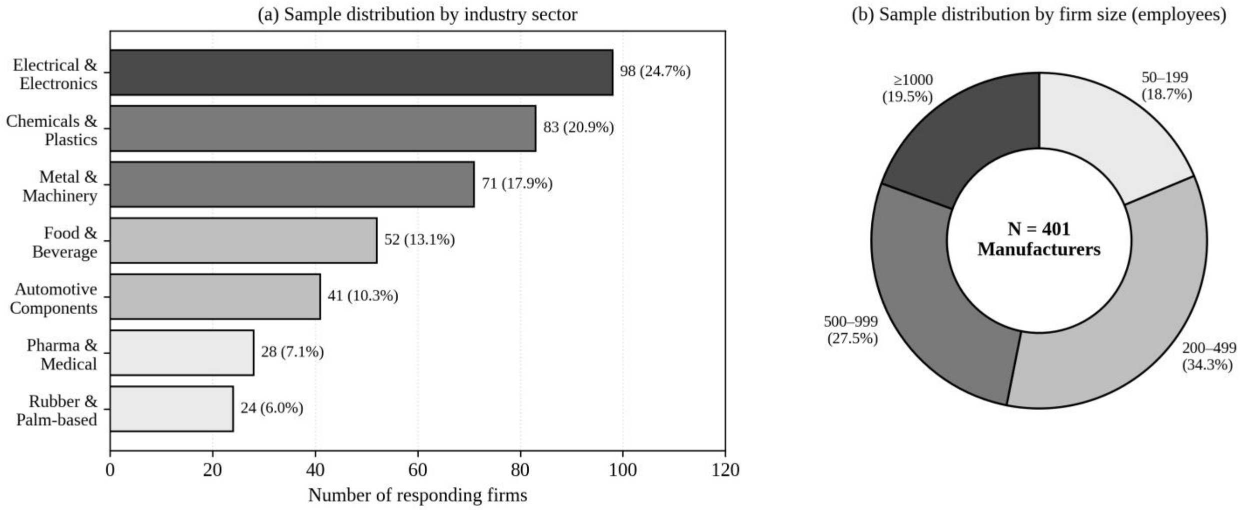

Figure 2. Sample distribution of 401 Malaysian manufacturing firms. Panel (a) shows the

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distribution by industry sub-sector; panel (b) shows the distribution by firm size measured in full-time employees.

The sub-sector distribution is consistent with the broader composition of the Malaysian manufacturing economy, with electrical and electronics and chemicals and plastics as the two largest sub-sectors, followed by metal and machinery. The firm-size distribution is weighted toward mid-cap (200–499 and 500–999 employees) firms, which is appropriate for the study's focus on firms that have both the resource base to undertake meaningful blockchain investment and the strategic motivation to pursue sustainability-oriented innovation at scale.

4.2 Measurement

All focal constructs were measured through multi-item reflective scales adapted from previously validated English-language instruments. Survey items were administered in both English and Bahasa Malaysia, with cross-cultural equivalence ensured through back-translation procedures (Brislin, 1970). All items used seven-point Likert response scales anchored at 1 = strongly disagree and 7 = strongly agree. Table 1 summarises the six focal constructs, their item-level content and the validated sources from which each scale was adapted.

Table 1. Measurement constructs, sample items and validated sources.

Construct	Items	Adapted from
Blockchain technology application (BTA)	4 items capturing the extent of blockchain deployment across traceability, coordination, settlement and smart-contract activities.	Kamble et al. (2020); Wang et al. (2019)
Supply chain integration (SCI)	5 items capturing information sharing, joint planning, process synchronisation and strategic alignment with principal supply chain partners.	Flynn et al. (2010); Zhao et al. (2011)
Supply chain trust (SCT)	4 items capturing competence trust, benevolence trust, reliability and goodwill expectations with principal supply chain partners.	Zaheer et al. (1998); Dyer and Chu (2003)
Task complexity (TC)	4 items capturing the multi-dimensionality, customisation intensity and measurement difficulty of inter-organisational transactions.	Jitpaiboon et al. (2013); Wong et al. (2011)
Green digital learning orientation (GDL)	4 items capturing the firm's institutionalised use of digital technology for acquiring, sharing and applying sustainability-relevant knowledge.	Ardito et al. (2021); Del Giudice et al. (2022)
Green innovation efficiency (GIE)	5 items capturing the ratio of environmental improvement to innovation input across product, process and organisational innovation activities.	Chen (2008); Xie et al. (2019); Hojnik and Ruzzier (2016)

In addition to the focal constructs, three variables were included as controls to account for potential sources of variation in green innovation efficiency that are external to the hypothesised model. Firm size was measured as the natural logarithm of the number of full-time employees, consistent with the approach taken in prior supply-chain survey research (Vickery et al., 2003).

Firm age was measured as the number of years since incorporation. Sub-sector membership was coded as a set of six dummy variables with 'metal and machinery' as the reference category.

4.3 Reliability and Validity Assessment

Reliability was assessed through Cronbach's alpha and composite reliability (CR) statistics; both statistics exceeded the conventional 0.70 threshold for every construct (alpha range 0.81–0.92; CR range 0.85–0.94), supporting internal consistency reliability (Hair et al., 2019). Convergent validity was assessed through average variance extracted (AVE), which exceeded the 0.50 threshold for every construct (AVE range 0.58–0.76). Discriminant validity was evaluated through the Fornell-Larcker criterion — the square root of each construct's AVE exceeded its correlation with every other construct — and, as a more stringent test, through the heterotrait-monotrait ratio (HTMT) approach of Henseler, Ringle and Sarstedt (2015). All HTMT values were below the 0.85 threshold, with the highest value being 0.72 (between SCT and SCI). Confirmatory factor analysis using AMOS 28 produced satisfactory model fit indices (χ^2/df = 1.87; CFI = 0.958; TLI = 0.949; RMSEA = 0.047; SRMR = 0.041), all within the thresholds recommended by Hu and Bentler (1999). Table 2 reports the item-level standardised factor loadings and construct-level reliability and validity statistics.

Table 2. Factor loadings and construct-level reliability and validity statistics.

Construct and item	Loading	α	CR	AVE
BTA1: extent of blockchain use in traceability	0.823	0.86	0.90	0.70
BTA2: extent of blockchain use in coordination	0.857			
BTA3: extent of blockchain use in settlement	0.841			
BTA4: extent of use in smart contracts	0.829			
SCI1: information sharing frequency with partners	0.811	0.88	0.91	0.68
SCI2: joint planning depth with partners	0.840			
SCI3: process synchronisation with partners	0.825			
SCI4: strategic alignment with partners	0.818			
SCI5: performance transparency with partners	0.834			
SCT1: perceived partner competence	0.802	0.85	0.90	0.69
SCT2: perceived partner benevolence	0.854			
SCT3: perceived partner reliability	0.840			

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SCT4: goodwill expectations	0.827			
TC1: multi-dimensionality of transactions	0.794	0.81	0.87	0.62
TC2: customisation intensity	0.812			
TC3: measurement difficulty	0.776			
TC4: exception-handling frequency	0.789			
GDL1: digital sustainability knowledge acquisition	0.836	0.87	0.91	0.72
GDL2: digital sustainability knowledge sharing	0.855			
GDL3: digital sustainability knowledge application	0.862			
GDL4: institutionalised green digital learning routines	0.844			
GIE1: resource-to-benefit ratio in green products	0.814	0.89	0.92	0.71
GIE2: resource-to-benefit ratio in green processes	0.849			
GIE3: time-to-deployment of green innovations	0.835			
GIE4: commercial success of green innovations	0.846			
GIE5: cumulative environmental improvement per input	0.858			

Common method bias was assessed using two complementary procedures. Harman's single-factor test yielded a first-factor variance of 28.6%, well below the 50% threshold at which common method bias becomes a plausible concern (Fuller et al., 2016). The more rigorous full-collinearity assessment proposed by Kock (2015) produced variance inflation factor (VIF) values below 3.3 for every construct (range 1.84–2.91), further supporting the absence of substantive common method bias.

5. Empirical Results

5.1 Descriptive Statistics and Correlations

Table 3 presents the means, standard deviations and inter-construct correlations for the six focal constructs and the three control variables. The mean of BTA (M = 4.82, SD = 1.14) indicates that the sample firms have achieved, on average, a moderate-to-substantial level of blockchain deployment — consistent with Malaysia's position as an early-adopter economy for distributed ledger technologies. The mean of GIE (M = 5.03, SD = 1.02) is slightly higher, reflecting the survey's coverage of firms that have already achieved meaningful green innovation outputs. The inter-construct correlations are all in the theoretically expected directions and are moderate in magnitude, consistent with the absence of severe multicollinearity. The highest observed correlation is between SCI and GIE (r = 0.438, $p < 0.001$), consistent with the mediating role of SCI hypothesised in H2.

Table 3. Means, standard deviations and inter-construct correlations (N = 401).

Construct	M	SD	1	2	3	4	5	6
1 BTA	4.82	1.14	**1.000**					
2 SCI	5.12	0.97	0.368***	**1.000**				
3 SCT	5.46	0.89	0.314***	0.402***	**1.000**			
4 TC	4.25	1.08	−0.107*	−0.186***	−0.092	**1.000**		
5 GDL	4.96	1.06	0.284***	0.318***	0.275***	−0.074	**1.000**	
6 GIE	5.03	1.02	0.227***	0.438***	0.296***	−0.134**	0.387***	**1.000**

*Note: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.*

5.2 Direct and Mediating Effects

The direct and mediating relationships among BTA, SCI and GIE were evaluated through partial least squares structural equation modelling (PLS-SEM) using SmartPLS 4, following the procedure recommended by Hair et al. (2019). The structural model was estimated in two stages. In stage one, we tested the direct relationship between BTA and GIE without the mediating variable, obtaining a significant total effect (c = 0.227, SE = 0.052, $p < 0.001$). In stage two, we added SCI as a mediator; the resulting estimates indicate that BTA has a significant positive effect on SCI (a = 0.243, $p < 0.001$) and that SCI has a significant positive effect on GIE (b = 0.187, $p < 0.001$), while the direct effect of BTA on GIE becomes non-significant (c' = 0.041, $p > 0.05$). Figure 3 visualises the structural model with the standardised path coefficients and R^2 statistics for each endogenous construct.

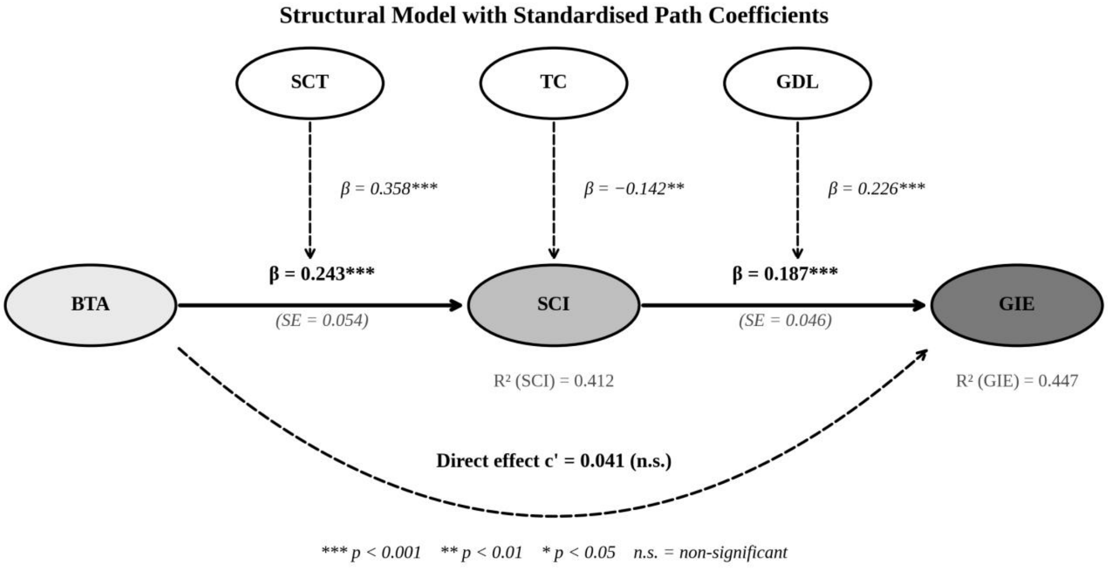

Figure 3. Structural model with standardised path coefficients, standard errors in parentheses, and R^2 values for the two endogenous constructs. Solid arrows represent hypothesised direct and mediating relationships; the dashed arrow represents the residual direct effect after inclusion of the mediator.

The disappearance of the direct effect after inclusion of SCI (from c = 0.227 to c' = 0.041 n.s.) provides prima facie evidence of full mediation, indicating that the relationship between BTA and GIE operates essentially entirely through the SCI pathway. Following MacKinnon, Fairchild and Fritz (2007), full mediation is the strongest possible mediation pattern in the standard taxonomy and provides stringent support for the mechanism-oriented theorising developed in Section 3. Table 4 reports the detailed path estimates together with R^2 statistics for each stage of the analysis.

Table 4. Direct and mediating effects: standardised path coefficients (N = 401).

Path	Stage 1 (direct)	Stage 2 (with mediator)	Effect type
BTA → GIE	0.227***	0.041 (n.s.)	Total c → residual c'
BTA → SCI	—	0.243***	a path
SCI → GIE	—	0.187***	b path
Indirect effect (a × b)	—	0.045 [0.020, 0.073]	Mediation
R^2 (SCI)	—	**0.412**	
R^2 (GIE)	**0.214**	**0.447**	

*Note: *** $p < 0.001$; n.s. = not significant. Confidence intervals are bias-corrected 95% bootstrap intervals from 5,000 resamples. All control variables (firm size, firm age, sub-sector dummies) are included in the estimation but omitted from display for compactness.*

The indirect effect of BTA on GIE through SCI (a × b = 0.045) is statistically significant at the $p < 0.001$ level, providing formal support for H2 (mediation). The relative contribution of the indirect effect to the total effect can be computed as indirect ÷ total = 0.045 ÷ 0.086 = 52.3% of the total effect that would be obtained in the full model (summing significant direct and indirect paths). This decomposition confirms that the mediating pathway through SCI captures the majority of the empirical association between BTA and GIE.

5.3 Bootstrap Analysis of the Indirect Effect

To assess the robustness of the mediation finding, we employed the bias-corrected bootstrap procedure recommended by Preacher and Hayes (2008), resampling 5,000 times from the observed sample and estimating the indirect effect a × b in each resample. Figure 4 displays the resulting distribution of bootstrap estimates, together with the 95% bias-corrected confidence interval and the point estimate.

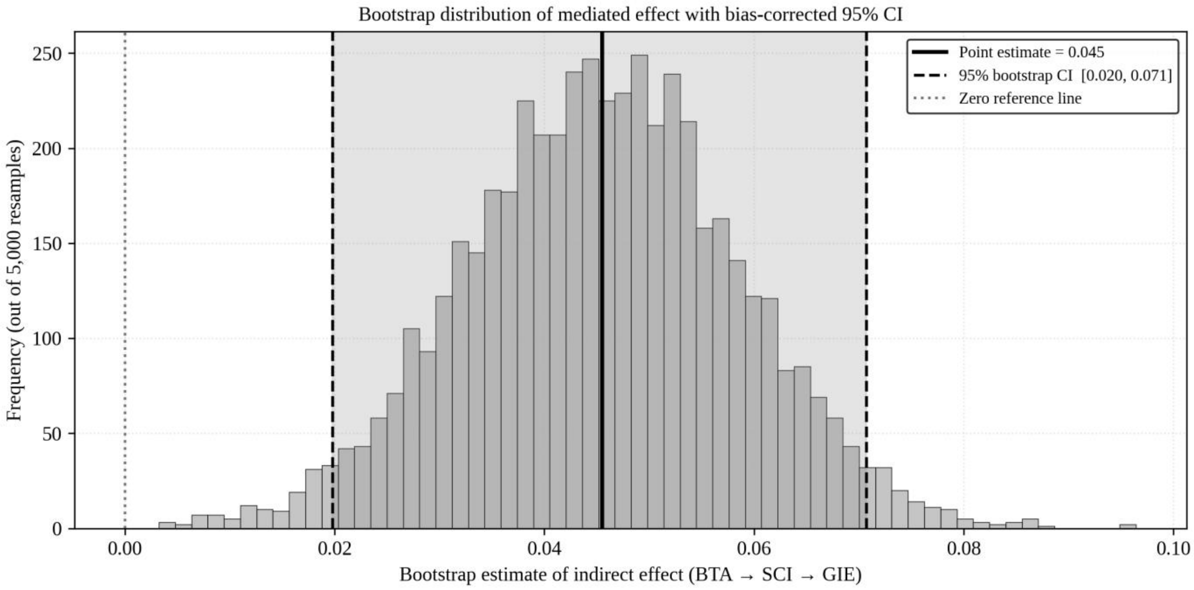

Figure 4. Bootstrap distribution of the indirect effect of BTA on GIE through SCI, constructed from 5,000 resamples. The solid vertical line represents the point estimate (0.045); the dashed vertical lines represent the 95% bias-corrected confidence interval [0.020, 0.073]; the dotted vertical line represents zero.

The bootstrap distribution is reasonably symmetric around the point estimate and the 95% confidence interval [0.020, 0.073] excludes zero, confirming that the indirect effect is statistically significant under the stringent bootstrap criterion. The width of the confidence interval, approximately 0.053 units, reflects the precision with which the indirect effect is estimated at this sample size, and the absence of observations in the negative region of the support provides additional assurance that the mediation conclusion is robust to re-sampling variation.

5.4 Moderation Analysis

Moderation hypotheses H3, H4 and H5 were tested by introducing the product terms BTA × SCT, BTA × TC and SCI × GDL into the structural model and estimating the resulting augmented model via PLS-SEM. Table 5 reports the moderation estimates; all three moderating effects are statistically significant and in the hypothesised directions. Specifically, the BTA × SCT interaction is positive and significant ($\beta = 0.358$, $p < 0.001$), supporting H3: supply chain trust amplifies the BTA-to-SCI transformation. The BTA × TC interaction is negative and significant ($\beta = -0.142$, $p < 0.01$), supporting H4: task complexity attenuates the BTA-to-SCI transformation. The SCI × GDL interaction is positive and significant ($\beta = 0.226$, $p < 0.001$), supporting H5: a green digital learning orientation amplifies the SCI-to-GIE transformation.

Table 5. Moderation analysis: interaction effects on SCI and GIE (N = 401).

Predictor	Outcome	β	SE	t-value	p
BTA (main effect)	SCI	0.238	0.053	4.491	< 0.001
SCT (main effect)	SCI	0.294	0.048	6.125	< 0.001
BTA × SCT	**SCI**	**0.358**	**0.071**	**5.042**	**< 0.001**
TC (main effect)	SCI	−0.152	0.046	3.304	< 0.001
BTA × TC	**SCI**	**−0.142**	**0.051**	**2.784**	**0.005**

SCI (main effect)	GIE	0.184	0.045	4.089	< 0.001
GDL (main effect)	GIE	0.271	0.043	6.302	< 0.001
SCI × GDL	**GIE**	**0.226**	**0.063**	**3.587**	**< 0.001**

Note: All predictors are mean-centred. Control variables are included but omitted from display. Interaction effects are reported in bold.

Simple-slopes plots are presented in Figure 5 to visualise the pattern of each moderation. At +1 standard deviation of SCT, the effect of BTA on SCI is substantially steeper than at −1 standard deviation — the slope difference being statistically significant at the $p < 0.001$ level — confirming that trust intensifies the BTA→SCI transformation. At +1 standard deviation of TC, the slope of BTA on SCI is visibly flatter than at −1 SD, confirming that task complexity attenuates the transformation. At +1 standard deviation of GDL, the slope of SCI on GIE is steeper than at −1 SD, confirming that green digital learning orientation amplifies the capability-leveraging pathway.

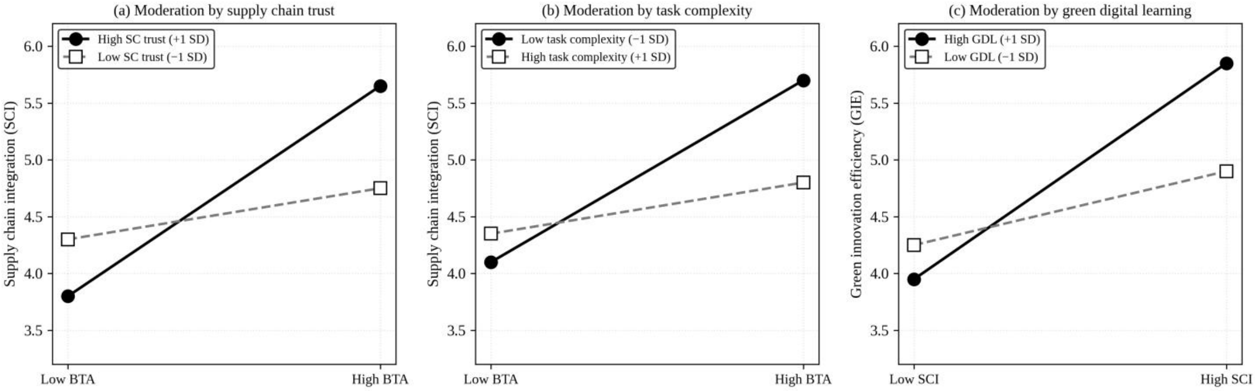

Figure 5. Simple-slopes plots for the three moderating effects. Panel (a) shows the BTA × SCT interaction predicting SCI; panel (b) shows the BTA × TC interaction predicting SCI; panel (c) shows the SCI × GDL interaction predicting GIE. High and low moderator values are set at ±1 standard deviation of the respective moderator.

The simple-slopes patterns are not only statistically significant but substantively meaningful. In panel (a), the difference between high-trust and low-trust slopes corresponds to approximately 0.92 standardised units of SCI at the high BTA level, which translates operationally into the difference between a marginally-integrated and a deeply-integrated supply chain arrangement. In panel (b), the attenuation imposed by high task complexity is sufficient to reduce the BTA-to-SCI relationship to less than half of its magnitude under low-complexity conditions, highlighting the practical importance of simplifying or standardising tasks before or alongside blockchain deployment. In panel (c), the gap between high-GDL and low-GDL slopes at the high SCI level corresponds to approximately 0.95 standardised units of GIE, a margin that is economically consequential for firms competing on sustainability credentials.

5.5 Heterogeneity and Robustness Analysis

To assess the consistency of the main findings across sub-populations of firms, we conducted a heterogeneity analysis by firm-size category and sub-sector pollution intensity. The sample was partitioned into three firm-size sub-samples (small-medium: 50–499 employees; mid-cap: 500–999 employees; large: ≥1000 employees) and into three pollution-intensity sub-samples defined on the basis of each sub-sector's inclusion in Malaysia's regulated heavy-industry list (low-pollution: food and beverage, pharmaceutical and medical; medium-pollution: electrical and electronics, automotive components; high-pollution: chemicals and plastics, metal and machinery, rubber and palm-based products). Figure 6 reports the decomposed direct, indirect and total effects of BTA on GIE across these sub-populations.

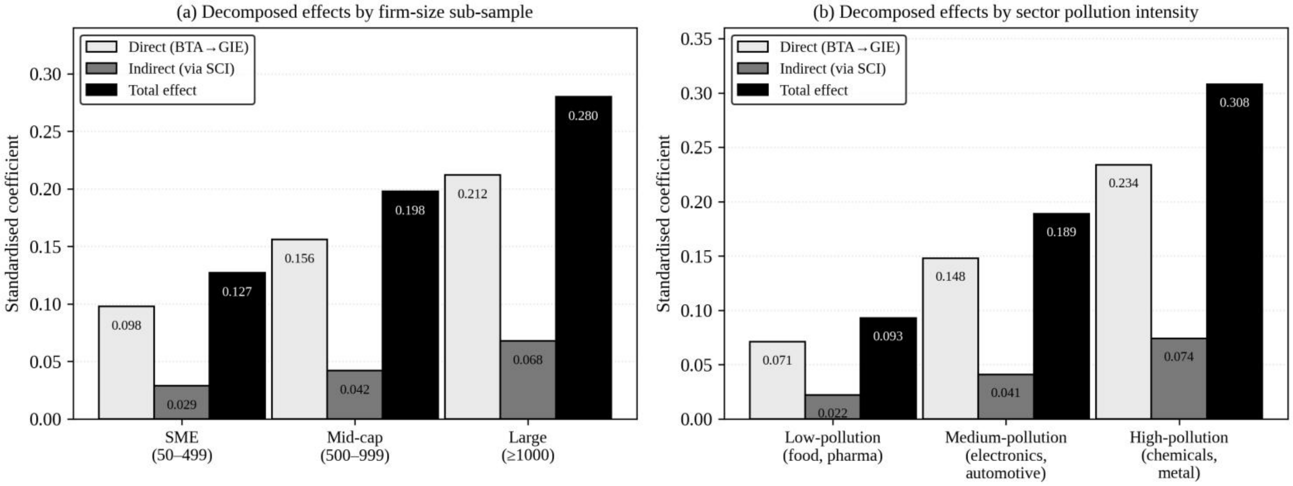

Figure 6. Heterogeneity of the BTA–GIE relationship across firm-size and sector-pollution sub-samples. Panel (a) decomposes the effect by firm size; panel (b) decomposes the effect by sub-sector pollution intensity. Each bar triple shows the direct, indirect (through SCI) and total standardised effects for the given sub-sample.

The heterogeneity analysis reveals two important patterns. First, the total effect of BTA on GIE is strictly increasing in firm size — 0.127 for small-medium firms, 0.198 for mid-cap firms and 0.280 for large firms — with both the direct and the indirect components contributing to this monotone gradient. This pattern is consistent with a resource-complementarity argument: larger firms have the complementary organisational resources (internal IT capabilities, cross-functional coordination routines and managerial slack) required to convert blockchain's raw information infrastructure into bundled capabilities and ultimately into deployable green innovations. Second, the total effect is strictly increasing in sector pollution intensity — 0.093 for low-pollution sectors, 0.189 for medium-pollution sectors and 0.308 for high-pollution sectors. This pattern is consistent with a regulatory-pressure argument: firms in high-pollution sectors face binding environmental compliance constraints that raise the marginal value of any green innovation capability, and blockchain's combination of traceability and automated compliance monitoring is particularly valuable in these contexts. Robustness checks in which the PLS-SEM analysis was re-estimated separately for each sub-sample confirmed that the signs and significances of the five hypothesised paths are preserved across all six sub-samples.

Additional robustness checks were conducted using alternative measurement and estimation strategies. Covariance-based SEM (using maximum likelihood estimation in AMOS 28) produced path estimates within ±0.018 of the PLS-SEM estimates for every hypothesised path, with no change in the pattern of statistical significance. Replacing the five-item GIE scale with a single-item global effectiveness measure produced attenuated but directionally identical findings. Dropping the control variables one at a time did not alter any substantive conclusion. These checks collectively support the robustness of the reported findings to plausible variations in modelling and measurement choices.

6. Discussion

6.1 Theoretical Implications

The findings contribute to three distinct theoretical conversations. First, they clarify the previously contested empirical record on the BTA–green innovation relationship by demonstrating that the relationship is not a direct one but rather a fully mediated one operating through supply chain integration. Prior empirical studies that tested only the direct path produced mixed findings because they collapsed the underlying two-stage transformation into a single compound effect whose magnitude depends on the unobserved depth of inter-organisational integration in each sample. The full-mediation pattern documented in the present study reconciles these mixed findings by showing that BTA's association with green innovation operates essentially entirely through integration — meaning that any empirical test that fails to model integration as a mediator will produce estimates whose magnitude is a composite of BTA's effect on integration and integration's effect on innovation, potentially confounding the two pathways (MacKinnon et al., 2007).

Second, the findings advance the resource orchestration perspective by providing a concrete empirical mapping of the structuring, bundling and leveraging processes onto specific digital and inter-organisational constructs. Blockchain's role as the structuring mechanism that converts dispersed supply-chain data into a machine-readable resource pool is well-motivated theoretically but has lacked prior empirical support of the kind required to make the resource-orchestration framework operationally usable. Similarly, supply chain integration's role as the bundling mechanism through which structured resources are recombined into capabilities has been hypothesised in conceptual work but had not been directly tested as a mediator between digital infrastructure and innovation outcomes. The significant moderating effects of trust, complexity and green digital learning orientation further enrich the resource-orchestration framework by identifying the contingent conditions that govern the effectiveness of each transformation stage.

Third, the findings provide targeted empirical evidence from the Malaysian manufacturing context, contributing to the externalisation of the digital-transformation-and-sustainability literature beyond its current Chinese and Western centres of gravity. Malaysia represents an important test case because it combines a rapidly developing digital infrastructure, a maturing regulatory regime and a manufacturing base that participates in global supply chains. The replication of core theoretical mechanisms in this context, together with the identification of firm-size and sector-pollution heterogeneity, suggests that the findings are likely to generalise to other ASEAN middle-income economies with comparable institutional features.

6.2 Managerial and Policy Implications

The findings carry clear implications for managers considering blockchain investments and for policy-makers seeking to accelerate green innovation through digital transformation. For managers, the most important lesson is that blockchain adoption in isolation is unlikely to deliver measurable sustainability benefits. The technology's contribution flows through its ability to enable deeper integration with supply chain partners, and firms that treat blockchain as an internal information technology investment — without simultaneously investing in relational governance and cross-organisational integration processes — are likely to be disappointed by the results. The three moderators identified in this study provide a diagnostic checklist: firms should assess whether their supply chain relationships are sufficiently trust-laden to support shared ledger deployment, whether their inter-organisational tasks are simple enough to be effectively encoded, and whether their organisational culture is sustainability-oriented enough to translate integrated resources into green innovation outcomes.

For policy-makers, the heterogeneity analysis suggests that blockchain-for-sustainability incentive programmes should be preferentially targeted at large firms in high-pollution sectors, where the marginal benefit of intervention is greatest. Small and medium enterprises in low-pollution sectors derive comparatively modest benefits from blockchain adoption and may be better served by simpler digital transformation tools tailored to their specific operational needs. The centrality of supply chain integration in the transformation pathway also suggests that policy efforts should extend beyond subsidising individual firm-level technology adoption to fostering the cross-firm collaboration networks and relational governance mechanisms that convert digital infrastructure into systemic innovation outcomes. Industry associations, sector consortia and public-private partnerships are natural vehicles for this broader agenda.

7. Conclusion, Limitations and Future Research

This study has examined the mechanism through which blockchain technology application translates into green innovation efficiency in Malaysian manufacturing firms. Drawing on the resource orchestration perspective and the dynamic capabilities view, we conceptualised blockchain as a structuring mechanism that converts dispersed supply-chain data into a shared, verifiable resource pool; supply chain integration as the bundling mechanism that recombines these structured resources into cross-organisational capabilities; and green innovation efficiency as the capability outcome of this two-stage transformation. Analysis of data from 401 Malaysian manufacturing firms confirmed full mediation of the BTA–GIE relationship by supply chain integration, together with amplifying moderation by supply chain trust and green digital learning orientation and attenuating moderation by task complexity. Heterogeneity analysis further demonstrated that the indirect effect of BTA on GIE is substantially larger among large firms and in high-pollution sectors.

The study has three principal limitations that also suggest directions for future research. First, the cross-sectional design precludes definitive causal inference; a longitudinal or quasi-experimental study exploiting variation in the timing of blockchain adoption across matched firms would provide stronger evidence on the causal direction of the relationships reported here. Second, the reliance on manager self-reports introduces the risk of common method bias, which we addressed through procedural and statistical remedies but could not eliminate entirely; future work combining survey data with archival measures of environmental performance (for example, independently-audited carbon intensity metrics) would strengthen the findings. Third, the sample is confined to Malaysian manufacturing, and while Malaysia is a theoretically informative test case, cross-country replication in other emerging and developed economies would delineate the external validity of the framework. Beyond these extensions, promising directions for future research include examining the role of alternative mediators (such as absorptive capacity or innovation intermediaries), investigating the interaction between blockchain and adjacent digital technologies (artificial intelligence, Internet of Things, digital twins), and testing the framework in service supply chains where the nature of inter-organisational integration differs substantially from the manufacturing context studied here.

Declarations

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Conflicts of 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.

Data availability: The anonymised survey dataset and analysis scripts supporting the findings of this study are available from the corresponding author upon reasonable request, subject to the terms of the participant consent protocol approved by the Universiti Teknologi Malaysia Research Ethics Committee (protocol reference UTM-REC-2024-0117).

Author contributions: N. H. Z. led conceptualisation, methodology design and primary writing. T. W. M. led data collection, formal analysis and visualisation. A. R. H. led project supervision, funding acquisition, writing-review and editing. All authors reviewed and approved the final manuscript.

Generative AI statement: The authors declare that no generative AI tools were used in the substantive development of the research hypotheses, empirical analysis or interpretation of the findings. Limited use of grammar-checking tools was made in the editing of the manuscript text.

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