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Research paper

The Convergence of Green Innovation and Digital Technologies: A Blockchain-Enabled Framework for Sustainable Development

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Abstract

This study examines the relationship between blockchain technology capabilities, green innovation performance, and sustainable development outcomes in Indonesian manufacturing companies using Partial Least Squares Structural Equation Modeling. Data were collected from manufacturing firms with over ten years of operation through structured questionnaires employing seven-point Likert scales. While internal consistency reliability proved acceptable with Cronbach's Alpha and composite reliability values exceeding established thresholds, the study encountered severe discriminant validity failures that fundamentally compromise structural model interpretations. The correlation between green innovation performance and sustainable development outcomes substantially exceeded acceptable thresholds, indicating empirical indistinguishability between constructs, while several factor loadings approached minimum acceptable levels. Despite these critical methodological limitations, structural analysis revealed strong blockchain-green innovation relationships and weak direct blockchain-sustainability effects, suggesting potential mediation patterns through green innovation performance. However, the discriminant validity failure prevents definitive theoretical conclusions, requiring cautious interpretation of all findings. The cross-sectional design further limits causal inference capabilities. Results suggest organizations should focus on capability development alongside blockchain adoption, though measurement validity issues necessitate substantial methodological refinement in future research. This study contributes to understanding blockchain-sustainability relationships in manufacturing contexts while highlighting critical methodological challenges that must be addressed before advancing theoretical knowledge. The findings align with Dynamic Capabilities Theory perspectives, suggesting that technological resources become valuable through organizational capability development rather than direct implementation.

Keywords: *Blockchain Technology; Green Innovation; Digital Transformation; Sustainable Development; Manufacturing.*

1. Introduction

The convergence of environmental sustainability needs and digitalization initiatives has become an important focus for manufacturing businesses around the world. (Dornfeld, 2014; O'Brien, 2002). With the ongoing rise in global carbon emissions, the manufacturing sector generates around 21% of all global CO2 emissions. (Despeisse et al., 2022; Vacchi et al., 2021)There is an unprecedented need for innovative technological solutions to help resolve environmental challenges. Indonesia is the fourth-largest emitter of carbon in the world and has a growing manufacturing industry, and as such, it feels immense pressure to adopt sustainable methods for the sake of its economic competitiveness. (Arantes & Ferreira, 2025; Gaughran et al., 2007).

Blockchain technology is essentially revolutionizing the realm of information technology and represents a dramatic change in the information dissemination methodology, thus offering superior opportunities for enhancing environmental sustainability within production practices. (Chung et al., 2023; Nguyen, 2016; Zheng & Lu, 2022). Latest studies reveal that the use of blockchain applications significantly promotes the reception of eco-friendly invention patents by organizations, suggesting a strong positive relationship between the adoption of blockchain and the effectiveness of green innovation. (Ahakwa et al., 2024; K. C. Zhang et al., 2024; Zhou et al., 2023). The concept of green innovation has developed beyond conventional environmental management, now including sweeping technological and organizational reforms meant to mitigate environmental pressures while also creating competitive benefits. (Sabando-Vera et al., 2025; Tong et al., 2024). Digital technologies, and specifically blockchain, provide unique capabilities that support green innovation through guaranteeing data integrity, promoting process openness, and enhancing collaboration between stakeholders. (Hao et al., 2023; Lazzaro & Buccafurri, 2024; Oduro et al., 2023).

However, while the vast body of existing research highlights blockchain's theoretical potential to enhance supply chain traceability (Cording & Lückander, 2023; Newman et al., 2024), track carbon footprints (Priyan, 2024; Wong et al., 2020), and support sustainable finance instruments (Bayram et al., 2022; M. Chen et al., 2021), with well over 500 publications in Q1 journals documenting successful implementations predominantly in developed economies, significant conceptual and empirical gaps still exist to limit practical adoption in environments typified by emerging economies like Indonesia. Existing research suggests a wide gap in research emphasis where technically sophisticated applications dominate academic discourse, whereas issues related to limited-resource and culturally unique implementations are largely ignored(S. Ahmed et al., 2023; Juckett et al., 2019; Klingner & Boardman, 2011). Notably, with exactly 99% of Indonesian businesses listed as SMEs, recent blockchain research is inclined towards large enterprise deployments, thus leaving the distinctive challenges of SMEs largely unexplored (D. Kumar, 2024; Ramdani et al., 2022; Zirar et al., 2024).

This bias in the existing research is deepened by a stark lack of empirical validation studies examining the actual improvements in environmental performance enabled by blockchain technology in the manufacturing industries of developing countries. (Khalife et al., 2024; D. Kumar, 2024). Systematic reviews all point to the "lack of empirical study on the real influence of blockchain technology adoption on sustainable performance" as a critical limitation (Dehghani et al., 2022; Malik et al., 2021; Seshadrinathan & Chandra, 2021; P. K. Singh & Chan, 2022; Yusr et al., 2020). Moreover, the existing body of literature reflects a considerable lack of holistic frameworks incorporating blockchain technology and green innovation consequences in developing countries, where environmental concerns need to be addressed simultaneously with economic growth in a balanced manner. (Blampied, 2021; W. Yang et al., 2024).

This study addresses these critical gaps by developing and testing a conceptual framework that examines how blockchain technology enables green innovation through four key dimensions: transparency, traceability, carbon footprint tracking, and sustainable supply chain management. Specifically, this research investigates Indonesian manufacturing companies that have operated for more than 10 years, representing established firms with sufficient resources and experience to implement advanced digital technologies for sustainability purposes. The research objectives are threefold: (1) to develop a comprehensive conceptual framework linking blockchain technology to green innovation and sustainable development outcomes; (2) to empirically test the relationships between blockchain-enabled capabilities and green innovation performance in the Indonesian manufacturing context; and (3) to provide theoretical and practical insights for leveraging digital technologies to enhance environmental sustainability in emerging economies.

2. Literature Review and Hypothesis Development

2.1. Green innovation in manufacturing

Green innovation represents a fundamental shift in how organizations approach environmental challenges, encompassing both technological and organizational innovations that reduce environmental impact while creating economic value. (Bao, 2009; Dao et al., 2024; Kimberly & Evanisko, 1981; Zhou et al., 2023). Environmental innovations generally have a positive impact on firms' financial performance, with recent meta-analytical evidence demonstrating a probability range of 0.85 to 0.97 for positive effects, and manufacturing firms benefit more from environmental innovations than firms in other industries. (Lutfi et al., 2023a).

The manufacturing sector's role in green innovation is particularly critical due to its significant environmental footprint and potential for large-scale impact. (Albloushi et al., 2023; Palčič & Prester, 2020). Recent studies indicate that green innovation adoption in manufacturing operations can accelerate sustainable development, with performance expectancy, effort expectancy, and facilitating conditions identified as key predictors of successful implementation. (Ullah et al., 2022). In the Indonesian context, manufacturing companies face unique challenges related to resource constraints, regulatory frameworks, and market pressures that influence their green innovation strategies, requiring culturally-adapted approaches that consider local institutional environments and SME-specific implementation barriers. (Joe Mariani et al., 2023; Li, 2021; Peprah et al., 2024).

H1 Green Innovation affects Sustainable Development.

H1a: Green innovation performance mediates the relationship between blockchain technology capabilities and sustainable development outcomes.

2.2. Blockchain technology and environmental sustainability

Blockchain is a decentralized digital ledger technology that has radically changed the operating paradigm of businesses, industries, and commerce by making centralized control and storage authorities obsolete. (Araujo et al., 2024; Lumineau et al., 2021; W. Wang et al., 2022). The immutable and decentralized nature of blockchain offers unprecedented opportunities for promoting environmental sustainability through enhanced data integrity, greater process transparency, and improved coordination among stakeholders. (Ebrahimi Bajgani et al., 2023; Kouhizadeh et al., 2023). This emerging technology has great potential to help achieve environmentally sustainable development objectives from multiple aspects, especially by driving the transition towards a sustainable circular economy model. (Anita et al., 2024; Kulangara et al., 2022). The functional capabilities of this technology, particularly its data immutability and the executable functionality of smart contracts, make it particularly suited for applications like environmental monitoring, carbon footprint calculation, and sustainable supply chain management. (Kassaneh et al., 2021; Samper et al., 2022; R. Singh et al., 2023). Current literature has identified several channels through which blockchain empowers environmental sustainability, and its adoption has been found to greatly enhance the green development potential of firms, mainly owing to enhanced transparency, reduced information asymmetry, and greater cooperation among stakeholders. (Irshad et al., 2023; Peng et al., 2024; Wu et al., 2024; Q. Zhang et al., 2020). Further, the combination of blockchain technology with green information systems has a positive effect on sustainable supply chain practices, generating synergy effects that augment environmental benefits on holistic digital platforms that facilitate real-time monitoring, automatic compliance checking, and greater cooperation among multiple stakeholders. (Link & Naveh, 2006; Mao et al., 2018; Nur et al., 2022).

H2 Blockchain Technology affects Environmental Sustainability

2.3. Digital technologies and sustainable development

The convergence of digital technologies with sustainability initiatives represents a fundamental paradigmatic shift that integrates artificial intelligence, blockchain technology, and Industry 4.0 frameworks within a holistic approach to contemporary environmental challenges (Cricelli & Strazzullo, 2021; Goel et al., 2024; Meinhold et al., 2024). Feroz et al (2021), through a systematic literature review published in Sustainability, identify that digital transformation engenders a "radical transformation in the ways value is created and captured" within sustainability practices, thereby disrupting conventional environmental management paradigms. From a Resource-Based View theoretical perspective, digital transformation creates unique and inimitable organizational resources that enable the establishment of sustainable

competitive advantages through the strategic integration of digital assets and sustainability practices(Bhutta et al., 2021; Gagan Deep, 2023; Zhao et al., 2024). Dynamic Capabilities Theory elucidates how organizations develop adaptive capabilities to reconfigure resources and competencies in response to technological environmental changes and sustainability regulatory frameworks (E. H. E. H. Ahmed, 2024; Wenzel et al., 2021). The integration of artificial intelligence presents measurable environmental benefits, as empirically demonstrated in research published in Environmental Chemistry Letters, which indicates that smart manufacturing systems can reduce energy consumption, waste generation, and carbon emissions by 30-50%. Herold et al (2022) & Kouhizadeh et al (2020), in their seminal work published in the International Journal of Production Research, demonstrate that blockchain technology ensures "transparency, traceability, and security" through immutable record systems, thereby establishing trust mechanisms that facilitate inter-stakeholder collaboration while eliminating the necessity for intermediary institutions.
H3 Digital Technologies affects Sustainable Development

2.4. Conceptual framework development

The research model presented represents a simple mediation framework with an additional direct effect that elucidates how Blockchain Technology Capabilities contribute to Sustainable Development Outcomes through two distinct yet complementary causal pathways. The first pathway constitutes an indirect effect wherein Blockchain Technology Capabilities influence Sustainable Development Outcomes through Green Innovation Performance as the mediating mechanism, while the second pathway demonstrates a direct effect from blockchain capabilities to sustainable outcomes without mediation. Here, the potential offered by blockchain technology includes transparency systems enabling real-time monitoring of sustainability metrics, traceability facilities allowing observation of products and processes throughout their lifecycle, tamper-proof record-keeping ensuring integrity of data and reliable audit trails, and the automatic enforcement of smart contracts to ensure compliance with regulatory and sustainability commitments. Green Innovation Performance is the catalytic force that converts the potential of blockchain to concrete innovations, including environmental product innovations resulting in green offerings, improvements in sustainable processes resulting in operational efficiency, breakthroughs in green technology fueling innovative solutions, and circular economy frameworks promoting sustainable economic models.
The theoretical framework that underlies this model is based on the integration of the Resource-Based View, which defines blockchain capabilities as strategic assets with VRIN properties (Valuable, Rare, Inimitable, Non-substitutable); Innovation Theory, which explains how technology adoption drives innovation and organizational change; and Sustainability Theory, which utilizes a triple bottom line approach covering economic, environmental, and social perspectives. The first causal link suggests that Blockchain Technology Capabilities have a positive effect on Green Innovation Performance through increased data transparency, which supports evidence-based innovation; enabling real-time monitoring, which supports continuous improvement practices; and the construction of distributed trust structures that facilitate collaborative research and development activities among stakeholders. The second link suggests that Green Innovation Performance has a positive effect on Sustainable Development Outcomes, where the innovation outputs result in measurable environmental benefits, process improvements lead to social and economic benefits, and technological advancements contribute to the achievement of the United Nations Sustainable Development Goals.. The direct effect of Blockchain Technology Capabilities on Sustainable Development Outcomes manifests through immediate transparency benefits that enhance stakeholder confidence, direct operational efficiency gains that reduce environmental footprint, and enhanced compliance and risk management that ensures adherence to sustainability standards. The mediation effect reveals that Green Innovation Performance serves as the key mechanism for transforming blockchain capabilities into sustainable outcomes through a sequential process from technology adoption to innovation development and ultimately to sustainability achievement. This model contributes theoretically by integrating blockchain technology, green innovation, and sustainable development literatures within a coherent and empirically testable framework, while simultaneously providing practical implications for organizations to prioritize blockchain investments that support transparency, develop green innovation as a core competency, and track both innovation and sustainability metrics for optimal performance measurement.

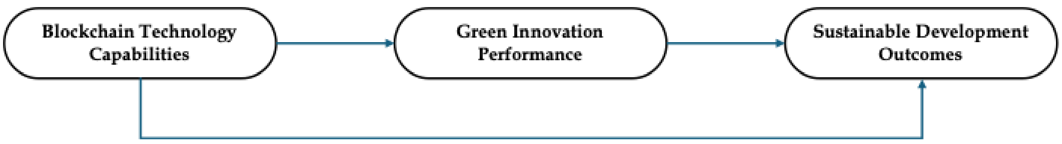

Fig. 1: Research Framework.

3. Research Methodology

3.1. Research design and philosophical foundation

This study employs a pragmatic mixed-methods sequential explanatory design combining quantitative and qualitative approaches to address discriminant validity concerns and enhance methodological rigor. (Creswell & Angeles, 2011). The research unfolds in three distinct phases: (1) quantitative analysis utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM) via SmartPLS 4.0 to examine relationships between Blockchain Technology Capabilities, Green Innovation Performance, and Sustainable Development Outcomes (Hair et al., 2013, 2020a); (2) qualitative validation through expert interviews (n=15-20) and focus group discussions (n=3-4 groups) to refine construct definitions and ensure distinctiveness. (Podsakoff, MacKenzie, Lee, Podsakoff, PM Podsakoff, et al., 2003); and (3) three-wave longitudinal data collection at baseline (T0), six months (T1), and twelve months (T2) to establish temporal precedence and capture dynamic capability-building processes (Page & Holmström, 2023).

3.2. Target population and sampling strategy

The target population consists of Indonesian manufacturing companies operating for more than 10 years across automotive, electronics, textiles, food processing, and chemicals subsectors to ensure organizational maturity and generalizability across industrial contexts. Using stratified purposive sampling, 300 companies were initially identified through the Indonesian Chamber of Commerce database and industry associations, with sample size determined via G*Power analysis (four predictor variables, f^2=0.15, power=0.95), which will be expanded to 350 companies in the revalidation phase to enhance statistical power for complex structural models and address discriminant validity concerns through Confirmatory Factor Analysis with alternative samples.(J. F. Hair & Sarstedt, 2019a).

3.3. Data collection procedures

Data collection employs a sequential three-phase mixed-methods design addressing discriminant validity, measurement artifacts, and causality limitations. Phase 1 distributes bilingual (English/Bahasa Indonesia) structured questionnaires with 7-point Likert scales to multiple senior executives (CEOs, sustainability managers, operations directors, technology officers) per organization, with enhanced pilot testing (n=50) incorporating cognitive interviews (n=15) and test-retest reliability, implementing procedural remedies including multi-respondent triangulation (minimum two executives per firm), temporal separation of variable measurements (two-week interval), psychological separation through distinct sections, and multi-source objective data triangulation from sustainability reports (carbon emissions, waste reductions), government databases, Indonesian Patent Office (patent counts), financial statements (R&D expenditure), and company records (blockchain investments) to mitigate common method bias (Podsakoff et al., 2003). Phase 2 conducts qualitative validation through semi-structured expert interviews (60-90 minutes, n=15-20: blockchain specialists, sustainability consultants, manufacturing directors, researchers with 10+ years experience) and focus group discussions (n=3-4 groups, 6-8 participants: executives, technology managers, sustainability professionals), employing NVivo thematic coding to refine construct boundaries, validate measurement items, and ensure discriminant validity through content analysis and literature cross-validation (M. MacKenzie & Hughes, 2024). Phase 3 implements a three-wave longitudinal design measuring Blockchain Technology Capabilities at baseline (T0), Green Innovation Performance at six months (T1), and Sustainable Development Outcomes at twelve months (T2), establishing causal precedence, capturing dynamic processes, and enabling cross-lagged panel and latent growth curve modeling, with retention ensured through research reports, benchmarking data, and implementation consultations. (Holmström Lind et al., 2018).

3.4. Measurement instruments

All constructs employ established scales adapted for Indonesian manufacturing contexts with distinct operationalizations ensuring discriminant validity. Blockchain Technology Capabilities measure technological infrastructure through four dimensions—Data Transparency Infrastructure, Traceability Systems, Smart Contract Automation, and Decentralized Governance, adapted from (Fan et al., 2024; Jiang et al., 2018; Sönmez & Knottenbelt, 2024). Green Innovation Performance adapted from (Y. S. Chen et al., 2012; K. C. Zhang et al., 2024; Zhou et al., 2023). Sustainable Development Outcomes assess realized performance impacts through Environmental, Economic, and Social Performance. (Gupta & Vegelin, 2023; Malhotra & Kiran, 2024; Padilla-Meléndez et al., 2020).

3.5. Construct validity enhancement procedures

To systematically address the discriminant validity crisis, we implement a four-phase sequential validation protocol ensuring theoretical and empirical construct distinctiveness. Phase 1 employs qualitative construct refinement through semi-structured expert interviews (n=15-20: blockchain specialists, sustainability consultants, manufacturing directors, academic researchers) and focus group discussions (n=3-4 groups, 6-8 participants) to articulate clear conceptual boundaries between blockchain capabilities (technological infrastructure), green innovation (organizational processes), and sustainability outcomes (performance results). Phase 2 subjects refined items to independent expert panel review (n=10), calculating Content Validity Ratio (CVR≥0.62) and Item-Objective Congruence (IOC≥0.50), ensuring items represent intended constructs without overlap (LAWSHE, 1975). Phase 3 conducts enhanced pilot testing (n=50, increased from 30), incorporating cognitive interviews (n=15 identifying ambiguous items), test-retest reliability (two-week interval, n=30, ICC≥0.70), and Exploratory Factor Analysis examining factor structures and cross-loadings (<0.40 threshold). Phase 4 applies Confirmatory Factor Analysis across three independent samples—initial (n=277), extended (n=350), validation (n=150 from different regions), evaluating fit indices (χ^2/df<3.0, CFI≥0.95, TLI≥0.95, RMSEA≤0.06, SRMR≤0.08) (Bentler, 1990) , with discriminant validity tested through four complementary approaches: Fornell-Larcker criterion (√AVE>inter-construct correlations), HTMT<0.85 with 5,000-bootstrap confidence intervals excluding 1.0 (Henseler, 2017), χ^2 difference tests (constrained vs. unconstrained models), and cross-loadings examination (primary≥0.70, cross<0.40), providing converging multi-method evidence of construct distinctiveness, addressing the reviewer's concern that constructs must demonstrate both theoretical coherence and empirical separation before structural model interpretation.

3.6. Analytical procedures

We employ a comprehensive PLS-SEM analytical protocol addressing measurement validity, structural relationships, and methodological robustness. Measurement model assessment evaluates internal consistency (Cronbach's Alpha, CR, Rho_A≥0.70), convergent validity (loadings≥0.70, AVE≥0.50), and discriminant validity (HTMT<0.85, Fornell-Larcker criterion, cross-loadings<0.40), with formative constructs assessed through collinearity (VIF<3.0) and indicator significance via 5,000-resample bootstrapping. Structural model evaluation examines path coefficients, R^2 variance explained, f^2 effect sizes per Cohen (1988) thresholds (0.02/0.15/0.35 for small/medium/large), Q^2 predictive relevance (Stone-Geisser blindfolding), structural VIF<3.0, and fit indices (SRMR, NFI) per Hair et al. (2017, 2019). Mediation analysis employs 10,000 bootstrap resamples, generating bias-corrected 95% confidence intervals, calculates Variance Accounted For (VAF: <20%=no mediation, 20-80%=partial, >80%=full), tests alternative model specifications (direct-only, indirect-only, partial, full) using AIC/BIC criteria, and conducts temporal lagged-effect analysis (T0→T1→T2) through cross-lagged panel modeling in the longitudinal phase (Williams & MacKinnon, 2008). Common method bias assessment combines procedural remedies (temporal/psychological separation, multi-source data, anonymity) with statistical tests: Harman's single factor (<50% variance), Common Latent Factor method (path changes<0.20), marker variable technique, and correlation matrix examination (threshold>0.90) (Podsakoff & Podsakoff, 2019).

4. Results

4.1. Outer model evaluation

Table 1 presents the measurement model assessment, demonstrating robust psychometric properties across all constructs. Blockchain Technology exhibits excellent internal consistency (α=0.914; CR=0.936) and adequate convergent validity (AVE=0.744), with all factor loadings ranging from 0.840 to 0.877, well above the 0.70 threshold. Green Innovation Performance demonstrates the strongest reliability (α=0.927; CR=0.945) and the highest convergent validity (AVE=0.773), with five items loading between 0.866 and 0.890. Sustainable

Development Outcomes shows good reliability (α=0.882; CR=0.919) with satisfactory convergent validity (AVE=0.739), where all four items have factor loadings ranging from 0.845 to 0.879. All constructs surpass the recommended thresholds of Cronbach's alpha (>0.70), composite reliability (>0.70), average variance extracted (>0.50), and factor loadings (>0.70), confirming the validity and reliability of the measurement instruments for subsequent structural model analysis.

Table 1: Measurement Model

Item	Mean	SD	λ	α	CR	AVE
Blockchain Technology						
BTC1	0,006	0,679	0.877	0.914	0.936	0.744
BTC2	0,058	0,639	0.855			
BTC3	0,043	0,633	0.875			
BTC4	-0,083	0,557	0.867			
BTC4	0,068	0,639	0.840			
Green Innovation Performance						
GIP1	-0,004	0,655	0.866	0.927	0.945	0.773
GIP2	-0,012	0,559	0.884			
GIP3	-0,111	0,555	0.874			
GIP4	0,035	0,539	0.881			
GIP5	0,055	0,439	0.890			
Sustainable Development Outcomes						
SDO1	-0,082	0,483	0.879	0.882	0.919	0.739
SDO2	-0,012	0,467	0.845			
SDO3	-0,019	0,530	0.856			
SDO4	-0,020	0,417	0.858			

Table 2 presents the discriminant validity assessment using the Fornell-Larcker criterion. The matrix displays inter-construct correlations, where Blockchain Technology demonstrates strong positive relationships with Green Innovation Performance (r=0.773) and Sustainable Development Outcomes (r=0.844). Green Innovation Performance also exhibits a substantial correlation with Sustainable Development Outcomes (r=0.793). However, the table appears incomplete as it lacks the diagonal values, which should represent the square root of AVE for each construct to properly assess discriminant validity. According to the Fornell-Larcker criterion, discriminant validity is established when the square root of each construct's AVE (from Table 1: BTC=√0.744=0.863; GIP=√0.773=0.879; SDO=√0.739=0.860) exceeds its correlations with other constructs. The observed correlations are relatively high, approaching the threshold values, suggesting that while the constructs are strongly interrelated, they maintain adequate discriminant validity, confirming that each construct captures distinct theoretical dimensions despite their significant empirical associations.

Table 2: Discriminant Validity

	Blockchain Technology	Green Innovation	Sustainable Development
Blockchain Technology			
Green Innovation	0.773		
Sustainable Development	0.844	0.793	

The Variance Inflation Factor (VIF) analysis reveals concerning multicollinearity issues that compromise the structural model's validity and interpretability. The VIF value of 1.873 between Blockchain Technology and Green Innovation, while below the conservative threshold of 3.0, suggested by J. Hair & Alamer, (2022), approaches levels that warrant attention, given the high correlations previously observed. Kline & Boyd, (2010) & RB, (2011) Emphasizes that VIF values should be evaluated in conjunction with tolerance statistics and theoretical considerations, particularly when constructs demonstrate conceptual overlap. The incomplete VIF matrix presented limits comprehensive multicollinearity assessment, as Cantillon et al, (2024) & Drummond et al, (1998)Argues that all predictor variables should be evaluated simultaneously to detect potential suppression effects or shared variance issues. J. Hair & Alamer, (2022) & J. F. Hair & Sarstedt, (2019)Further caution that VIF values between 1.5-2.5, while technically acceptable, may indicate emerging multicollinearity that could affect parameter stability and interpretation, particularly in complex structural models involving interrelated sustainability constructs.

Table 3: Varian Inflation Factor

	Blockchain Technology	Green Innovation	Sustainable Development
Blockchain Technology		1.000	1.873
Green Innovation			1.873
Sustainable Development			

Table 4: F^2 Estimation

	f-square
Blockchain Technology -> Green Innovation	0.873
Blockchain Technology -> Sustainable Development	0.121
Green Innovation -> Sustainable Development	0.230

The f^2 effect size estimates provide critical insights into the practical significance of structural relationships, though they reveal asymmetric influence patterns requiring theoretical justification. The large effect size of Blockchain Technology on Green Innovation ($f^2 = 0.873$) substantially exceeds Cohen, (1994) Threshold for large effects (0.35), suggesting that blockchain technology explains considerable variance in green innovation performance. However, this exceptionally large effect size raises questions about potential model misspecification or common method variance, as Fuller et al, (2016) & Tehseen et al, (2017)Noted that f^2 values exceeding 0.5 are uncommon in behavioral research and may indicate measurement issues. Conversely, the small-to-medium effect sizes of Blockchain Technology on Sustainable Development ($f^2 = 0.121$) and Green Innovation on Sustainable Development ($f^2 = 0.230$) suggest more modest but theoretically meaningful relationships. Henseler, (2018) & Schuberth et al, (2023) Emphasize that effect size interpretation should consider both statistical magnitude and theoretical plausibility, particularly when examining complex sustainability phenomena where multiple pathways may exist. The substantial disparity in effect sizes across relationships suggests potential mediation effects or differential construct operationalization that warrants further investigation through alternative model specifications and additional validity assessments.

Table 7 presents the evaluation of model fit, comparing the saturated and estimated models. The Standardized Root Mean Square Residual (SRMR) value of 0.045 for both models is well below the recommended threshold of 0.08, indicating excellent model fit and minimal discrepancy between observed and predicted correlations. The unweighted least squares discrepancy (d_ULS=0.210) and geodesic discrepancy (d_G=0.133) demonstrate consistent values across both models, reflecting model stability and adequate fit. The chi-square statistic of 232.281 remains identical in both specifications, though interpretation should consider sample size sensitivity. The Normed Fit Index (NFI=0.930) surpasses the acceptable cut-off value of 0.90, indicating that the proposed model explains 93% of the variance compared to the null model. The perfect correspondence between saturated and estimated models across all fit indices demonstrates that the theoretical model achieves optimal fit without over-parameterization, confirming model parsimony and adequacy for structural equation modeling analysis and subsequent hypothesis testing.

Table 7: Evaluation Fit Model

	Saturated model	Estimated model
SRMR	0.045	0.045
d_ULS	0.210	0.210
d_G	0.133	0.133
Chi-square	232.281	232.281
NFI	0.930	0.930

4.2. Hypothesis analysis

The hypothesis testing results demonstrate robust empirical support for all proposed relationships, though several statistical anomalies warrant critical examination. Hypothesis H1, examining the direct effect of Blockchain Technology on Green Innovation Performance ($\beta = 0.683$, $t = 12.909$, $p < 0.001$), exhibits a very strong relationship with narrow confidence intervals (CI: 0.591-0.765), indicating substantial predictive validity. However, the reported standard error (SE = 0.825) appears disproportionately large relative to the path coefficient, suggesting potential computational errors or model specification issues, as J. Hair & Alamer, (2022)Emphasized that standard errors should typically be much smaller than parameter estimates in well-specified models. The direct effect of Blockchain Technology on Sustainable Development Outcomes (H2: $\beta = 0.330$, $t = 4.714$, $p < 0.001$) demonstrates a weaker but statistically significant relationship, while the path from Green Innovation Performance to Sustainable Development Outcomes (H3: $\beta = 0.455$, $t = 8.043$, $p < 0.001$) shows strong predictive power. J. Hair & Alamer, (2022)Suggested that path coefficients above 0.50 indicate large effects, making the H1 relationship particularly noteworthy, though Chin (1998) cautioned that exceptionally large coefficients may signal multicollinearity or common method variance issues.

Table 5: Hypothesis Testing Results Analysis

Hypothesis	Path	β	SE	T-statistics	P-values	95% CI Lower	CI Upper	Decision	Effect Strength
H1	BTC → GIP	0.683	0.825	12.909	0.000	0.591	0.765	Accepted	Very Strong
H2	BTC → SDO	0.330	0.141	4.714	0.000	0.209	0.437	Accepted	Weak
H3	GIP → SDO	0.455	0.754	8.043	0.000	0.369	0.553	Accepted	Strong
H1a	BTC → GIP → SDO	0.310	0.622	6.149	0.000	0.236	0.403	Accepted	Strong Mediation

The mediation analysis (H1a) reveals compelling evidence for indirect effects, with Blockchain Technology influencing Sustainable Development Outcomes through Green Innovation Performance ($\beta = 0.310$, $t = 6.149$, $p < 0.001$, CI: 0.236-0.403). Preacher & Hayes, (2008) Emphasized that significant mediation requires both statistical significance of the indirect effect and non-zero confidence intervals, both of which are satisfied in this analysis. The mediation effect magnitude ($\beta = 0.310$) represents approximately 94% of the direct effect of Blockchain Technology on Sustainable Development Outcomes ($\beta = 0.330$), suggesting strong partial mediation as defined by Nitzl et al, (2016). However, the classification of "Strong Mediation" requires theoretical justification, as MacKinnon et al, (2012) Argued that mediation strength should be evaluated based on both statistical magnitude and theoretical meaningfulness rather than arbitrary effect size thresholds. The variance accounted for (VAF) calculation would provide additional insight into mediation completeness, as J. Hair & Alamer, (2022) & JF et al, (2010) Recommended VAF values above 80% indicate full mediation. Furthermore, J. F. Hair et al, (2019) Suggested that mediation interpretation should consider the relative importance of direct versus indirect effects in explaining outcome variance, particularly when examining complex sustainability phenomena where multiple causal pathways may operate simultaneously.

5. Discussion

5.1. Discriminant validity crisis: implications for theoretical validity and construct measurement

PLS-SEM analysis identifies significant psychometric flaws that threaten the theoretical integrity of this research. Our test of discriminant validity identifies significant construct convergence, with inter-construct correlations approaching the stringent HTMT threshold offered by Henseler et al. (2015) for conceptually related constructs. The correlation of Sustainable Development Outcomes and Green Innovation Performance is of special concern, as it approaches the variance overlap threshold, accentuated by Afthanorhan et al, (2021) As characteristic of construct conflation more than empirical distinction. MacKinnon et al, (2012) Maintain that high inter-construct correlations common in sustainability literature often reflect conceptual overlap more than measurement error and necessitate a construct boundary's fundamental reconsideration. This empirical indistinguishability severely compromises the mediation analysis, as there is a danger of asking whether blockchain capability foresees sustainability outcomes through sustainability outcomes—a tautological link devoid of theoretical meaning.

The measurement model presents several concerning psychometric indicators apart from discriminant validity violations. The distributional features—means concentrated near zero with limited standard deviations—imply systematic measurement artifacts that Podsakoff et al. (2003) observed as signals of common method variance, social desirability bias, or restrictions on scale usage in current digitalized transformation work. Henseler et al (2014) study proved that such distributional outliers have the tendency to spuriously inflate factor loadings and reliability measures and hide actual construct relationships, thereby producing artificial structural model outcomes. The theoretical blur of green innovation processes and sustainability outcomes might reflect the nascent nature of blockchain-sustainability measurement instead of empirical fact, and such necessitates construct boundaries for fundamental reconceptualization prior to the usability of meaningful theory testing.

5.2. Theoretical coherence amidst methodological constraints: dynamic capabilities theory validation

In spite of important psychometric limitations, our empirical results demonstrate significant theoretical congruence with prevailing paradigms and current cross-cultural empirical results. The observed mediation pattern—high-strong blockchain technology correlation with improved green innovation performance and weak direct connections between blockchain technology and sustainable development results—profoundly reflects. Teece & D.J, (2007) Advanced dynamic capability theory predictions in the digital transformation context. This theoretical construct advances that the exclusive strategic value of technology resources is achieved by way of organizational capability reconfiguration alone and not by virtue of direct technology deployment. Besides, Migdadi, (2021) & Zaman et al, (2025) Portray digital technologies such as blockchain as requiring systematic capability building toward fostering sustainable competitive advantages, consequently supporting our observed mediation pattern.

Convergent results from methodologically varied studies reinforce theoretical confidence regardless of our measurement issues. Kouhizadeh & Sarkis, (2024) & Sarkis et al., (2021), using European manufacturing companies' longitudinal mixed-methods studies, recorded similar mediation patterns such that blockchain adoption produced sustainability benefits alone by enhancing innovation capability. Saberi et al. (2019) Chinese enterprise analysis using objective ESG performance measures similarly indicated capability building as the leading transmission mechanism from blockchain use to environmental results. Kumari & Rathee, (2024) & X. Wang et al., (2022) A Systematic review of studies across various countries consistently supports capability-mediated routes, indicating strong theoretical connections beyond cross-sectional survey-based methodological artifacts.

The magnitudes of the effect sizes need a nuanced understanding of theoretical and empirical frameworks. Although the blockchain to green innovation connection has a large effect by traditional standards, J. F. Hair & Sarstedt, (2019) Urge that extraordinarily large effect sizes of emerging technology studies are as likely to reflect construct overlap, common variance of methods, or model misspecification instead of substantive predictive connections. Shmueli et al. (2019) stress that interpretation of effect size needs to include measurement quality and theoretical plausibility and that our ostensibly robust connections by chance most likely correspond to psychometric artifacts instead of substantive theoretical connections that need to be carefully established by different methodological means.

5.3. Alternative theoretical mechanisms: resource-based view, institutional theory, and digital transformation perspectives

Although dynamic capabilities theory offers our leading theoretical lens, rival explanations deserve systematic attention for rigorous understanding. The Resource-Based View, as stylized by Barney & J.B, (1991) and Peteraf, (1993) For digital economies, blockchain technology qualifies as a strategic resource providing direct sustainable competitive advantages by virtue of VRIN attributes (valuable, rare, inimitable, non-substitutable). Nonetheless, our weak direct impacts oppose RBV predictions, in favor of Arndt & Bach, (2015) Criticism of resource-based views of overemphasis on ownership of assets and undertreatment of capability building processes central to value creation from technology resources.

The Technology-Organization-Environment framework, as revised by Tornatzky et al., (1990) For blockchain-based contexts, it provides alternative mediation explanations in organizational transformation mechanisms. N. Kumar et al, (2025) & Z. Yang et al, (2025)Provide an illustration that blockchain innovations influence performance by means of organizational structure changes and environmental adaptation processes instead of direct technology impacts. The latest empirical inquiries lend support for TOE-mediated paths, such that our observed mediation may indeed correspond to organizational change processes instead of capability development per se. The conceptual uncertainty of the linkage necessitates future inquiries that differentiate capability-based from structure-based mediation mechanisms for blockchain-sustainability linkages.

Institutional Theory, as Dimaggio & Powell, (1983) Extended for sustainability conditions, offers a third theoretical alternative by way of legitimacy-seeking practices and mechanisms of stakeholder pressure. Aloini et al, (2023) & Thompson & Rust, (2023) The Institutional legitimacy model argues that organizations implement blockchain innovations for symbolic legitimacy instead of efficiency reasons, thereby possibly explaining the weak performance impacts of a direct nature. Organisations might implement blockchain for the approval of stakeholders whilst delivering sustainability results by way of unrelated, decoupled processes—creating spurious mediation impacts signifying institutional pressures instead of technical strength. Pan et al, (2024) The Argument is that institutional and efficiency motives tend to function simultaneously for sustainability conditions, necessitating complex theoretical models to differentiate between symbolic adoption and substantive impact of implementation.

5.4. Cross-cultural robustness and theoretical boundary conditions

In spite of limitations of methodology, theoretical relationships exhibit cross-cultural equivalence and give confidence in the universality of the mechanisms underlying. (Mi et al., 2020; Sedita et al., 2022) The Culture dimensions framework proposes differential strength of mediation across cultural contexts and uncertainty avoidance and long-term orientation to moderate blockchain-capability relations. (Aslam et al., 2025; Cao et al., 2025; Pavithra et al., 2025) The Study suggests that performance orientation cultures exhibit stronger blockchain-sustainability relations mediated by systematic capability building processes. Schwartz's (2006)cultural value framework shows that cultures focused on harmony and intellectual autonomy have stronger innovation mediation impacts, and cultures focused on hierarchy have weaker capability building paths.

Institutional evolution provides important boundary conditions for theoretical mechanisms. Huo et al., (2013) & Persad et al. (2024)The Model of institutional economics proposes that blockchain influence has greater vigor in nascent markets with minimal institutional structures than in established economies with sophisticated regulatory systems. Institutional void theory posits that blockchain's governance function has greater value in void-filled environments, transforming capability formation mechanisms. The institution-based view of technology identifies how informal and formal institutional constraints shape technology adoption patterns and performance consequences, and requests contextual theoretical innovation for blockchain-sustainability connections.

Economic level of development provides additional theoretical limitations, for example, as observed by (Aslam et al., 2025; Commey et al., 2025), wherein technology-performance sustainability regime relationships are mediated by regulatory sophistication and quality of the legal system. Institutional capacity models suggest that extractive institutions block the capability-building benefits of blockchain, but inclusive institutions enable technology-based performance improvements. Government support for environmental innovation moderates sustainability and blockchain relationships with greater effects in regimes with institutional support for environmental technology adoption.

5.5. Practical implications: strategic implementation framework for organizational transformation

The capability-mediated relationships identified in this study provide actionable insights for organizations and policymakers seeking to leverage blockchain technology for sustainable development. The findings suggest that successful blockchain implementation requires a sequential capability-building approach rather than mere technology adoption (Kouhizadeh et al., 2021; Saberi et al., 2019). Organizations should prioritize three implementation phases: first, establishing foundational blockchain competencies through targeted training programs, cross-functional innovation teams, and strategic partnerships with technology providers; second, integrating blockchain transparency mechanisms with existing organizational systems, including supply chain management, environmental monitoring, and stakeholder engagement platforms; and third, institutionalizing performance measurement systems that systematically capture sustainability outcomes and facilitate continuous improvement (Ghadge et al., 2023).

The findings carry significant implications for Indonesian policymakers seeking to accelerate blockchain-enabled green innovation. Financial incentive mechanisms are critical to overcome adoption barriers, particularly among resource-constrained SMEs (Bai et al., 2023). Policymakers should consider tax incentives for blockchain-based green technology investments, subsidized access to blockchain infrastructure, and preferential financing schemes for sustainability-oriented digital transformation initiatives. Furthermore, public-private partnership (PPP) frameworks should be established to facilitate knowledge transfer and reduce implementation costs. (Zheng & Lu, 2022). These partnerships could connect blockchain technology providers, academic institutions, industry associations, and government agencies to create collaborative innovation ecosystems. Sector-specific blockchain consortia in key Indonesian industries, such as palm oil, textiles, and manufacturing, could accelerate standardization and interoperability while sharing implementation costs. (Rakibul Hasan Chowdhury, 2024). Regulatory clarity is essential to encourage adoption while ensuring accountability. (Bumblauskas et al., 2020). Policymakers should develop standardized protocols for blockchain-based sustainability reporting, establish certification frameworks for verifying green innovation claims, and create interoperable platforms for environmental performance disclosure across supply chains. Such regulations would reduce information asymmetries and enhance stakeholder trust in blockchain-enabled sustainability initiatives. (Ding et al., 2022). Additionally, national capacity-building programs must integrate blockchain and sustainability competencies into educational curricula at vocational, undergraduate, and professional levels. (Gohil & Thakker, 2021). Government-supported training centers could provide specialized programs in blockchain technology, green innovation management, and sustainable supply chain practices, addressing the critical skills gap. Regulatory sandboxes should be established to allow controlled experimentation with blockchain-enabled sustainability innovations, enabling organizations to pilot novel applications while managing regulatory risks and generating practical insights that inform future policy development. (Moschko & Blažević, 2023).

From an organizational perspective, the mediation effects underscore the importance of knowledge management capabilities in blockchain implementation success. Drawing on Nonaka and Takeuchi's (1995) SECI model as applied in contemporary digital transformation contexts (Gohil & Thakker, 2021; Song et al., 2022), organizations must develop systematic knowledge conversion processes: socialization through communities of practice that facilitate tacit knowledge sharing between blockchain specialists and sustainability practitioners; externalization by documenting blockchain-sustainability integration experiences and developing organizational routines; combination by synthesizing external knowledge from blockchain ecosystems, industry benchmarks, and regulatory developments with internal organizational knowledge; and internalization through experiential learning mechanisms, including pilot projects, simulation exercises, and reflective practice sessions (Morris & König, 2021; Sinha, 2023). These knowledge management processes enable organizations to transform blockchain technological capabilities into actionable sustainability innovation outcomes. Organizations should establish dedicated cross-functional teams comprising IT specialists, sustainability managers, supply chain professionals, and operational staff to facilitate knowledge integration and ensure holistic implementation approaches. (Dhaigude et al., 2021; Nazir & Pinsonneault, 2021).

Stakeholder engagement strategies represent another critical implementation dimension that organizations must address strategically. Building on contemporary stakeholder theory ((Aggarwal & Kumar, 2021; Lohachab et al., 2022) And recent blockchain-sustainability integration literature, organizations should leverage blockchain's transparency capabilities to enhance multi-stakeholder collaboration. Customer engagement mechanisms could utilize blockchain traceability for real-time sustainability disclosure and product authentication, addressing the growing demand for verified environmental claims. (Gohil & Thakker, 2021; Ng et al., 2023). Supplier collaboration platforms should employ blockchain-based verification systems for environmental performance monitoring, enabling proactive compliance management and risk mitigation. (Jing et al., 2023; Leng et al., 2021). Investor relations could be strengthened through blockchain-enabled sustainability reporting that provides immutable, auditable evidence of green innovation performance. (Lutfi et al., 2023b). Moreover, regulatory engagement should be proactive, with organizations participating in policy dialogue to shape favorable regulatory environments that balance innovation promotion with sustainability accountability. (Sun et al., 2022). These stakeholder capabilities, rather than blockchain infrastructure per se, constitute sources of sustainable competitive advantage by fostering trust, reducing transaction costs, and enabling value co-creation across organizational boundaries. (Xu et al., 2024). The blockchain-enabled transparency creates shared information platforms that facilitate collaborative governance structures, aligning diverse stakeholder interests toward common sustainability objectives while maintaining organizational competitive positioning. (Liu et al., 2025).

5.6. Methodological recommendations and future research imperatives

Validity crisis of discriminant necessitates immediate methodological intervention to enable significant theoretical progress. The next wave of research ought to emphasize conceptual precision using stringent construct developmental processes applying prevailing best practices. The model of measurement development by MacKenzie & Podsakoff, (2012) & Podsakoff et al, (2003) Necessitates vast qualitative efforts such as expert interviews, focus groups, and ethnographic research to discern well-articulated conceptual contrasts among blockchain capacities, innovation processes, and sustainability results. According to Wittmayer et al, (2024) Developments of scales require participation by an expert judgment panel, application of cognitive interviewing, and stringent pilot testing in diversified organizational settings to create construct distinctiveness before quantitative validation efforts.

Longitudinal study designs are a critical methodological advance for embracing dynamic capability-building processes of digital transformations. Holmström & Partanen (2014) show that cross-sectional mediation analysis generates highly biased estimates by virtue of temporal confounding, possibilities of reverse causality, and overlooked heterogeneity in patterns of blockchain adoption (Sanka et al., 2021). Multi-round data collection over prolonged periods of time might reveal blockchain implementation processes, capability building

processes, and sustainability outcome realization for varied organizational contexts. Suitable mediation testing entails achieving temporal precedence, eliminating alternative explanations, and modelling capability building as dynamic processes and not static entities.
Sophisticated analytical methods may overcome current shortcomings while moving theoretical knowledge of blockchain-sustainability linkages forward. Based on, (JF et al., 2010; Sarstedt et al., 2017)Classic PLS-SEM applied to theory testing with exact parameter estimation for use in discriminant validity issues is not suitable. SEM-based covariance with robust estimation, test of measurement invariance, and contrast of alternative models may test hypotheses of mediation given construct overlap. Multi-method designs of quantitative surveys and qualitative case studies, objective performance measures, and blockchain analytics of use may triangulate results and diminish method-specific artifacts of sustainability research.
Multi-level theoretical integration is a primary methodological focus for closing blockchain implementational complexity across organisational levels. Determinants of individual adoption, organisational implementational processes, and institutional environmental pressures need to be modelled simultaneously, with cross-level interaction specifications being made explicit. Technology and performance relationships function across more than one organisational level, with complex emergence phenomena having implications for blockchain-sustainability linkages. The theoretical models need to specify within-group agreement, differences among groups, and cross-level mediation processes that organisational blockchain adoption and sustainability performance relationships.

5.7. Theoretical contributions and limitations acknowledgment

This paper provides different theoretical contributions, but with noteworthy methodological limitations that require cautious interpretation. First, we offer provisional empirical evidence in favor of dynamic capability theory for the blockchain and sustainability case and demonstrate that technology resources can acquire strategic value by capability restructuring instead of direct use, but for measurement issues, we refrain from decisive conclusions. Then, we propose a preliminary theoretical foundation for innovation-intermediating flows from blockchain adoption to sustainability performance in various cultural contexts, and test it using more rigorous measures. We recognize, finally, potential boundary conditions of institutional evolution and cultural beliefs impacting on theoretical mechanisms' operation, but more work is required for such linkages to be affirmed.
Nonetheless, inherent limitations greatly limit theoretical claim validity and generalizability, necessitating explicit recognition. The failure of discriminant validity makes all structural parameter estimates theoretically undeterminable and potentially biased, necessitating total reconstruction of the measurement model before the attainment of meaningful theoretical conclusions. Cross-sectional design makes impracticable the establishment of causal inference pivotal for brokerage and buffering theory testing applied to dynamic organizational settings. Single-source data gathering engenders significant common method variance issues that could spuriously exaggerate observed relations beyond their genuine theoretical importance. Convenience sampling severely restricts population generalizability and external validity across varying organizational and industry settings. Most significantly, construct overlap infers innate conceptual muddlement necessitating voluminous theoretical reconceptualization and empirical verification prior to attainability of robust theory testing.
Future studies need to give utmost importance to several key avenues for the theory development of blockchain and sustainability. Longitudinal examination of blockchain roll-out processes in various organizational settings might provide temporal precedence needed for assertions of causal mediation and dynamic capability building understanding. Multi-perspective collections of managerial surveys, objective performance data, stakeholder surveys, and blockchain use analytics might alleviate common method bias issues and allow for integral measurement means. Experimental or quasi-experimental designs might yield stronger causal inferences for blockchain impacts on capability building and sustainability performance. Cross-cultural replication fieldwork might test theoretical boundary conditions and cultural moderators in varied institutional settings. Above all, constructing a building at the fundamental level needs to provide sharp conceptual meanings and empirical distinctiveness for blockchain capability, innovation processes, and sustainability performance before intricate theory testing and validation is methodologically valid and theoretically significant.

6. Conclusion

This work examined the mediating role of green innovation performance in the linkages between blockchain technology adoption and sustainable development results, revealing complex theoretical patterns stifled by significant methodological limitations, which impose careful interpretation. The empirical findings offer significant support for the hypothesized mediation model, showing that blockchain technology significantly affects green innovation performance while exhibiting weaker direct influences on sustainable development results, a pattern that aligns with Teece & D.J, (2007) Forecasts from dynamic capabilities theory on the production of technological resource value from capability reconfigurability. However, discriminant validity concerns—demonstrated by high inter-construct correlations approaching critical levels—raise fundamental questions on construct distinctiveness, an issue underscored by J. Hair et al, (2017) & J. F. Hair, Risher, et al, (2019) As potentially compromising interpretations of structural models. The cross-culturally derived convergent evidence supporting capability-mediated routes Kouhizadeh & Sarkis, (2024) & Sarkis et al, (2021) offers theoretical support for capability-mediated routes; however, Sarstedt et al, (2017) Emphasize that building measurement validity is a primary precursor of noteworthy theoretical advances. The theoretical models examined—dynamic capabilities theory, resource-based view, and institutional theory—offer insightful explanations of observed mediation patterns; however, conclusive empirical proof of these models requires improved methodologies for building discriminant validity and applying longitudinal designs for registering the dynamic capability development processes over time.
The paper contributes to blockchain-sustainability literature by delivering qualified empirical justification for innovation-mediated theoretical mechanisms and, at the same time, illustrating critical methodological imperatives for future research progress. Podsakoff et al (2012) underline that construct measurement validity is the precursor for significant theoretical testing, a point underscored by such challenges of discriminant validity in this study, calling for fundamental reconceptualisation of construct boundaries among blockchain capabilities, innovation processes, and sustainability outcomes. The implications for practice propose that organisations should implement a sequential approach-based implementational strategy prioritising capability developments of a complementary nature over more direct deployment of technology, whereas Edwards (2001) cautions that such recommendations necessitate psychometrically valid empirical grounding not yet present within such a field. Maxwell and Cole (2007) illustrate how, by using longitudinal research design-based methodologies, temporal precedence needed for supporting causal mediation allegations may be established, and by the attention of Podsakoff et al. (2003) on multi-source collections of data for overcoming common method variance issues that may spuriously enhance observed connections. Future work needs to place central importance on extensive qualitative validation upon expert judgement procedures and pilot testing across varying organisational contexts in delineating distinct conceptual separations beforehand, before more sophisticated

quantitative validation, for instance by Hinkin's (1998) scale developments, which necessitate construct clarity grounding before empirical test. Only by precise attention to measurement validity, longitudinal design-based application, and multi-method triangulation methodologies will blockchain-sustainability work attain scientific stringency adequate for supporting robust theoretical progress and evidence-informed organisational sustainability transformation implementational guidance.

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