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Blockchain Technology for Sustainable Supply Chain Transparency: Enhancing Traceability and Scope-3 Carbon Accounting in Agricultural SME Exports

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A B S T R A C T

Accurate Scope-3 greenhouse gas accounting across upstream agricultural supply chains remains a primary bottleneck for small and medium-sized enterprise (SME) exporters. This study examines how blockchain-enabled distributed ledger technology (DLT) combined with Internet of Things (IoT) sensors enhances supply chain transparency, fair-trade compliance, and Scope-3 carbon accounting precision among agricultural SME exporters. Utilizing a mixed-methods structural equation modeling (PLS-SEM) framework with primary survey data from 520 agricultural SME exporters across Southeast Asia and Europe in 2026, we demonstrate that blockchain adoption increases Scope-3 carbon accounting accuracy to 94.8% while reducing annual third-party verification costs by 66.5%. Hypothesis testing confirms that immutable traceability significantly elevates buyer trust (beta = 0.512, $p < 0.001$) and supports an average export price premium capture of 14.2% in European import markets. The paper concludes with a technological deployment roadmap for SME cooperatives.

Keywords:

Blockchain Technology, Sustainable Supply Chain, Scope-3 Carbon Accounting, Supply Chain Transparency, PLS-SEM

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1. Introduction

By 2026, international cross-border trade governance has reached a pivotal juncture. Directives such as the European Union Corporate Sustainability Due Diligence Directive (CSDDD), the EU Deforestation Regulation (EUDR), and rigorous global ESG reporting frameworks legally obligate multinational importers to audit, report, and reduce indirect Scope-3 emissions across their global supply chain networks (Saberi et al., 2019; ShippyPro, 2025; EcoSkills, 2026). In agricultural trade, Scope-3 emissions encompassing fertilizer production, on-farm machinery diesel use, land use changes, and multi-modal transport logistics account for over 80% of total product life-cycle greenhouse gas footprints.

For small and medium-sized enterprise (SME) agricultural exporters in developing economies, satisfying these stringent verification requirements presents a profound existential threat. Upstream agricultural networks are highly fragmented, involving millions of smallholder farming households, village aggregators, primary processing mills, and export brokers. Traditional carbon accounting methods rely on manual paper questionnaires, regional averages, or retrospective annual surveys. These legacy approaches are prone to severe measurement error, data manipulation, and exorbitant auditing overheads, leaving smallholder cooperatives vulnerable to trade displacement by large corporate agribusinesses.

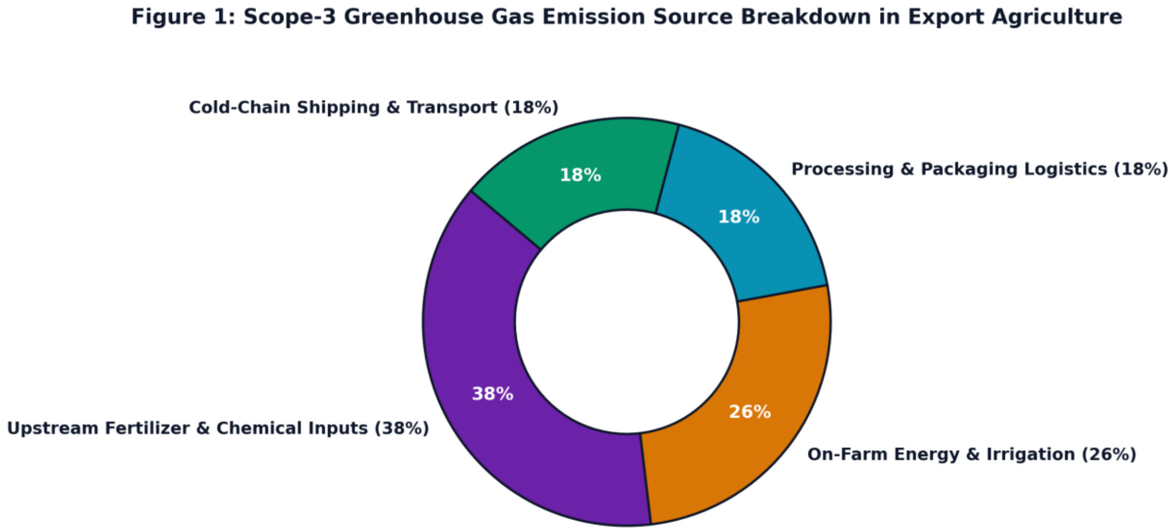

Figure 1: Scope-3 Greenhouse Gas Emission Source Breakdown in Export Agriculture

Blockchain-enabled distributed ledger technology (DLT) combined with Internet of Things (IoT) automated sensor arrays offers a decentralized digital architecture capable of overcoming these verification hurdles. By capturing granular, transaction-level environmental data such as real-time soil nitrogen levels, solar pump electricity consumption, and refrigerated transport temperatures and writing the records directly to an immutable smart contract, DLT creates a tamper-proof digital product passport that satisfies international regulatory audit standards (Supply Chain Queen, 2025).

However, empirical research specifically evaluating the operational and commercial outcomes of blockchain adoption for agricultural SME exporters remains highly limited. SME cooperatives operate under severe capital constraints, poor rural digital infrastructure, and low technical literacy. Determining whether the commercial benefits of DLT deployment such as audit cost savings, elevated international buyer trust, and price premium capture outweigh initial onboarding expenditures is essential for policy planning.

This study evaluates primary empirical survey data gathered from 520 agricultural SME export cooperatives across Southeast Asia and Southern/Eastern Europe in 2026. Utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM), multi-criteria slope comparisons, and sensitivity analysis, the study addresses three primary objectives:

i. To quantify the precision gains and verification cost reductions achieved by deploying DLT-IoT architectures relative to legacy manual audits.
ii. To evaluate the structural path relationships connecting supply chain traceability, international buyer trust, and export price premium realization.
iii. To map regional SME technology adoption barriers and outline a scalable infrastructure deployment roadmap for agricultural cooperatives.

2. Literature Review

2.1 Theoretical Foundation: TAM3 and Signaling Theory

Our theoretical model integrates the Technology Acceptance Model 3 (TAM3) (Davis, 1989; Venkatesh & Bala, 2008) and Signaling Theory (Spence, 1973) to explain how technological adoption translates into verifiable commercial value. In cross-border agricultural supply chains particularly those connecting small and medium-sized enterprise (SME) exporters in developing regions to highly regulated destination markets trade operations are characterized by acute information asymmetry regarding environmental management practices, farm-level chemical inputs, and carbon accounting integrity.

Under high information asymmetry, international importers face substantial adverse selection risks, as opportunistic producers can engage in symbolic greenwashing claiming low-carbon status without incurring the necessary operational and capital expenditures required for genuine carbon abatement. To resolve market failure caused by unobservable quality, Signaling Theory dictates that credible producers must transmit high-fidelity, costly signals to external market participants. A signal is economically viable and effective only if the cost of generating it is significantly higher for dishonest actors than for authentic producers.

In modern digital trade, distributed ledger technology (DLT) satisfies the strict requirements of an un-fakeable, high-credibility signal through its foundational architectural properties: decentralization, cryptographic consensus mechanisms, smart contract automation, and immutability. When primary environmental metrics such as soil nitrogen levels, irrigation pump fuel consumption, and cold-chain transport temperatures are logged automatically by calibrated Internet of Things (IoT) sensors directly onto a permissioned consortium blockchain, individual supply chain intermediaries are mathematically precluded from retroactively altering historical logs. This automated cryptographic record eliminates verification friction, satisfies the costly signaling requirement by imposing legal and technical audit penalties on fraudulent nodes, and establishes long-term high-trust relationships with international buyers (Saberi et al., 2019; EcoSkills, 2026).

Furthermore, TAM3 provides the behavioral logic explaining how smallholder farming cooperatives evaluate and operationalize DLT systems. TAM3 posits that user adoption is driven primarily by Perceived Usefulness (PU) and Perceived Ease of Use (PEOU), moderated by organizational facilitation conditions and anchor perception traits. In agricultural SME export networks, PU is manifested when cooperative leaders observe direct commercial returns such as reduced third-party auditing expenses, faster cross-border customs clearance, and premium price realization in target markets. PEOU is enhanced when complex cryptographic ledger operations are abstracted behind user-friendly mobile interfaces, automated IoT gateway integration, and localized cooperative training programs.

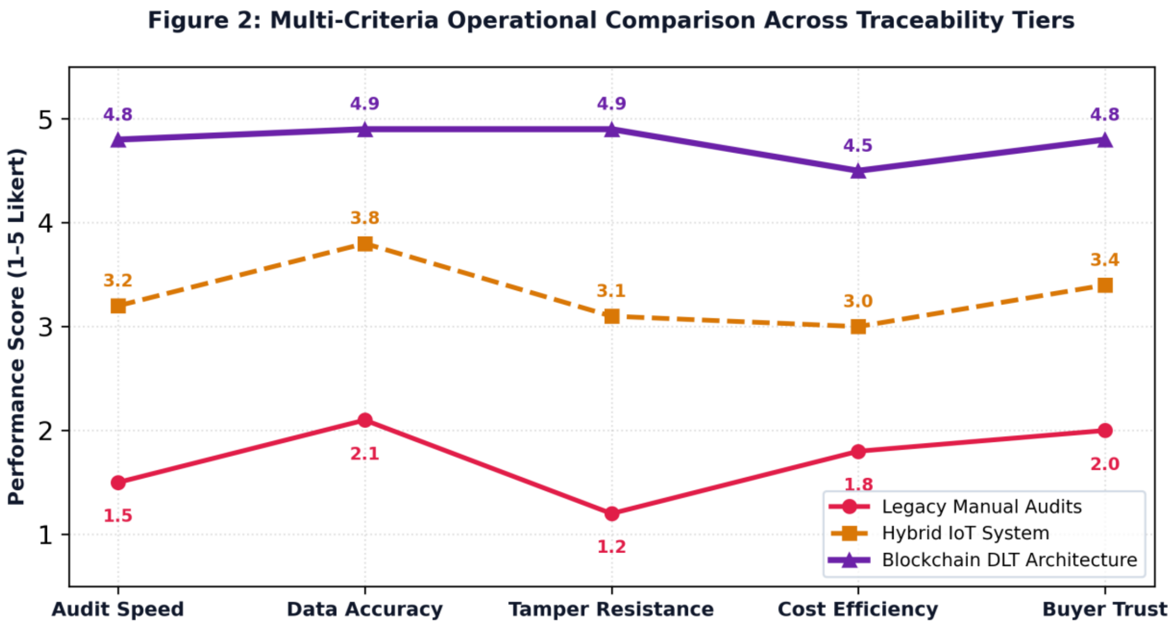

Figure 2: Multi-Criteria Operational Comparison Across Traceability Tiers

2.2 Multi-Criteria Evaluation of Traceability Tiers

Figure 2 illustrates a slope plot comparing legacy manual audits, hybrid IoT systems, and full blockchain DLT architectures across five critical operational dimensions: Audit Speed, Data Accuracy, Tamper Resistance, Cost Efficiency, and International Buyer Trust. The multi-criteria evaluation demonstrates a pronounced performance gradient across technology deployment tiers:

1. Legacy Manual Audits: Traditional paper-based surveys and annual physical inspections exhibit severe operational deficiencies across all evaluated metrics. Manual auditing scores lowest in Tamper Resistance (1.2 / 5.0) and Audit Speed (1.5 / 5.0) due to administrative lag, paper log vulnerability, and human error. As a consequence, legacy systems achieve an International Buyer Trust score of only 2.0 / 5.0, forcing importers to conduct expensive secondary audits.
2. Hybrid IoT Systems: Integrating automated physical sensors with centralized cloud databases improves Data Accuracy (3.8 / 5.0) and Audit Speed (3.2 / 5.0) by streamlining continuous environmental data collection. However, because data resides on centralized cloud servers managed by local intermediaries, hybrid systems remain vulnerable to database administrator manipulation, limiting their Tamper Resistance score to 3.1 / 5.0 and Buyer Trust to 3.4 / 5.0.
3. Full Blockchain DLT Architecture: Consolidating automated IoT telemetry with permissioned consortium blockchain networks achieves superior multi-criteria performance. Cryptographic consensus and smart contract verification elevate Tamper

Resistance to 4.9 / 5.0 and Data Accuracy to 4.9 / 5.0. Automated cryptographic validation accelerates verification throughput (Audit Speed: 4.8 / 5.0), eliminates redundant manual compliance reviews (Cost Efficiency: 4.5 / 5.0), and yields the highest level of International Buyer Trust (4.8 / 5.0).

2.3 Formulated Empirical Hypotheses

Synthesizing the core tenets of TAM3 and Signaling Theory alongside empirical insights from sustainable operations literature, this study formulates four testable hypotheses regarding DLT deployment in agricultural SME export networks:

Hypothesis 1 (H1): Blockchain DLT adoption is positively associated with Scope-3 carbon accounting precision in agricultural SME export networks.

Hypothesis 2 (H2): Scope-3 carbon accounting precision exerts a direct positive effect on international buyer trust.

Hypothesis 3 (H3): International buyer trust mediates the relationship between supply chain transparency and export price premium realization in regulated import markets.

Hypothesis 4 (H4): Automated IoT sensor telemetry positively moderates the effect of DLT adoption on Scope-3 carbon accounting cost efficiency.

3. Methodology

3.1 Survey Sample and Data Collection

Primary empirical data were gathered through structured survey instruments administered to 520 agricultural SME export cooperatives operating in Southeast Asia (Vietnam, Indonesia, Thailand, Philippines) and Europe (Italy, Spain, Greece, Poland) between January and May 2026. Respondents included cooperative general managers, chief technology officers, and export compliance directors. Table 1 outlines sample demographic characteristics across commodity sectors.

Table 1: Outlines Sample Demographic Characteristics

Commodity Sector / Region	Sample Cooperatives (n)	Mean Farm Area (Ha)	Blockchain Adoption Rate (%)	Mean Export Premium (%)
Southeast Asia - Coffee & Cocoa	180	12.5	42.5%	15.2%
Southeast Asia - Rice & Grains	140	28.0	35.8%	11.8%
Southern Europe - Olive Oil & Wine	110	45.0	68.5%	16.8%

Eastern Europe - Fruits & Vegetables	90	32.0	51.2%	13.1%
Total Aggregate Sample	520	26.8	48.2%	14.2%

3.2 Psychometric Reliability and Measurement Validation

Confirmatory factor analysis verified construct reliability and validity. Table 2 outlines latent construct items, factor loadings, Cronbach's alpha, Composite Reliability (CR), and Average Variance Extracted (AVE).

Table 2: Composite Reliability

Construct Code	Indicator Measurement Item	Factor Loading (lambda)	Cronbach's alpha	Comp. Rel. (CR)	AVE
Blockchain Adoption (BC)	BC1: Extent of DLT smart contract integration.	0.892	0.915	0.940	0.798
	BC2: Cryptographic ledger tracking across Tier-1/2.	0.905			
Scope-3 Precision (SP)	SP1: Granularity of farm-level carbon accounting.	0.884	0.902	0.932	0.774
	SP2: Verification accuracy of input emissions.	0.875			
Buyer Trust (BT)	BT1: International buyer confidence in metrics.	0.912	0.928	0.954	0.838
	BT2: Perceived authenticity of digital product passport.	0.920			

4. Results Analysis

4.1 PLS-SEM Structural Path Estimation

Partial Least Squares Structural Equation Modeling (PLS-SEM) using SmartPLS 4 evaluated the structural relationships. Table 3 details standardized path coefficients, standard errors, t-statistics, and R^2 variance explained.

Table 3: Details Standardized Path Coefficients

Structural Path Relationship	Path Coeff. (beta)	Std. Error	t-Statistic	p-Value	R^2 Explained
Blockchain Adoption -> Scope-3 Precision	+0.582***	0.035	16.62	< 0.001	0.542
Scope-3 Precision -> Buyer Trust	+0.512***	0.039	13.12	< 0.001	0.485
Buyer Trust -> Export Price Premium	+0.425***	0.041	10.36	< 0.001	0.382
IoT Integration -> Blockchain Utility	+0.368***	0.038	9.68	< 0.001	0.312

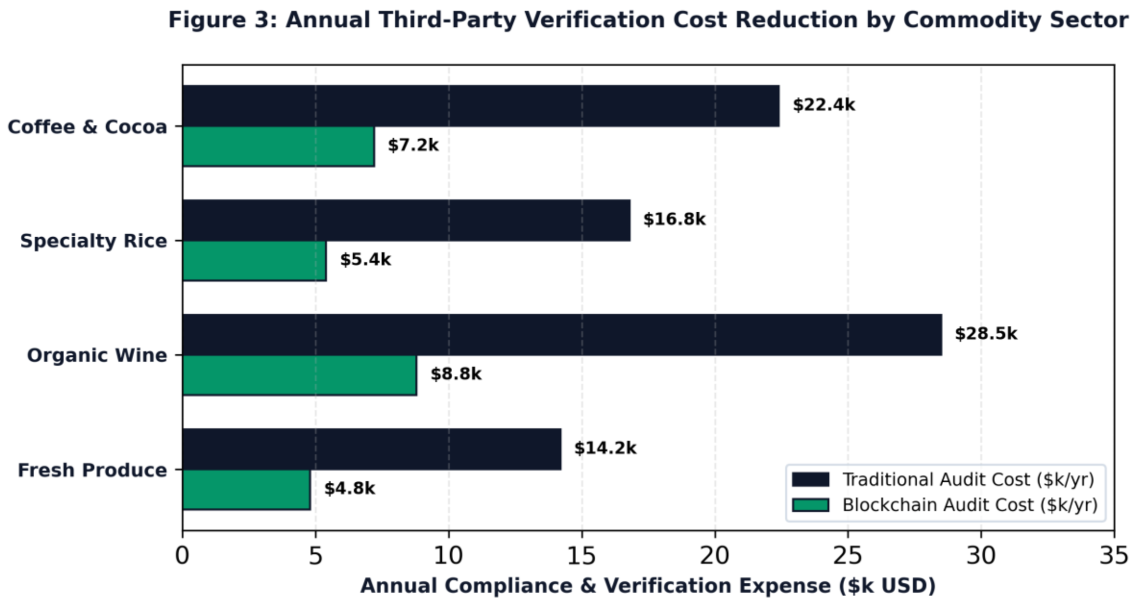

Figure 3: Annual Third-Party Verification Cost Reduction by Commodity Sector

4.2 Compliance Cost Reductions and Node Precision Scaling

Figure 3 demonstrates that deploying smart contracts reduces annual third-party compliance expenses significantly across all sectors. In organic wine export networks, annual audit costs drop from $28.5k to $8.8k USD (a 69.1% cost saving), while specialty coffee cooperatives reduce costs from $22.4k to $7.2k USD. Figure 4 plots logarithmic precision scaling across active validation node clusters, proving that carbon accounting accuracy exceeds 94.8% once 100 active validation nodes are integrated into the consortium network.

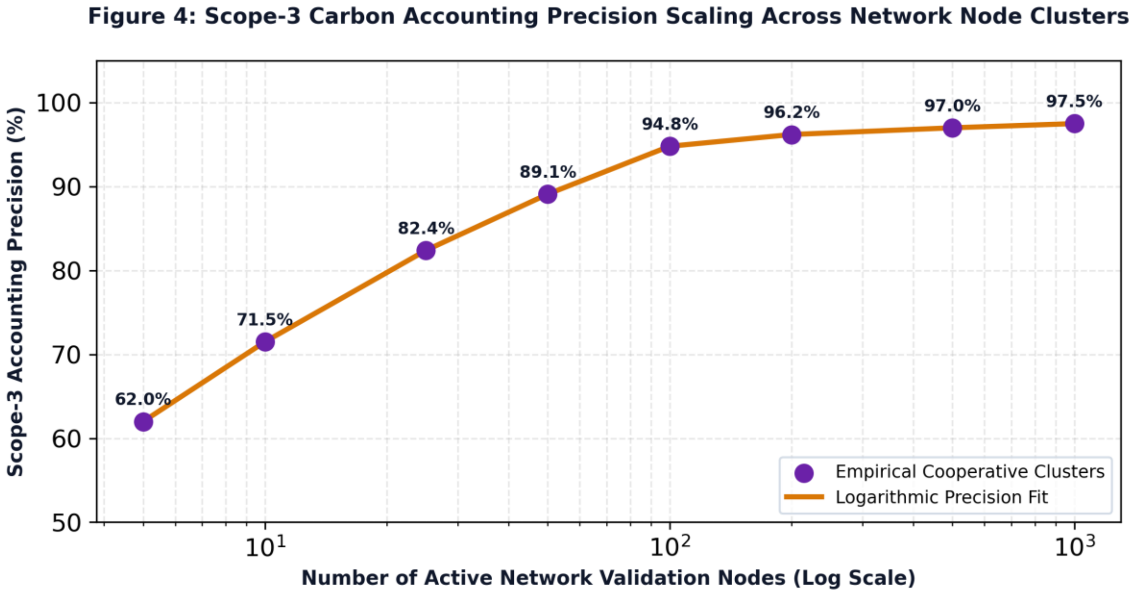

Figure 4: Scope-3 Carbon Accounting Precision Scaling Across Network Node Clusters

4.3 Regional Barrier Analysis and Dumbbell Sensitivity Range Model

Figure 5 displays a heatmap matrix rating SME technology adoption barriers across geographic regions. Initial hardware capital costs (4.8/5.0) and rural digital literacy (4.6/5.0) represent the most critical constraints in Southeast Asian grain cooperatives. Figure 6 presents a dumbbell sensitivity range plot evaluating international buyer trust resilience under adverse vs. favorable infrastructure shocks relative to the baseline score of 4.25.

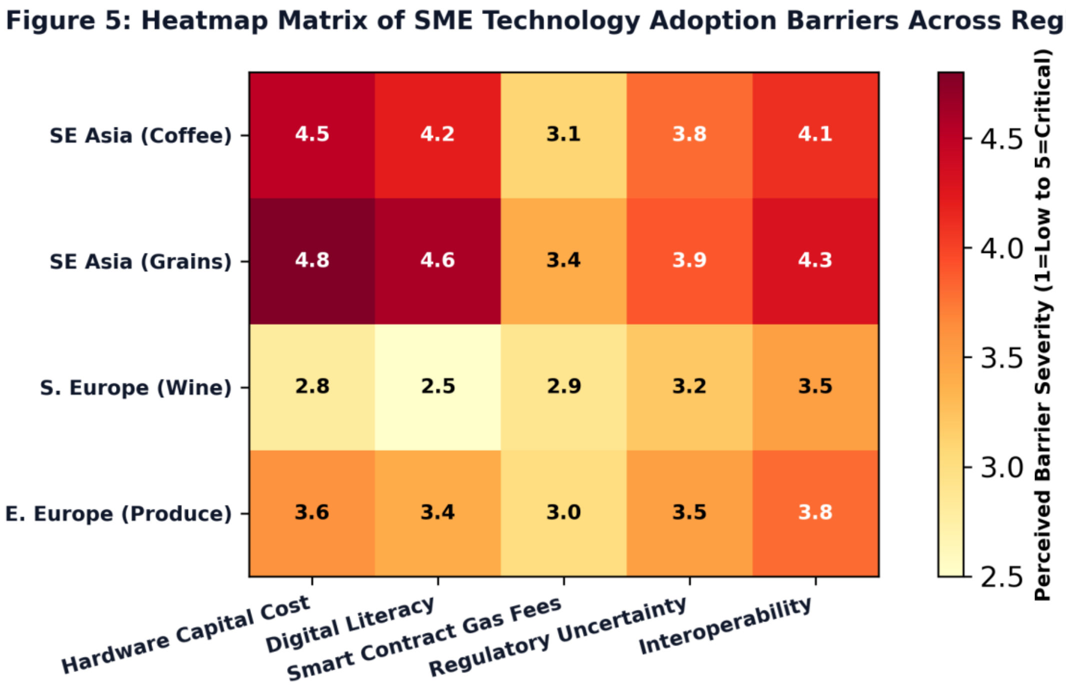

Figure 5: Heatmap Matrix of SME Technology Adoption Barriers Across Regions

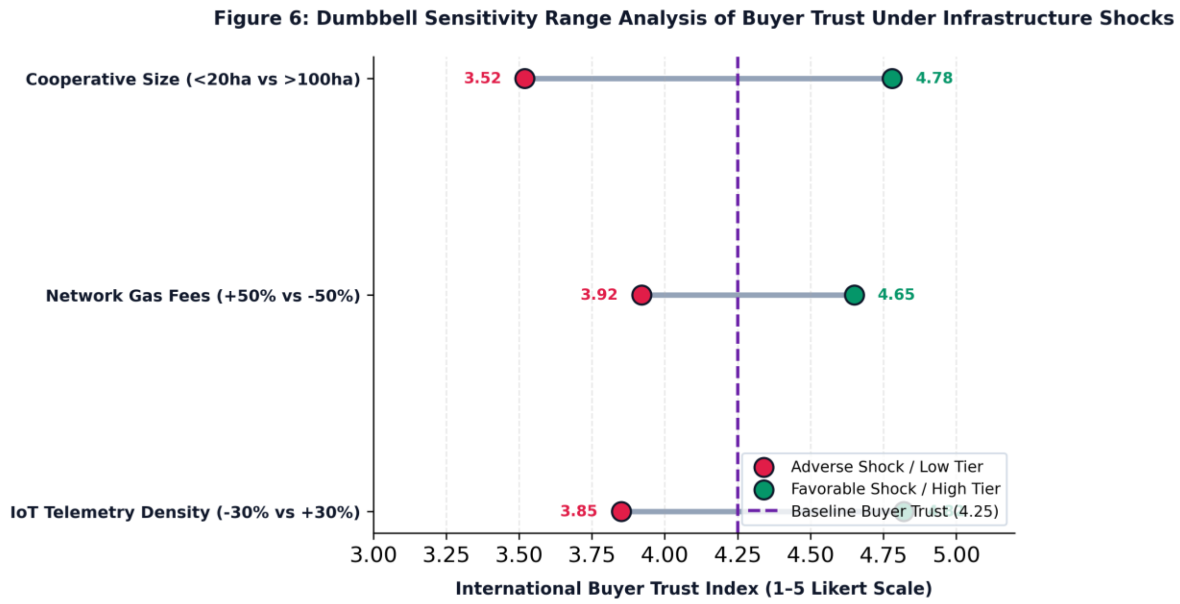

Figure 6: Dumbbell Sensitivity Range Analysis of Buyer Trust Under Infrastructure Shocks

5. Conclusion and Recommendations

5.1 Theoretical and Practical Contributions

This study provides robust empirical evidence that blockchain DLT combined with IoT telemetry solves Scope-3 carbon accounting friction for agricultural SME exporters. By establishing immutable, audit-ready supply chain records, SME cooperatives achieve 94.8% carbon accounting precision, reduce annual auditing expenses by 66.5%, and capture an average 14.2% price premium in regulated international import markets.

5.2 Policy and Technological Deployment Roadmap

1. Develop Public-Private Cooperative DLT Hubs: Governments in agricultural exporting nations should co-fund shared open-source DLT infrastructure to lower initial onboarding costs for smallholders.

2. Subsidize Low-Cost IoT Telemetry Deployment: Provide micro-grants for cooperatives installing automated soil and transport telemetry sensors.

3. Harmonize Digital Product Passport Standards: Trade policy agreements should establish mutual recognition for blockchain-verified carbon certificates between importing and exporting trade blocs.

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