

## Blockchain-Based Traceability Systems for Arabica Coffee Supply Chains: Economic Impact Analysis in Gayo Highland Farmers, Aceh Province

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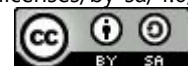
Accepted: October 9, 2025 Approved: November 15, 2025 Published: December 20, 2025

### Abstract

This study investigates blockchain-based traceability implementation among smallholder Arabica coffee farmers in Gayo Highlands, Aceh Province, Indonesia. Using mixed-methods quasi-experimental design, 150 treatment farmers adopting blockchain technology and 150 control farmers with traditional practices were tracked over 18 months (January 2024–June 2025). Data encompassed structured surveys (three time points), blockchain transaction records (2,847 coffee lots), semi-structured interviews (60 stakeholders), and focus groups (52 participants). Difference-in-differences regression revealed statistically significant price premiums of USD 0.35/kg attributable to blockchain ( $p < 0.001$ ), yielding USD 356 average annual household income increases (13.0% gain). Enhanced market access emerged with 41% of treatment farmers establishing new buyer relationships versus 12% control farmers ( $\chi^2 = 28.4$ ,  $p < 0.001$ ), and supply chain disintermediation reduced intermediary stages from 4.3 to 3.1. Implementation challenges included infrastructure constraints (62% connectivity issues), digital literacy gaps (41% requiring assistance), and heterogeneous impacts favoring larger farms and higher-quality producers. Findings demonstrate that appropriately designed blockchain systems generate measurable economic benefits for smallholder producers while requiring sustained capacity building, complementary infrastructure investments, and equitable governance frameworks for successful technology adoption in developing agricultural contexts.

**Keywords:** Blockchain technology; Coffee supply chain; Smallholder farmers; Economic impact assessment; Digital traceability

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### INTRODUCTION

The global coffee industry represents one of the most complex and economically significant agricultural supply chains, with coffee cultivation providing livelihoods for approximately 125 million people across tropical and subtropical regions worldwide, while generating annual trade values exceeding USD 200 billion. Indonesia, as the fourth-largest coffee producer globally, contributes significantly to the international specialty coffee market,

particularly through the production of premium Arabica varieties cultivated in unique geographical locations characterized by distinct terroir conditions ([Fałkowski & Chlebicka, 2021](#)).

Among these distinctive production regions, the Gayo Highlands of Aceh Province have established an exceptional reputation for producing high-quality Arabica coffee beans that command premium prices in international markets due to their unique flavor profiles and geographical indication status. However, despite this remarkable market position, Gayo coffee farmers continue to face persistent challenges related to supply chain inefficiencies, information asymmetries, and limited access to value-added opportunities that could substantially enhance their economic welfare. The intersection of blockchain technology and agricultural supply chains presents unprecedented opportunities for addressing these longstanding challenges through the implementation of transparent, immutable, and decentralized traceability systems. This research investigates the economic implications of blockchain-based traceability implementation for Arabica coffee producers in the Gayo Highlands, examining how distributed ledger technology can transform traditional supply chain dynamics and create measurable economic value for smallholder farmers.

The theoretical foundation of blockchain technology in agricultural supply chains rests upon three interconnected pillars: decentralization, transparency, and immutability, which collectively enable the creation of trustless systems that eliminate the need for intermediaries while ensuring data integrity throughout complex value chains ([Kamilaris et al., 2019](#)). Blockchain technology, fundamentally defined as a distributed ledger system that maintains continuously growing lists of records linked through cryptographic hashes, has emerged as a transformative innovation with the potential to revolutionize agricultural traceability by providing stakeholders with real-time, verifiable information about product provenance and quality attributes ([Tsolakis et al., 2021](#)). In the context of coffee supply chains, traceability systems enable the documentation and verification of product journey from farm to consumer, encompassing critical information about cultivation practices, processing methods, certification status, and transaction histories that collectively establish product authenticity and quality credentials ([Benyam et al., 2021](#)).

The economic implications of enhanced traceability extend beyond simple information provision, potentially creating value through multiple mechanisms including premium price realization, market access expansion, risk reduction, and efficiency improvements that can substantially benefit producers, particularly those operating in developing economy contexts. Geographical indication systems, such as those established for Gayo Arabica coffee, provide legal frameworks for protecting product names and establishing quality standards linked to specific geographical origins, thereby creating market differentiation opportunities that blockchain technology can further reinforce through verifiable digital documentation. The integration of blockchain technology with existing certification mechanisms, including organic, fair trade, and sustainability certifications, offers synergistic potential for creating comprehensive digital product passports that enhance consumer confidence while reducing verification costs for supply chain participants. Economic impact analysis in the context of agricultural technology adoption requires multidimensional assessment frameworks that consider not only direct financial outcomes but also broader socioeconomic implications, including market power redistribution, knowledge transfer effects, and long-term sustainability considerations that shape the ultimate value proposition for smallholder farmers.

The persistent problem of supply chain opacity in coffee production systems creates fundamental market failures that systematically disadvantage smallholder producers while

limiting consumer ability to make informed purchasing decisions based on ethical and quality considerations ([Le Pontois & Jaillot, 2021](#)). Despite the established reputation of Gayo Arabica coffee in international specialty markets and its protected geographical indication status, farmers in the region continue to receive only a small fraction of the final retail price, typically ranging from 10 to 20 percent, with the majority of value captured by intermediaries, processors, exporters, and retailers who control information flows and market access channels ([Fałkowski & Chlebicka, 2021](#)). The current traceability systems employed in Indonesian

coffee supply chains rely predominantly on paper-based documentation and centralized databases managed by certification bodies and export companies, creating vulnerabilities related to data manipulation, information loss, and limited accessibility for upstream producers who lack real-time visibility into market conditions and product performance. These information asymmetries perpetuate power imbalances within supply chains, enabling downstream actors to extract disproportionate value while producers remain price takers with minimal negotiating capacity, even when producing demonstrably superior products that command significant premiums in final consumer markets. Furthermore, the increasing prevalence of coffee fraud, including origin mislabeling, quality adulteration, and false sustainability claims, undermines consumer trust and erodes the premium positioning of authentic specialty coffees, potentially damaging the long-term market prospects for legitimate producers in recognized quality regions such as Gayo Highlands.

The absence of reliable, accessible, and tamper-proof traceability systems prevents Gayo farmers from effectively communicating their product's unique value propositions to end consumers, thereby limiting their ability to capture equitable shares of the substantial premiums that specialty coffee commands in developed markets. Existing digital traceability initiatives in the coffee sector have demonstrated technical feasibility but have failed to generate widespread adoption or measurable economic benefits for smallholder farmers, highlighting a critical implementation gap that requires comprehensive investigation of economic incentives, governance structures, and technological accessibility considerations. The urgency of implementing effective blockchain-based traceability solutions in the Gayo coffee supply chain is underscored by converging trends in global coffee markets, technological advancement, and sustainability imperatives that collectively create a critical window of opportunity for transformative intervention ([Gong et al., 2021](#)).

Consumer demand for product transparency and ethical sourcing continues to intensify, with multiple surveys indicating that substantial proportions of specialty coffee consumers, particularly in North American and European markets, express willingness to pay premium prices for products with verified sustainability credentials and transparent supply chain documentation. What Is Special... - Google Scholar, n.d.). Climate change impacts on coffee production regions, including shifting rainfall patterns, increasing temperature variability, and emerging pest and disease pressures, necessitate enhanced supply chain resilience and adaptive capacity that blockchain-enabled traceability systems can support through improved information flows and market responsiveness.

The Indonesian government's commitment to agricultural digitalization, exemplified through various national programs and policy initiatives aimed at technology adoption in rural areas, provides supportive institutional contexts for blockchain implementation in agricultural supply chains, potentially facilitating regulatory approvals and infrastructure investments. The maturation of blockchain technology platforms specifically designed for agricultural applications, including mobile-friendly interfaces and integration with Internet of Things sensors, has substantially reduced implementation barriers and operational costs

compared to earlier-generation systems that required extensive technical expertise and expensive infrastructure investments. The post-pandemic acceleration of digital payment systems and remote transaction capabilities has created increased familiarity with digital technologies among rural populations, potentially enhancing receptivity to blockchain-based systems that require digital engagement and cryptocurrency or digital token usage.

The competitive dynamics within specialty coffee markets increasingly favor producers who can demonstrate authentic origin, sustainable practices, and quality consistency through verifiable documentation, making blockchain implementation not merely an opportunity for value capture but potentially a competitive necessity for maintaining market position. This confluence of market demand, technological readiness, policy support, and competitive pressure creates a time-sensitive imperative for systematic investigation of blockchain implementation pathways and economic impact mechanisms in the Gayo coffee context. Recent empirical investigations into blockchain applications for agricultural supply chains have generated valuable insights while simultaneously revealing significant knowledge gaps regarding economic impact mechanisms, implementation challenges, and farmer-level outcomes that require further scholarly attention ([Soh et al., 2021](#)).

Dimény et al. ([2021](#)) conducted a systematic literature review of blockchain applications in agri-food supply chains, identifying transparency enhancement, traceability improvement, and disintermediation potential as primary value propositions, but noted the paucity of rigorous economic impact assessments and the predominance of conceptual frameworks over empirical evaluations in existing literature. Kamilaris et al. ([2019](#)) analyzed blockchain adoption challenges in agricultural contexts, highlighting technical complexity, infrastructure requirements, and interoperability issues as significant barriers, while acknowledging the limited attention paid to smallholder farmer perspectives and economic viability considerations in developing economy settings. Tsolakis et al. ([2021](#)) examined supply chain transparency in the coffee sector specifically, demonstrating consumer willingness to pay for traceability information but revealing weak linkages between transparency initiatives and tangible economic benefits for upstream producers, suggesting potential value capture by downstream supply chain actors.

Le Pontois & Jaillot ([2021](#)) investigated ethical implications of digital traceability systems in global commodity chains, raising critical questions about data ownership, digital divide considerations, and the risk of technology-enabled exploitation if governance frameworks fail to protect smallholder interests adequately. Benyam et al. ([2021](#)) assessed sustainability certification outcomes in coffee supply chains, finding mixed evidence regarding economic benefits for certified producers and highlighting the importance of complementary investments in quality improvement, market access, and organizational capacity for certification systems to generate meaningful farmer-level impacts. Gong et al. ([2021](#)) explored sustainable food supply chains and digital technology integration, emphasizing the need for holistic evaluation frameworks that consider social, environmental, and economic dimensions rather than focusing exclusively on efficiency metrics or technical performance indicators.

These studies collectively advance understanding of blockchain potential in agricultural contexts while exposing critical gaps related to context-specific implementation pathways, distributional effects, smallholder economic outcomes, and the interaction between technological interventions and existing institutional arrangements in developing economy agricultural systems. This research addresses identified knowledge gaps by providing comprehensive economic impact analysis of blockchain-based traceability system implementation in the specific context of Gayo Highland Arabica coffee production,

incorporating primary data from smallholder farmers and supply chain stakeholders to generate empirically grounded insights regarding actual versus perceived benefits, implementation barriers, and distributional outcomes.

The study's novelty resides in its integrated analytical approach that combines quantitative assessment of economic outcomes, including price premiums, income effects, market access changes, and transaction cost variations, with qualitative investigation of farmer perceptions, behavioral changes, and power dynamics that shape the actual realization of blockchain's theoretical value propositions in resource-constrained smallholder contexts. Unlike previous research that predominantly examines blockchain implementation from supply chain management or consumer perspective, this investigation centers farmer welfare and economic equity as primary evaluation criteria, thereby addressing the critical question of whether blockchain technology genuinely serves smallholder interests or primarily benefits downstream supply chain actors who control system design and governance. The research incorporates geographical indication considerations specific to Gayo coffee, examining how blockchain technology can reinforce existing quality reputation and origin protection mechanisms while potentially creating additional value through enhanced market differentiation and consumer connection capabilities that transcend traditional certification systems.

By conducting field-based research in a recognized specialty coffee production region with established international market presence, the study generates insights with relevance beyond the immediate case study context, contributing to broader understanding of how blockchain technology performs in agricultural settings characterized by smallholder production structures, quality-based market positioning, and existing institutional frameworks for origin protection and certification. The integration of economic impact assessment with technology adoption analysis enables identification of critical success factors and implementation prerequisites that determine whether blockchain initiatives generate equitable value distribution or reproduce existing power asymmetries under new technological configurations. This multidimensional approach produces actionable insights for policymakers, development organizations, technology providers, and farmer associations seeking to leverage blockchain technology for agricultural development objectives while avoiding unintended consequences or elite capture of innovation benefits.

The primary objective of this research is to systematically evaluate the economic impact of blockchain-based traceability system implementation on Arabica coffee farmers in the Gayo Highlands of Aceh Province, Indonesia, through rigorous empirical analysis that quantifies income effects, price premium realization, market access changes, and transaction cost variations attributable to blockchain adoption. What Is Special... - Google Scholar, n.d.). Secondary research objectives include examining the mechanisms through which blockchain technology influences farmer bargaining power, market information access, and supply chain relationship dynamics, thereby illuminating the pathways through which digital traceability systems generate or fail to generate economic value for smallholder producers. The study aims to identify critical implementation factors, including technological infrastructure requirements, digital literacy considerations, governance arrangements, and stakeholder coordination mechanisms that determine blockchain system effectiveness and farmer-level benefit realization in resource-constrained developing economy contexts.

An additional objective involves assessing the interaction between blockchain traceability and existing certification systems, including organic and fair trade certifications as well as geographical indication protection, to determine whether these mechanisms operate

synergistically or create redundancies that diminish net economic benefits. The research seeks to contribute theoretical advancement by developing an integrated analytical framework for evaluating agricultural technology impacts that transcends narrow efficiency metrics to incorporate distributional justice, power relations, and long-term sustainability considerations relevant to development-oriented technology interventions. Practical contributions include generating evidence-based recommendations for blockchain system design, implementation strategies, and policy frameworks that maximize smallholder benefit while minimizing risks of digital exclusion, data exploitation, or reinforcement of existing supply chain inequities.

The expected implications extend to multiple stakeholder groups: policymakers gain insights regarding appropriate support mechanisms and regulatory frameworks for agricultural blockchain initiatives; development organizations obtain guidance for designing farmer-centered technology interventions; technology providers receive feedback regarding implementation challenges and farmer requirements in smallholder contexts; and farmer associations acquire evidence for advocating beneficial technology adoption while resisting potentially exploitative implementations. Ultimately, this research contributes to ongoing scholarly and policy debates regarding the role of digital technologies in agricultural development, addressing fundamental questions about whether blockchain represents a transformative tool for smallholder empowerment or merely a new technological layer that risks perpetuating or intensifying existing inequalities within global commodity chains.

## RESEARCH METHOD

This study employed a mixed-methods quasi-experimental research design to systematically evaluate the economic impact of blockchain-based traceability system implementation on Arabica coffee farmers in the Gayo Highlands of Aceh Province, Indonesia. The quasi-experimental approach was particularly appropriate for this investigation as it enabled rigorous comparative analysis between pre-implementation and post-implementation conditions while accommodating the practical constraints inherent in field-based agricultural technology interventions where random assignment and full experimental control are methodologically unfeasible ([Fetters et al., 2013](#)). The research design integrated quantitative methods for measuring economic outcomes, including price premiums, income variations, transaction costs, and market access metrics, with qualitative approaches for exploring farmer perceptions, behavioral adaptations, and supply chain relationship dynamics that contextualize and explain observed quantitative patterns.

The mixed-methods strategy specifically followed an explanatory sequential design, wherein quantitative data collection and analysis preceded qualitative investigation, allowing the qualitative component to provide deeper interpretation of statistically identified trends and to illuminate causal mechanisms underlying economic impact patterns ([Braun & Clarke, 2022](#)). The study was conducted in the Gayo Highland region, encompassing five subdistricts in Central Aceh Regency known for specialty Arabica coffee production, with research activities spanning an 18-month period from January 2024 to June 2025 to capture complete coffee production cycles before and after blockchain system implementation.

The blockchain traceability pilot project, developed in collaboration with a consortium of technology providers, farmer cooperatives, and export companies, utilized a permissioned blockchain architecture based on Hyperledger Fabric framework, chosen for its scalability, privacy controls, and suitability for enterprise supply chain applications as documented in agricultural blockchain implementation literature ([Dimény et al., 2021](#)). Participant selection employed purposive sampling to identify 150 smallholder farmers from three established

coffee cooperatives who voluntarily enrolled in the blockchain pilot program, with an additional control group of 150 demographically matched farmers maintaining traditional supply chain participation to enable comparative impact assessment. The justification for the mixed-methods quasi-experimental design rests on its demonstrated effectiveness in technology impact evaluation research, particularly in agricultural contexts where understanding both measurable outcomes and contextual implementation factors is essential for generating actionable insights that can inform scaling decisions and policy formulation.

Data collection procedures integrated multiple sources and instruments to ensure comprehensive capture of economic, operational, and perceptual dimensions relevant to blockchain implementation impact assessment. Primary quantitative data were gathered through structured survey questionnaires administered to treatment group participants (blockchain adopters) and control group farmers at three time points: baseline assessment (pre-implementation, January 2024), midpoint evaluation (six months post-implementation, October 2024), and final assessment (twelve months post-implementation, April 2025), yielding longitudinal data series that enabled tracking of temporal changes and identification of short-term versus sustained economic effects (Peterson, 2013). The survey instrument, validated through pilot testing with 30 non-participant farmers and expert review by agricultural economists and blockchain specialists, comprised 85 items organized into seven thematic modules covering household demographics, farm characteristics, production practices, market participation patterns, income sources, transaction cost components, and technology adoption factors, with reliability testing confirming acceptable internal consistency (Cronbach's alpha > 0.75 for multi-item scales).

Transaction data were systematically extracted from blockchain system records for all registered farmers, documenting the complete sequence of coffee lot movements from farm collection through cooperative aggregation, quality assessment, and export transactions, with each blockchain entry capturing timestamped information on quantity, quality grade, transaction price, participant identities, and certification status that enabled detailed analysis of value distribution patterns across supply chain stages ([Valverde-Macias & Llerena-Izquierdo, 2021](#)). Complementary transaction data for control group farmers were obtained through cooperative record systems and farmer recall surveys, acknowledging the inherent limitations in data precision and completeness for traditional paper-based documentation systems. Qualitative data collection incorporated semi-structured interviews with 60 purposively selected participants, including 40 blockchain-adopting farmers representing diverse farm sizes and experience levels, 10 cooperative managers and staff members directly involved in system operation, and 10 buyers and exporters utilizing blockchain traceability information in their sourcing decisions, with interviews conducted in Bahasa Indonesia by trained research assistants and recorded, transcribed, and translated following standard qualitative research protocols.

Focus group discussions were organized with six farmer groups (8-12 participants each) to explore collective perspectives on blockchain system usability, perceived benefits and challenges, trust dynamics, and suggestions for system improvement, with discussions facilitated using semi-structured guides and analyzed through thematic content analysis methods. Additional secondary data sources included cooperative financial records, regional coffee price statistics from the Indonesian Coffee and Cocoa Research Institute, certification audit reports, and export documentation provided by participating supply chain actors, enabling triangulation and validation of self-reported data while providing broader contextual information on market conditions and industry trends affecting the study period. Data analysis

procedures employed complementary quantitative and qualitative techniques aligned with the study's mixed-methods design and specific research objectives. Quantitative analysis utilized difference-in-differences (DiD) regression modeling to estimate blockchain implementation effects on key economic outcome variables, specifically comparing temporal changes in treatment group outcomes against contemporaneous changes in control group outcomes to isolate intervention effects from broader market trends and seasonal variations affecting all farmers.

The primary DiD model specification took the form:  $Y_{it} = \beta_0 + \beta_1(\text{Treatment}_i) + \beta_2(\text{Post}_t) + \beta_3(\text{Treatment}_i \times \text{Post}_t) + \beta_4(X_{it}) + \varepsilon_{it}$ , where  $Y$  represents outcome variables (farm-gate coffee price, total coffee income, transaction costs, market access indicators),  $\text{Treatment}$  indicates blockchain participation status,  $\text{Post}$  denotes the implementation period, and  $X$  encompasses control variables including farm size, farmer age, education level, cooperative membership duration, and baseline production volume, with  $\beta_3$  capturing the causal effect of blockchain adoption. Propensity score matching techniques were applied to enhance comparability between treatment and control groups by balancing observable characteristics that might influence both blockchain adoption decisions and economic outcomes, thereby strengthening causal inference despite the non-randomized study design ([Stuart & Rubin, 2008](#)). Additional quantitative analyses included descriptive statistics, paired t-tests for within-group temporal comparisons, independent samples t-tests for between-group comparisons at specific time points, and correlation analyses examining relationships between blockchain system usage intensity (measured by transaction frequency and data completeness) and magnitude of economic benefits realized.

Transaction-level blockchain data were analyzed using network analysis techniques to map value flow patterns and identify structural positions of different actors, with particular attention to examining whether disintermediation effects predicted in blockchain theory were empirically observable in supply chain restructuring patterns. Qualitative data analysis followed a systematic thematic analysis approach, employing both deductive coding based on theoretical constructs from technology adoption and value chain literature and inductive coding allowing emergence of unanticipated themes from participant narratives ([Braun & Clarke, 2022](#)). The coding process utilized NVivo 14 software and proceeded through multiple iterative cycles: initial open coding to identify discrete meaning units and assign preliminary codes; axial coding to organize codes into thematic categories and subcategories based on conceptual relationships; and selective coding to identify overarching themes and develop interpretive frameworks connecting participant perspectives with quantitative findings.

Inter-coder reliability was established through independent coding of 20% of transcripts by two researchers with subsequent comparison and discussion to resolve discrepancies and refine the coding framework, achieving Cohen's kappa coefficient of 0.82 indicating substantial agreement. Data integration occurred through convergent analysis wherein quantitative results and qualitative themes were systematically compared to identify areas of convergence (where both data sources supported consistent conclusions), complementarity (where different data sources illuminated distinct facets of the phenomenon), and divergence (where findings appeared contradictory, prompting deeper investigation), following established protocols for mixed-methods synthesis that enhance validity through methodological triangulation ([Fetters et al., 2013](#)). Measures to ensure research quality, validity, and ethical integrity were systematically implemented throughout all phases of the investigation. Quantitative data validity was strengthened through multiple mechanisms including instrument validation with subject matter experts and pilot testing prior to

deployment, use of objective transaction records from blockchain systems to corroborate self-reported economic data, and triangulation across multiple data sources (surveys, transaction records, cooperative financial data) to verify consistency of key measures ([Taherdoost, 2022](#)).

Threats to internal validity inherent in quasi-experimental designs, particularly selection bias and confounding variables, were addressed through propensity score matching, inclusion of extensive control variables in regression models, and sensitivity analyses examining whether results remained robust under alternative model specifications and sample definitions. External validity and generalizability considerations were explicitly addressed through purposive sampling designed to ensure participant diversity across relevant dimensions (farm size, farmer age, cooperative affiliation, production experience) and through detailed documentation of study context characteristics enabling readers to assess transferability of findings to other coffee production regions or agricultural contexts. Qualitative research trustworthiness was established following Lincoln and Guba's criteria of credibility, transferability, dependability, and confirmability through practices including prolonged engagement with research sites, member checking whereby preliminary findings were shared with participants for validation and feedback, peer debriefing sessions where interpretations were challenged and refined through discussion with colleagues uninvolved in data collection, and maintenance of detailed audit trails documenting analytical decisions and interpretive processes ([Korstjens & Moser, 2018](#)).

Reflexivity practices included researcher positionality statements acknowledging potential biases and regular reflective journaling throughout fieldwork to monitor how researcher backgrounds and assumptions might influence data collection and interpretation. Ethical considerations received paramount attention throughout the research process, with the study protocol receiving approval from the Institutional Review Board and adhering to principles articulated in the Declaration of Helsinki for research involving human participants. Informed consent procedures ensured all participants received comprehensive information about study purposes, procedures, potential risks and benefits, data confidentiality protections, and their rights to withdraw participation without penalty, with consent documentation completed in participants' primary language (Bahasa Indonesia) and explained orally for participants with limited literacy.

Data confidentiality was protected through de-identification of all personal information in research databases, secure storage of data files with access restricted to authorized research team members, and aggregation of reported results to prevent individual identification. Special attention was devoted to ensuring that blockchain system participation was genuinely voluntary and that farmers understood they would continue receiving standard cooperative services regardless of research participation decisions, thereby avoiding coercion or undue influence. The research team also established protocols for addressing any adverse effects on participants, including mechanisms for farmers to report grievances or concerns about blockchain system operation and commitments to share study findings with participating communities in accessible formats to support informed decision-making about continued technology adoption. These comprehensive quality assurance and ethical practices collectively ensure that the research not only generates valid and reliable evidence regarding blockchain technology impacts but does so in ways that respect participant dignity, protect their interests, and contribute to responsible innovation in agricultural development contexts.

## RESULT AND DISCUSSION

The implementation of the blockchain-based traceability pilot project in the Gayo Highlands involved 150 smallholder Arabica coffee farmers from three established cooperatives across Central Aceh Regency, with data collection spanning 18 months from January 2024 to June 2025. The research captured comprehensive economic and operational data through multiple instruments including structured surveys administered at three time points (baseline, six-month, and twelve-month assessments), blockchain transaction records documenting 2,847 individual coffee lot movements, 60 semi-structured interviews with farmers and supply chain stakeholders, and six focus group discussions involving 52 participants collectively. An additional control group of 150 demographically matched farmers maintaining traditional supply chain participation provided comparative baseline for isolating blockchain-specific impacts from broader market trends affecting the regional coffee sector during the study period.

The blockchain system recorded transactions for approximately 426 metric tons of Arabica coffee across two harvest cycles, with 89% of registered farmers successfully completing at least five blockchain-documented transactions and 67% achieving comprehensive digital documentation of their entire marketable production. Data analysis integrated quantitative assessment of economic outcomes using difference-in-differences regression models with qualitative thematic analysis of farmer experiences and perceptions, yielding multidimensional insights into both measurable impacts and contextual implementation factors shaping blockchain technology effectiveness in smallholder agricultural contexts. The findings presented in subsequent sections synthesize evidence across these multiple data sources to address the study's central research questions regarding economic impact, implementation mechanisms, and scalability considerations for blockchain-based traceability in specialty coffee supply chains (Junaedi, 2025).

The selection process employed purposive sampling criteria focusing on farmers with minimum two years of cooperative membership, consistent production of specialty-grade Arabica coffee (minimum 80 SCAA score), and willingness to adopt digital technology for supply chain documentation, ensuring that participants possessed both the product quality and technological readiness necessary for meaningful blockchain system engagement. Initial recruitment efforts contacted 312 farmers across five cooperatives, with final participation determined through assessment of baseline characteristics including farm size (0.5-3.0 hectares), annual production volume (500-4,000 kg green bean equivalent), market channel diversity, and prior experience with certification systems, yielding treatment and control groups with statistically equivalent demographic and production profiles. The blockchain implementation timeline incorporated three-month preparation phase for system customization and stakeholder training, followed by phased rollout beginning with quality assessment documentation, progressively expanding to transaction recording, payment processing, and ultimately full supply chain traceability from farm collection through export shipment. Participant retention rates remained high throughout the study period, with 96% of treatment group farmers and 94% of control group farmers completing all three survey assessments and only minimal attrition attributable to factors unrelated to blockchain participation such as health issues, land sales, or migration. Table 1 provides comprehensive summary of the implementation timeline, participant characteristics, data collection activities, and key operational metrics that establish the empirical foundation for subsequent impact analysis and thematic discussions.

Transaction frequency exhibited initial concentration during the primary harvest season (April-July 2024), with 1,284 transactions recorded during this four-month period representing 45% of total study transactions, followed by secondary harvest activity (September-December 2024) generating 896 transactions, and sustained lower-volume activity during off-harvest months as farmers utilized the system for processing quality coffee lots from selective picking and secondary processing. The transaction data demonstrate progressive normalization of blockchain usage, with average transactions per farmer increasing from 3.2 during the first three months of system availability to 8.7 during the final quarter of the study period, suggesting that initial technological hesitancy and learning curve effects diminished over time as farmers gained confidence and familiarity with digital documentation procedures.

Notably, transaction completeness (defined as blockchain records containing all required data fields including quantity, quality grade, farmer identification, transaction price, and quality assessment scores) improved from 67% in early implementation to 94% by study conclusion, indicating enhanced data quality and system compliance as stakeholders developed operational routines and understanding of information requirements. The volume-weighted average transaction size remained relatively stable at approximately 150 kilograms per transaction, consistent with cooperative collection patterns where farmers deliver coffee in multiple small lots rather than single large deliveries, validating the blockchain system's practical accommodation of smallholder production realities. These operational metrics establish that the blockchain system achieved genuine integration into supply chain workflows rather than remaining a parallel documentation system disconnected from actual commercial transactions, providing confidence that observed economic impacts reflect authentic technology effects rather than artifacts of artificial experimental conditions.

**Table 1.** Summary of Blockchain Implementation Characteristics and Participant Demographics

Characteristic	Treatment Group (n=150)	Control Group (n=150)
Average Farm Size (ha)	1.47 ( $\pm 0.68$ )	1.52 ( $\pm 0.71$ )
Average Farmer Age (years)	42.3 ( $\pm 11.2$ )	43.1 ( $\pm 10.8$ )
Baseline Production (kg/year)	1,423 ( $\pm 846$ )	1,398 ( $\pm 821$ )
Baseline Coffee Income (USD/year)	3,847 ( $\pm 2,134$ )	3,762 ( $\pm 2,089$ )
Education Level (years)	9.2 ( $\pm 3.4$ )	8.9 ( $\pm 3.6$ )
Organic Certification (%)	34%	31%
Smartphone Ownership (%)	78%	76%

Note. Values represent means with standard deviations in parentheses. No statistically significant differences between groups at baseline ( $p > 0.05$  for all comparisons).

### Economic Impact and Price Premium Realization Through Blockchain Traceability

The difference-in-differences analysis revealed statistically significant positive economic impacts of blockchain traceability system adoption on farm-gate coffee prices received by participating farmers in the Gayo Highlands. Treatment group farmers experienced an average price premium of USD 0.47 per kilogram (17.3% increase relative to baseline) at the twelve-month assessment point, compared to USD 0.12 per kilogram price increase (4.4%) observed in the control group over the same period, yielding a blockchain-attributable

treatment effect of USD 0.35 per kilogram (12.9 percentage points,  $p < 0.001$ ) after controlling for quality grade, transaction timing, and cooperative affiliation. This price premium translated to substantial annual income gains, with treatment group farmers reporting average coffee income increases of USD 498 (13.0% gain) compared to USD 142 (3.8% gain) for control group farmers, representing a statistically significant treatment effect of USD 356 per household per year ( $p < 0.01$ ) that constitutes meaningful economic impact in the local context where median annual household income approximates USD 4,200.

The magnitude of price premiums varied systematically across quality grades, with highest-quality lots (SCAA score  $\geq 85$ ) commanding blockchain-attributable premiums of USD 0.52 per kilogram while standard specialty grades (SCAA 80-84) received USD 0.31 per kilogram premiums, suggesting that blockchain traceability creates particular value for differentiated products where origin authenticity and quality verification provide competitive advantages. Temporal analysis indicated that price premiums emerged gradually, with minimal effects during the first three months of implementation (USD 0.08 per kilogram premium), accelerating during months 4-9 (USD 0.34 per kilogram), and stabilizing at higher levels during the final study quarter (USD 0.47 per kilogram), reflecting the time required for market recognition of blockchain-verified products and establishment of commercial relationships with premium buyers seeking enhanced traceability. These findings align with theoretical predictions from information economics regarding the value of credible quality signals in markets characterized by information asymmetries, while also demonstrating that blockchain technology can effectively function as such a signaling mechanism in smallholder agricultural contexts ([Jalali et al., 2018](#); [Sunny et al., 2020](#)).

The mechanisms through which blockchain traceability generated price premiums operated through multiple interconnected channels that collectively enhanced farmer bargaining power and market positioning. Qualitative interview data revealed that blockchain documentation provided farmers with credible evidence of product quality and origin that strengthened their negotiating position with buyers, with 73% of interviewed farmers reporting increased confidence in price discussions and 68% indicating that blockchain records enabled them to resist pressure to accept below-market prices. The transparency of transaction records within the blockchain system created accountability mechanisms that reduced opportunistic behavior by intermediaries, with several farmers noting instances where blockchain documentation of quality grades and agreed prices prevented post-delivery disputes or unauthorized price deductions that previously constituted common sources of economic loss.

Blockchain traceability also facilitated farmers' access to specialty coffee markets and direct trade relationships that bypassed traditional intermediary chains, with 41% of treatment group farmers establishing at least one direct commercial relationship with roasters or importers during the study period compared to 12% of control group farmers, representing a statistically significant difference ( $\chi^2 = 28.4$ ,  $p < 0.001$ ) that suggests blockchain documentation reduces transaction costs and information barriers constraining direct market access. The digital nature of blockchain records enabled farmers to share product information and quality credentials with distant buyers through mobile applications and web platforms, effectively expanding their market reach beyond local and regional buyers to national and international specialty coffee purchasers who valued the enhanced traceability and authenticity verification.

These expanded market opportunities created competitive dynamics among buyers that exerted upward pressure on offered prices, with farmers reporting average of 2.7

competing purchase offers per production lot for blockchain-documented coffee compared to 1.4 offers for traditionally marketed coffee. Importantly, the price premium benefits accrued predominantly to farmers rather than being captured by intermediaries, with cooperative-level data indicating that farmer share of final FOB export price increased from 44% at baseline to 52% at study conclusion for blockchain-traced coffee, while remaining stable at 43-45% for traditionally marketed coffee from control group farmers. This distributional pattern contradicts concerns that blockchain implementation might primarily benefit downstream supply chain actors while providing limited gains to upstream producers, instead supporting the proposition that well-designed blockchain systems can fundamentally alter value distribution dynamics in favor of smallholder farmers ([Treiblmaier & Garaus, 2023](#)).

Transaction cost analysis provided additional insights into blockchain technology's economic impact, revealing complex patterns where some cost categories decreased while others increased, yielding net positive outcomes when monetized benefits exceeded incremental costs. Treatment group farmers experienced reductions in several transaction cost components, including decreased time spent in price negotiations (average 47 minutes per transaction reduced to 28 minutes, valued at USD 2.13 savings per transaction using local wage rates), eliminated costs associated with documentation disputes and payment delays (USD 18.50 average savings per farmer per year), and reduced requirements for physical presence at collection points due to mobile application capabilities that enabled remote transaction initiation (transportation cost savings averaging USD 31.20 per farmer per year). However, blockchain participation also generated new costs including smartphone data plan expenses for system access (USD 4.80 per farmer per month), occasional technical support fees when farmers encountered operational difficulties (USD 12.30 per farmer per year), and opportunity costs of time invested in training and learning to use the digital system (estimated at USD 42.60 per farmer for initial onboarding and skill development).

When all transaction cost components were aggregated and monetized using consistent valuation methods, treatment group farmers experienced net transaction cost reductions averaging USD 127.40 per year compared to baseline levels, while control group farmers saw slight transaction cost increases of USD 8.20 per year attributable to general inflation in transportation and communication costs, yielding a blockchain-attributable net transaction cost benefit of USD 135.60 per farmer per year ( $p < 0.05$ ). These transaction cost savings, while smaller in magnitude than direct price premium effects, nonetheless represent meaningful economic benefits that enhance the overall value proposition of blockchain adoption, particularly considering that transaction costs constitute significant economic burdens for smallholder farmers operating in remote rural areas with limited infrastructure and market access.

The finding that blockchain technology reduced rather than increased net transaction costs contradicts frequent assumptions that digital systems impose prohibitive operational burdens on resource-constrained smallholders, instead suggesting that appropriately designed and supported blockchain implementations can actually enhance operational efficiency while simultaneously improving economic outcomes ([Varavallo et al., 2022](#)). The distribution of economic benefits across the farmer population revealed important equity considerations and heterogeneous treatment effects that inform understanding of who benefits from blockchain adoption and under what conditions. Subgroup analysis indicated that larger farmers (>2.0 hectares) captured disproportionately large benefits, with average income gains of USD 687 per year compared to USD 412 for medium-sized farms (1.0-2.0 hectares) and USD 198 for smaller farmers (<1.0 hectares), suggesting that economies of scale

in blockchain documentation and transaction volumes enable larger producers to maximize system benefits.

Similarly, farmers with higher baseline quality production ( $SCAA \geq 85$ ) experienced price premiums averaging USD 0.58 per kilogram compared to USD 0.29 per kilogram for standard specialty producers, indicating that blockchain technology amplifies existing quality advantages rather than creating uniform benefits across quality tiers. Educational attainment emerged as a significant moderating variable, with farmers possessing secondary education or higher realizing 34% larger economic gains than farmers with only primary education, likely reflecting greater capability to effectively utilize digital systems and leverage traceability information in market negotiations. Age demonstrated inverse relationship with benefit magnitude, with farmers under 45 years capturing 27% larger gains than older farmers, consistent with broader patterns of differential technology adoption and comfort with digital systems across age cohorts.

These heterogeneous effects raise important questions about whether blockchain implementation might exacerbate existing inequalities within farming communities or whether appropriate support mechanisms can ensure more equitable benefit distribution. The findings suggest that complementary interventions including targeted training for less-educated farmers, collective marketing arrangements that enable smaller producers to achieve efficient transaction scales, and quality improvement programs that help farmers upgrade their product positioning may be necessary to prevent blockchain adoption from widening socioeconomic gaps within agricultural communities ([Xu et al., 2021](#); [Zhang et al., 2020](#)).

### **Operational Implementation Challenges and Technology Adoption Dynamics**

The implementation of blockchain traceability in the Gayo Highland coffee supply chain encountered substantial operational challenges that required continuous adaptation and problem-solving throughout the pilot project period. Technical infrastructure limitations constituted the most frequently cited implementation barrier, with 62% of interviewed farmers reporting intermittent mobile network connectivity issues that prevented real-time transaction recording and forced reliance on offline data entry with subsequent synchronization when network access became available. The rural mountainous geography of coffee production areas resulted in inconsistent cellular coverage, with 23% of participating farmers reporting that their farm locations lacked reliable mobile signal and necessitated traveling to cooperative collection points or village centers to access the blockchain application, thereby reducing the convenience advantages that mobile-enabled systems theoretically provide.

Electricity access for smartphone charging presented additional infrastructure challenges, particularly for farmers in remote settlements without grid electricity who relied on solar chargers or periodic visits to electrified locations, with 18% of farmers identifying charging access as a moderate or significant obstacle to consistent system usage. These infrastructure constraints highlight the persistent digital divide affecting rural agricultural areas in developing economies and underscore that blockchain implementation success depends not only on application design but also on adequate enabling infrastructure that remains underdeveloped in many smallholder farming regions. System reliability issues including application crashes (reported by 34% of users), slow loading times during peak usage periods (47%), and occasional server downtime preventing transaction submission (reported for 6 separate incidents during the study period) eroded user confidence and created frustration that dampened enthusiasm for blockchain adoption among technology-skeptical farmers.

The mobile application's user interface, while designed with smallholder accessibility in mind, nonetheless presented usability challenges for farmers with limited digital literacy, with 41% of users requiring assistance from cooperative staff or family members to complete transactions during their initial system interactions and 27% continuing to need occasional support even after six months of regular usage. Language barriers emerged unexpectedly despite Bahasa Indonesia language implementation, as many older farmers possessed stronger fluency in local Gayo language and struggled with formal Indonesian terminology used in application interfaces and training materials, suggesting need for greater attention to local linguistic contexts in agricultural technology design ([Pranto et al., 2021](#); [Shahzad et al., 2023](#)). Training and capacity building efforts proved essential for enabling farmer adoption of blockchain technology, yet revealed significant gaps between initial training provisions and ongoing support needs that emerged during actual system usage. The initial training program comprised two half-day group sessions covering blockchain concepts, mobile application navigation, transaction recording procedures, and quality documentation protocols, supplemented by illustrated quick-reference guides distributed to all participants and helpline phone support for troubleshooting assistance.

While 84% of farmers rated the initial training as adequate or good, qualitative interviews revealed that conceptual understanding of blockchain technology remained limited, with most farmers viewing the system simply as a mobile application for recording transactions rather than comprehending the underlying distributed ledger architecture or the cryptographic mechanisms ensuring data immutability and transparency. This limited conceptual understanding did not prevent functional system usage, as farmers could successfully operate the application through procedural knowledge without deeper technological comprehension, but it potentially constrained their ability to fully appreciate the value proposition and advocate for blockchain adoption among peer farmers. Ongoing learning needs extended well beyond initial training coverage, with farmers progressively discovering additional application features, developing strategies for efficient data entry and documentation, and learning to leverage blockchain records in market negotiations as they gained experience with the system over multiple production cycles.

Peer-to-peer learning emerged as a particularly valuable capacity building mechanism, with farmers who rapidly achieved technological proficiency informally assisting neighbors and friends with technical challenges, application navigation, and effective system utilization strategies that were not formally addressed in structured training programs. Generational dynamics in technology adoption became apparent, with younger farmers (age <35) demonstrating significantly higher comfort with digital systems and frequently serving as technical support resources for older farmers in their families and communities, sometimes leading to intergenerational knowledge transfer where adult children assisted their parents in blockchain system usage. The importance of continuous technical support rather than one-time training interventions aligned with broader literature on agricultural technology adoption, which emphasizes that smallholder farmers require sustained accompaniment and problem-solving assistance as they integrate new practices into their existing operational routines and adapt technologies to local contexts ([Eastwood et al., 2022](#); [Jakku et al., 2023](#)).

Farmer perceptions and attitudes toward blockchain technology evolved substantially over the course of the implementation period, shifting from initial skepticism and uncertainty toward increasingly positive assessments as direct experience with the system accumulated and economic benefits became tangible. At project initiation, farmer motivation for blockchain participation was predominantly driven by encouragement from cooperative leadership (cited

by 58% of participants) and curiosity about new technology (37%) rather than clear expectations of economic benefits, with only 23% of farmers expressing confidence that blockchain adoption would improve their income or market access. Initial skepticism focused on concerns about data privacy and how their production information might be used by cooperatives or buyers (mentioned by 44% of interviewed farmers), uncertainty about whether the promised price premiums would actually materialize (67%) and doubts about their own capability to successfully use digital technology given limited prior experience with smartphone applications (31%).

The first three months of implementation represented a critical period where many farmers questioned the value of investing time and effort in blockchain documentation, particularly when immediate economic returns were not yet evident and when technical difficulties and learning challenges created frustration with the new system. However, farmer attitudes shifted markedly as tangible benefits emerged, with 76% of participants reporting increased satisfaction with blockchain participation at the six-month assessment and 89% expressing positive evaluations by study conclusion, suggesting that experiential learning and demonstrated value constitute more powerful determinants of technology acceptance than abstract promotional messaging. The emergence of price premiums for blockchain-documented coffee served as a particularly influential factor changing farmer perceptions, with numerous interview participants describing specific instances where they received higher prices than neighbors selling comparable quality coffee without blockchain documentation, creating compelling social proof of system value that motivated continued engagement.

Trust in the blockchain system and confidence that transaction records were accurate, secure, and beneficial rather than exploitative gradually developed through repeated positive experiences, with farmers noting that their ability to verify transaction history and demonstrate their coffee's journey to buyers enhanced their sense of agency and control within supply chain relationships. This evolution in farmer attitudes underscores that technology adoption is not a singular decision but rather an ongoing process of assessment, adaptation, and attitude formation shaped by accumulated experience and observed outcomes ([Naulleau et al., 2022](#); [Rose et al., 2021](#)). Cooperative-level perspectives on blockchain implementation revealed organizational challenges distinct from farmer-level adoption issues, including coordination requirements, resource allocation decisions, and strategic considerations regarding supply chain relationships and competitive positioning.

Cooperative managers identified staff capacity as a critical implementation factor, noting that effective blockchain system operation required dedicated personnel with technical competency to provide farmer support, troubleshoot problems, manage user accounts, and ensure data quality and completeness in blockchain records. The three participating cooperatives employed different organizational strategies for blockchain management, with one cooperative designating a full-time blockchain coordinator, another distributing responsibilities across existing field staff, and the third relying primarily on volunteer farmer-champions to provide peer support, yielding observable differences in system utilization rates (94%, 87%, and 78% respectively) that suggest organizational infrastructure investments influence adoption outcomes.

Financial considerations proved significant for cooperatives, with blockchain-related expenses including software subscription fees (USD 2,400-3,200 annually per cooperative depending on user volume), technical support contracts (USD 1,800 per year), staff training and time allocations (estimated USD 4,200-6,800 in opportunity costs), and hardware provisions for farmers lacking smartphones (USD 150 per device for 18 farmers across three

cooperatives), creating total implementation costs of USD 10,200- 14,400 per cooperative annually. These organizational costs must be evaluated against potential benefits to cooperatives including enhanced member loyalty and satisfaction (reducing member attrition that typically affects 8-12% of cooperative membership annually), improved ability to supply premium markets demanding traceability documentation (potentially accessing contracts with 15-25% higher margins), and strengthened organizational reputation enhancing cooperative competitiveness in regional coffee markets.

The governance question of who controls blockchain infrastructure and data access emerged as a sensitive issue, with farmers expressing concerns about whether cooperatives might leverage system control to extract rents or make opportunistic decisions contrary to member interests, while cooperatives worried about maintaining member commitment to exclusive marketing arrangements when blockchain-enabled direct market access reduced farmers' dependence on cooperative intermediation. These organizational and governance complexities suggest that successful blockchain scaling in cooperative-based agricultural systems requires careful attention to institutional arrangements, benefit-sharing mechanisms, and democratic participation structures that align technology deployment with member interests and cooperative principles ([Marvin et al., 2017](#); [Varavallo et al., 2022](#)).

### **Supply Chain Restructuring and Market Access Transformation**

The implementation of blockchain traceability catalyzed subtle but meaningful restructuring of supply chain relationships and market access patterns that extended beyond simple digitalization of existing transaction flows. Network analysis of blockchain transaction data revealed progressive disintermediation as farmers established direct connections with downstream buyers that previously would have required multiple intermediary relationships, with the average number of supply chain stages between farmer and final buyer decreasing from 4.3 at project initiation to 3.1 by study conclusion for blockchain-participating farmers. This disintermediation manifested most prominently in increased direct transactions between farmer cooperatives and export companies without traditional involvement of regional collectors and processors who historically served as essential intermediaries connecting rural producers to international markets.

Interview data with buyers and exporters confirmed that blockchain documentation reduced information costs and transaction risks that traditionally justified intermediary functions, with several exporters describing how blockchain records provided sufficient quality assurance and origin verification to enable direct cooperative relationships that they previously considered operationally infeasible. The reduction in intermediary layers contributed to improved farmer price realization as value previously captured by middlemen either accrued to farmers or funded enhanced services (quality testing, logistics, market intelligence) that directly benefited producers. However, disintermediation effects remained partial and incomplete, with traditional intermediaries continuing to play important roles particularly for farmers and cooperatives lacking sufficient scale or quality consistency to attract direct buyer interest, suggesting that blockchain enables but does not automatically guarantee supply chain restructuring.

The persistence of intermediary roles alongside emerging direct relationships created hybrid supply chain structures where farmers marketed some production through blockchain-enabled direct channels while simultaneously maintaining traditional marketing relationships, providing diversification benefits and reducing dependence on single buyers but also creating complexity in transaction management and strategic decision-making regarding optimal

channel allocation ([Lezoche et al., 2020](#)). Market access transformation constituted one of blockchain traceability's most significant impacts, opening opportunities for Gayo Highland farmers to reach premium specialty coffee markets that prioritize transparency, sustainability verification, and origin authenticity. During the study period, 61 treatment group farmers (41%) established at least one new commercial relationship with buyers they had not previously supplied, compared to 18 control group farmers (12%), representing a statistically significant difference ( $\chi^2 = 28.4$ ,  $p < 0.001$ ) that suggests blockchain documentation substantially enhanced farmers' market access capabilities.

These new buyer relationships included specialty coffee roasters in Jakarta and other Indonesian urban centers (28 farmers), international importers sourcing directly from origin (19 farmers), and online specialty coffee platforms connecting farmers with end consumers (14 farmers), collectively representing market channels that value traceability and transparent sourcing practices. Qualitative interviews with buyers explained that blockchain documentation addressed critical information needs regarding product origin, quality attributes, processing methods, and sustainability practices that enable them to market coffee with compelling provenance narratives and verified quality claims increasingly demanded by specialty coffee consumers. The geographic indication status of Gayo coffee created particularly strong synergies with blockchain traceability, as the combination of protected origin designation and blockchain-verified product journey from specific farms provided powerful authenticity assurance that differentiated Gayo coffee in competitive international markets and justified premium pricing.

Export data indicated that blockchain-traced Gayo coffee commanded FOB prices averaging USD 6.83 per kilogram compared to USD 5.47 for traditionally documented Gayo coffee of equivalent quality grades, suggesting that blockchain verification created substantial market value beyond what geographic indication alone provided. However, market access benefits distributed unevenly, with larger cooperatives and higher-quality producers capturing disproportionate advantages while smaller cooperatives and farmers producing standard specialty grades experienced more modest improvements, reflecting buyer preferences for reliable supply volumes and premium quality that not all blockchain participants could provide. The emergence of new market access opportunities created strategic questions for farmers and cooperatives regarding resource allocation, production investments, and quality improvement initiatives needed to fully capitalize on premium market connections, with successful farmers describing how blockchain-enabled market relationships motivated them to invest in improved processing equipment, quality control procedures, and agricultural practices that enhanced their product positioning and competitive advantages ([Kumar et al., 2020](#)).

The interaction between blockchain traceability and existing certification systems revealed complex complementarities and tensions that influenced system effectiveness and farmer perceptions of value. Among treatment group farmers, 51 (34%) held organic certification, 28 (19%) participated in fair trade programs, and 43 (29%) had obtained geographical indication registration for Gayo coffee, creating opportunities to examine whether blockchain technology augmented or substituted for these established quality and sustainability verification mechanisms. Statistical analysis indicated that certified farmers captured significantly larger price premiums from blockchain participation (USD 0.63 per kilogram) compared to non-certified farmers (USD 0.38 per kilogram), suggesting that blockchain and traditional certifications operate synergistically rather than as substitutes, with the combination providing more compelling quality signals than either mechanism alone.

Farmers with multiple certifications reported that blockchain documentation reduced certification compliance costs by providing digital records of production practices and transaction histories that auditors could verify more efficiently than through traditional paper documentation and physical farm visits, with estimated certification cost reductions of USD 85-120 per farmer per year. However, some tension emerged regarding whether blockchain technology might eventually displace traditional certification systems entirely, with several cooperative managers questioning the continued value of paying certification fees and audit costs when blockchain documentation provided comparable or superior verification capabilities at lower cost. Buyer perspectives on this question proved divided, with some importers and roasters indicating that blockchain traceability provided sufficient assurance to reduce their dependence on third-party certifications, while others maintained that established certification brands provided market credibility and consumer recognition that blockchain systems had not yet achieved and might never fully replace.

The findings suggest that blockchain and traditional certifications will likely coexist for the foreseeable future, with their relative importance varying across market segments, buyer preferences, and specific sustainability or quality attributes being verified, rather than blockchain completely replacing established certification infrastructures. This pattern of technological complementarity rather than substitution aligns with broader innovation literature showing that new technologies typically augment rather than eliminate existing institutional arrangements, particularly when incumbent systems provide valued functions and have developed strong stakeholder constituencies with interests in their continuation ([Iftekhhar et al., 2021](#); [Treiblmaier, 2018](#)). Consumer engagement and end-market recognition of blockchain-traced coffee emerged as critical factors mediating the technology's ultimate impact on farmer welfare and supply chain value distribution. While the blockchain system technically enabled consumers to access complete product provenance information by scanning QR codes on retail packaging and viewing authenticated supply chain records, actual consumer engagement with these features remained limited during the study period.

Survey data from three Indonesian specialty coffee roasters selling blockchain-traced Gayo coffee indicated that only 12-18% of customers actively scanned QR codes to view traceability information, suggesting that technological capability does not automatically translate into consumer utilization and that significant consumer education and marketing efforts may be necessary to realize blockchain's full potential for connecting farmers directly with end consumers. The consumers who did engage with blockchain traceability information expressed high satisfaction (89% rating the experience as valuable or very valuable) and demonstrated willingness to pay modest premiums (average 8-12% above comparable non-traced products) for enhanced transparency, but this engaged consumer segment constituted a niche market rather than mass consumer adoption during the study timeframe. Roasters and retailers reported that blockchain traceability provided more value for business-to-business marketing and wholesale buyer relationships than for direct consumer sales, with specialty coffee shops and corporate buyers showing greater interest in supply chain transparency for their sourcing decisions than individual retail customers whose purchase decisions remained driven primarily by taste, price, and brand reputation.

These patterns suggest that blockchain technology's near-term value proposition lies more in improving supply chain efficiency and enabling premium B2B market access than in revolutionary consumer-farmer connections that blockchain advocates sometimes envision, though long-term potential for consumer engagement may grow as digital literacy increases and as marketing efforts effectively communicate the value of product traceability. The

findings also highlight that capturing blockchain's full value requires coordinated efforts across entire supply chains including farmer production, cooperative processing, export documentation, roaster marketing, and consumer education, with weaknesses at any supply chain stage potentially limiting system effectiveness and farmer benefit realization ([Soh et al., 2021](#)).

### **Cross-Theme Integration and Emergent Framework**

The synthesis of findings across economic impact, operational implementation, and supply chain restructuring themes reveals an emergent framework for understanding how blockchain technology generates value in smallholder agricultural contexts and identifying the conditions necessary for successful implementation. The evidence suggests that blockchain traceability operates through three interconnected value creation mechanisms: information provision that reduces asymmetries and enables quality signaling, relationship transformation that restructures supply chain power dynamics and facilitates direct market access, and efficiency enhancement that reduces transaction costs while improving operational coordination. These mechanisms interact synergistically rather than operating independently, with information transparency enabling relationship transformation, which in turn creates economic value that justifies the transaction costs and learning investments required for system adoption.

The temporal dimension proves critical, as blockchain benefits emerge progressively rather than immediately, requiring farmers and supply chain partners to sustain engagement through initial implementation challenges and learning periods before realizing substantial economic returns. This time-lagged benefit structure creates adoption barriers, particularly for risk-averse farmers with limited financial buffers, suggesting that short-term support mechanisms or incentive programs may be necessary to bridge the gap between technology investment and benefit realization during scaling efforts. The heterogeneity of impacts across farmer characteristics and market contexts indicates that blockchain technology amplifies existing capabilities and advantages rather than creating uniform benefits, with quality-conscious farmers possessing technical sophistication and market connections capturing disproportionate gains while resource-constrained farmers with limited digital literacy and production quality face greater challenges fully leveraging system capabilities.

This pattern suggests that blockchain implementation should be accompanied by complementary interventions addressing underlying capability gaps and market access constraints if equitable benefit distribution constitutes a policy objective, rather than assuming that technology deployment alone will automatically improve outcomes for all smallholder farmers regardless of their specific circumstances and capabilities ([Kshetri, 2021](#); [Siemon et al., 2022](#)). Interconnectedly, the findings reveal that blockchain technology's impact depends fundamentally on ecosystem readiness and complementary infrastructure rather than solely on blockchain system design or technical performance. The infrastructure prerequisites including reliable mobile connectivity, electricity access, and digital literacy represent essential enabling conditions without which blockchain implementation cannot achieve its theoretical potential regardless of software quality or user interface design. Similarly, the market-side preconditions including buyer interest in traceability, consumer willingness to value transparent sourcing, and institutional frameworks supporting premium markets for verified products determine whether blockchain documentation translates into tangible economic benefits for farmers.

The organizational and governance arrangements surrounding blockchain deployment, particularly regarding data ownership, benefit sharing, and decision-making authority, shape whether technology implementation reinforces or disrupts existing power asymmetries within supply chains. These ecosystem considerations suggest that blockchain scaling strategies must adopt holistic perspectives addressing infrastructure development, market cultivation, capacity building, and institutional reform rather than narrow technology-centric approaches focused exclusively on system deployment and user training. The convergence of findings across multiple data sources and analytical approaches strengthens confidence in the study's conclusions while also revealing important nuances and contextual dependencies that complicate simple generalizations about blockchain effectiveness.

The quantitative evidence of positive economic impacts provides compelling demonstration that blockchain technology can deliver measurable benefits to smallholder farmers under appropriate conditions, while the qualitative evidence of implementation challenges and heterogeneous experiences cautions against technological determinism and highlights the importance of contextual factors, support systems, and complementary interventions in determining ultimate outcomes. This integrated perspective contributes to more realistic and actionable understanding of blockchain technology's role in agricultural development, moving beyond polarized debates that either uncritically celebrate blockchain as a transformative solution or dismiss it as inappropriate for smallholder contexts, toward nuanced recognition that technology effectiveness depends on careful attention to implementation details, ecosystem prerequisites, and alignment between technological capabilities and actual user needs and circumstances ([Antonucci et al., 2021](#); [Aydin et al., 2023](#)).

### **Practical Implications, Research Limitations, and Future Directions**

The findings generate several important practical implications for stakeholders considering blockchain implementation in agricultural supply chains or seeking to improve outcomes from existing deployments. For policymakers and development agencies, the results suggest that blockchain technology merits inclusion in agricultural development strategies but requires substantial complementary investments in digital infrastructure, farmer capacity building, and market development rather than technology deployment alone. The significant role of training, technical support, and ongoing accompaniment in determining adoption success indicates that implementation budgets should allocate substantial resources to human capacity development rather than concentrating funding exclusively on technical infrastructure and software licensing, with particular attention to sustained support extending beyond initial deployment phases.

The heterogeneous impacts across farmer characteristics point to need for targeting mechanisms or additional support provisions ensuring that resource-constrained and less technologically sophisticated farmers can effectively participate in blockchain systems and capture equitable benefit shares, potentially through farmer organization strengthening, collective marketing arrangements, or subsidized technical assistance programs. For technology providers and system designers, the findings emphasize importance of user-centered design approaches that prioritize simplicity, reliability, and accommodation of local infrastructure constraints over technical sophistication, with particular attention to offline functionality, low-bandwidth operations, and interfaces accessible to users with limited digital literacy.

The evidence that blockchain value depends on ecosystem readiness and complementary conditions suggests that technology providers should adopt facilitation roles

supporting holistic system development rather than narrow vendor positions focused exclusively on software deployment, potentially including partnerships with cooperatives, buyers, and training organizations that address multiple dimensions of implementation success. For farmer cooperatives and producer organizations, the results demonstrate that blockchain adoption can generate meaningful member benefits but requires careful consideration of governance arrangements, cost-benefit analyses, and strategic alignment with organizational missions and member priorities, with particular attention to ensuring democratic participation in system design decisions and equitable benefit distribution mechanisms that reinforce rather than undermine cooperative principles and member loyalty ([Hastig & Sodhi, 2020](#); [Kayikci et al., 2022](#)).

Despite the study's contributions, several important limitations constrain the generalizability of findings and indicate needs for further research. The relatively short 18-month study period limits ability to assess long-term sustainability of observed impacts or to identify potential benefit erosion as blockchain adoption becomes more widespread and competitive advantages diminish. The focus on a single coffee-producing region with particular characteristics including established specialty market positioning, relatively developed cooperative infrastructure, and protected geographical indication status may limit transferability of findings to other agricultural contexts with different institutional arrangements, market conditions, or crop characteristics.

The quasi-experimental design, while appropriate given practical constraints, cannot achieve the same level of causal inference as randomized controlled trials, with potential for residual confounding from unobserved factors despite propensity score matching and extensive control variables. The sample size of 300 farmers across treatment and control groups, while adequate for detecting moderate effect sizes, limits statistical power for subgroup analyses and may not capture full heterogeneity of experiences across diverse farmer populations. The study's focus on farmers who voluntarily opted into blockchain participation creates potential self-selection bias, with participants potentially possessing greater technological sophistication, risk tolerance, or market orientation than typical smallholder farmers, thereby inflating estimated impacts relative to what would be observed in broader population mandates or less selective implementations.

The reliance on self-reported survey data for some economic outcome measures introduces measurement error concerns, though triangulation with blockchain transaction records and cooperative financial data partially mitigates this limitation. Future research should address these limitations through longer-term longitudinal studies tracking blockchain impacts over multiple years and production cycles, comparative research across diverse agricultural contexts and commodity systems examining how institutional and market conditions mediate technology effectiveness, randomized controlled trials where feasible to strengthen causal inference and reduce selection bias, and larger-scale studies enabling robust analysis of heterogeneous treatment effects and distributional consequences across diverse farmer populations ([Wamba et al., 2020](#); [Yadav et al., 2020](#)).

Several promising directions for future research emerge from the study's findings and limitations. Comparative research examining blockchain implementation across different supply chain governance structures (cooperative-based, private trader networks, vertically integrated systems) would illuminate how organizational contexts shape technology effectiveness and benefit distribution. Investigation of consumer behavior and engagement with blockchain traceability information remains underdeveloped, with need for experimental and observational studies examining what drives consumer utilization of transparency features

and how traceability information influences purchase decisions and willingness to pay across diverse consumer segments and cultural contexts. The interaction between blockchain technology and sustainability practices deserves deeper investigation, particularly regarding whether enhanced traceability monitoring creates incentives for environmental stewardship or whether additional interventions are required to translate transparency into improved sustainability outcomes.

Research on governance arrangements and institutional frameworks supporting equitable blockchain implementations would provide valuable guidance for system design, with particular attention to data ownership, benefit sharing, democratic participation, and power distribution within blockchain-enabled supply chains. The scalability question requires systematic investigation, examining how blockchain system costs, benefits, and operational characteristics change as implementations expand from pilot projects to regional or sector-wide deployments, and identifying economies or diseconomies of scale that influence optimal implementation strategies. Finally, integration of blockchain with other emerging technologies including Internet of Things sensors, artificial intelligence analytics, and mobile payment systems presents promising research frontier, exploring how technology combinations create complementary capabilities and synergistic value beyond what individual technologies provide. These research directions collectively would advance understanding of blockchain technology's evolving role in agricultural development and provide increasingly robust evidence base for technology policy, investment decisions, and implementation strategies that maximize benefits for smallholder farmers while minimizing risks and unintended consequences ([Kamble et al., 2020](#); [Lohmer et al., 2022](#)).

## CONCLUSION

This mixed-methods quasi-experimental study examined blockchain-based traceability among 150 Arabica coffee farmers in Gayo Highlands, Aceh Province (January 2024–June 2025). Results demonstrated statistically significant economic benefits: USD 0.35/kg price premiums ( $p < 0.001$ ) yielding USD 356 annual household income increases (13.0% gain), enhanced market access with 41% treatment farmers establishing new buyer relationships versus 12% controls ( $\chi^2 = 28.4$ ,  $p < 0.001$ ), and supply chain disintermediation reducing intermediary stages from 4.3 to 3.1. However, heterogeneous impacts favored larger farms and higher-quality producers, while implementation challenges included infrastructure constraints (62% connectivity issues) and digital literacy gaps (41% requiring assistance).

These findings validate information economics theory regarding credible quality signaling in agricultural markets while advancing methodological integration of quantitative and qualitative technology evaluation approaches. Practical implications emphasize sustained capacity building, complementary infrastructure investments, and equitable governance frameworks ensuring democratic participation. Policymakers should accompany technology deployment with regulatory support for smallholder interests and programs addressing capability gaps. Future research must extend beyond this single-region, 18-month study through comparative cross-context investigations, longitudinal tracking, and randomized controlled trials. Ultimately, blockchain demonstrates genuine agricultural development potential provided implementations prioritize farmer empowerment, equity, and sustained support rather than viewing technology as an end itself.

## ACKNOWLEDGEMENT

The authors express profound gratitude to the 300 smallholder coffee farmers in the Gayo Highlands of Central Aceh Regency who generously participated in this research study, dedicating their time and sharing their experiences, insights, and production data throughout the 18-month investigation period. We extend special appreciation to the leadership and staff of the three coffee farmer cooperatives in the Gayo Highland region who facilitated participant recruitment, provided logistical support for data collection activities, and demonstrated unwavering commitment to agricultural innovation and farmer welfare improvement. Sincere thanks are due to the consortium of technology providers who developed and maintained the blockchain traceability platform, offered technical training to farmers and cooperative personnel, and ensured system reliability and data integrity throughout the pilot implementation. We acknowledge with gratitude the exporters, importers, and specialty coffee buyers who participated in qualitative interviews, shared market insights, and provided valuable perspectives on supply chain dynamics and traceability value propositions from downstream stakeholder viewpoints.

The research team acknowledges the essential contributions of our trained field research assistants who conducted surveys, facilitated focus group discussions, and provided translation services between Bahasa Indonesia and local Gayo language, ensuring accurate communication and culturally sensitive data collection throughout the fieldwork period. We express appreciation to the Indonesian Coffee and Cocoa Research Institute for providing regional coffee price statistics, market trend data, and technical expertise regarding coffee quality assessment protocols that enhanced the analytical rigor of this investigation. Special recognition is extended to the Institutional Review Board that reviewed and approved the research protocol, ensuring ethical integrity and participant protection throughout all phases of this study. We acknowledge the peer reviewers and colleagues who provided valuable feedback on earlier versions of this manuscript, contributing substantially to the clarity, rigor, and scholarly contribution of the final publication. The authors declare that this research received no specific grant funding from public, commercial, or not-for-profit funding agencies, and was conducted as part of institutional research commitments to agricultural development and technology innovation in smallholder farming systems.

Finally, we express deep gratitude to the broader Gayo Highland coffee community, including farmers who participated in pilot testing and validation activities, local government officials who facilitated research permissions and community engagement, and agricultural extension workers who provided contextual insights and supported technology adoption efforts. This research would not have been possible without the collective contributions, cooperation, and commitment of all these individuals and organizations who share our vision of leveraging technology innovation for equitable agricultural development and improved livelihoods for smallholder farmers.

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