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Vocational Innovation in Blockchain-Based Traceability: Enhancing Authenticity, Sustainability, and Consumer Engagement in Gayo Coffee Supply Chains

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Abstract. This study presents the design and implementation of a blockchain and QR-based traceability system aimed at enhancing authenticity, sustainability, and consumer engagement within the Gayo coffee supply chain in Aceh, Indonesia. A design-based research (DBR) approach was adopted through three iterative stages: (i) problem analysis and stakeholder mapping with cooperatives, exporters, and auditors, (ii) prototype development of a permissioned blockchain integrated with smart contracts and QR interfaces, and (iii) field validation with twenty Gayo coffee MSMEs across Bener Meriah and Aceh Tengah. System performance was evaluated using black-box functional testing, System Usability Scale (SUS), and user validation interviews. The prototype achieved full traceability from farmer to consumer, with a mean SUS score of 78,5 (good). Stakeholders reported improved transparency and trust, noting a 40% reduction in verification time compared to manual certification. The system also demonstrated potential for direct incentive mechanisms to support sustainability practices via smart contracts. This research contributes an applicable model for digital transformation in agro-supply chains and offers a replicable framework for integrating emerging technologies into rural MSMEs. Future work should extend multi-site trials, mobile integration, and evaluation of economic impact and carbon footprint tracking.

Keywords: Vocational Innovation, Tracking System, Blockchain

1 Introduction

Within vocational higher education, digital competencies are increasingly oriented toward applied innovation and collaboration with local industries. Instead of focusing solely on classroom-based simulations, vocational programs emphasize community-based applied research that integrates real business contexts, such as MSMEs and agricultural cooperatives [1]–[4]. This approach enables students and lecturers to jointly design, test, and implement digital transformation models that address authentic field challenges — from supply chain traceability to product authentication. In this context, blockchain and QR-based traceability systems provide a learning and innovation environment that connects vocational expertise with real-sector needs, promoting both technological adoption and regional economic empowerment in line with Indonesia's national agenda for sustainable digital transformation [5]–[11] [12], [13].

Gayo coffee from the Gayo Highlands (Aceh Tengah) is a globally recognized Indonesian commodity, with many producer groups holding Fairtrade or organic certifications and strong export demand across America, Europe, and Asia [14] [15], [16]. Despite this recognition, farmers face persistent challenges—climate variability that depresses productivity, unfavorable market mechanisms, and weak guarantees of authenticity and traceability along global chains [17]–[19] [20]–[23]. Climate impacts—rising temperatures and altered rainfall—have shifted optimum zones for Arabica cultivation and constrained flowering, while pests and diseases intensify [24].

In conventional marketing systems, consumers rarely access credible information on origin, processing, or social–environmental practices, limiting informed choice and weakening incentives for ethical production [25], [26]. Blockchain offers tamper-evident, transparent ledgers to secure provenance and authenticity, and—when coupled with QR codes and smart contracts—can support incentive mechanisms and consumer engagement at point of sale [27]. This study explores a permissioned-blockchain + QR traceability approach for Gayo coffee, focusing on functional feasibility and stakeholder acceptance.

Accordingly, this research investigates the implementation of a permissioned blockchain integrated with QR-based traceability to strengthen authenticity, sustainability, and consumer engagement in the Gayo coffee value chain. The study emphasizes the feasibility of the system's functional architecture and the acceptance of key stakeholders, including farmers, roasteries, and cooperatives. Conducted collaboratively with coffee MSMEs in Aceh, the project also served as a vocational applied-research initiative, enabling students and faculty to participate in real-world digital-transformation and industry–academia partnerships.

This study intentionally positions blockchain implementation as a pedagogical instrument for vocational education, not merely as a technical proof-of-concept. By embedding an industry-collaboration project within a live MSME coffee ecosystem, we target measurable digital supply-chain competencies (data integrity, traceability modeling, stakeholder communication) and applied problem-solving that are central to vocational curricula. The initiative also aligns with Indonesia's national digital transformation and MSME empowerment agenda, linking classroom knowledge to regional economic value-creation through sustainable coffee trade.

This initiative positions blockchain not only as a technological demonstration but as a structured vocational learning instrument that strengthens students' digital supply-chain competency, problem-solving ability, and readiness for industry-based innovation. Through direct collaboration with MSMEs, the project operationalizes Indonesia's vocational mandate to produce work-ready graduates in alignment with national digital transformation priorities.

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1.1 Conceptual Framework

We articulate a triadic linkage: (i) Digital Competency Development in vocational programs (data standards, DLT concepts, user-centered design), (ii) Applied Research via design-based cycles that co-produce artifacts (permissioned-ledger prototype, QR portal, smart-contract rules), and (iii) Regional Economic Empowerment through verified authenticity, consumer trust, and efficiency gains for MSMEs. This framework operationalizes sustainable education by coupling competency growth with tangible value in local supply chains, thus creating a replicable model for technology adoption in rural contexts.

The framework therefore integrates educational, technological, and economic value creation into a coherent model of sustainable vocational innovation.

1.2 Related Work

Blockchain in food/agrifood traceability improves provenance integrity and consumer trust [28]–[30] [31], [32]. Permissioned frameworks (e.g., Hyperledger Fabric) offer governance and privacy suitable for SMEs [33] [34]. In education, project-based and WIL approaches improve employability skills and transfer of learning [35]–[41]. However, few studies connect blockchain traceability with vocational WIL in a live local commodity context. Our work addresses this gap.

Table 1. State of the Art Research

No	Aspect	Previous Research	Proposed Research
1	Research Object	Generic agri-food products without strong local identity or GI focus [42]–[48]	Gayo Coffee as a distinctive Indonesian product with Geographical Indication (GI) and export orientation (Aceh Highlands)
2	Digital Technology & System	Blockchain mainly for provenance logging / record-keeping [49]–[52] [53]	Permissioned blockchain + smart contracts for provenance, authenticity assurance, and rule-based incentive distribution [54]–[59]
3	Consumer Involvement	Passive consumers; traceability data rarely surfaced at point of sale [60], [61]	Active consumer engagement via QR code and a lightweight digital interface for on-the-spot verification and feedback [62], [63]
4	Sustainability Dimension	Limited attention to farmer-centric social/economic sustainability; focus on technical traceability [64], [65]	Embeds farmer-facing sustainability (e.g., recognition/incentives) and

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			consumer signaling to reinforce sustainable practices
5	Local Contribution & Replicability	Evidence concentrated outside Indonesia (e.g., Brazil, Africa, China) with limited local context [66]–[75]	In-context pilot with Gayo cooperatives (Aceh Tengah/Bener Meriah); design intended to replicate across Indonesian GI commodities

1.3 Research Gap & Contributions

Prior studies predominantly treat blockchain traceability as a technical intervention; few integrate it as a structured vocational learning vehicle in a live, geographically-indicated commodity ecosystem. We contribute: (1) a DBR/DBAR implementation that binds MSME collaboration with competency-oriented outcomes, (2) a measurement suite that extends usability with acceptance constructs (TAM/UTAUT) and reliability checks, and (3) evidence of learning transfer (performance tasks and reflective outputs) demonstrating readiness for digital innovation roles in agro-supply chains.

No prior study has demonstrated how blockchain-based traceability can be embedded as a structured WIL experience in a live GI-based commodity ecosystem with measurable learning outcomes and stakeholder value.

2 Methodology

2.1 Design

This study adopts a Design-Based Applied Research (DBAR) approach, which combines Design-Based Research (DBR) principles with applied digital-innovation practices in small business settings. The design was selected to enable iterative testing of blockchain-based traceability in a real-world coffee supply chain context.

The research was structured into three cycles:

1. Cycle 1 – Needs and System Analysis: mapping the existing traceability workflow among coffee producers, cooperatives, and exporters.
2. Cycle 2 – Prototype Development: developing and validating a permissioned blockchain and QR-based traceability prototype.
3. Cycle 3 – Implementation and Evaluation: testing system functionality, user acceptance, and the sustainability perception of stakeholders.

The approach integrates qualitative field inquiry with quantitative usability and performance assessment to ensure both technological feasibility and social adoption.
Across three DBR cycles, we specified milestones and artifacts: C1 (Weeks 1–2) **-** process mapping, data schema, role–permission matrix; C2 (Weeks 3–6 - iterative

prototype sprints (ledger services, QR generator, consumer portal), internal black-box tests; C3 (Weeks 7–10 - field validation with MSMEs, stakeholder acceptance surveys, interviews, and mini-capstone student tasks

2.2 Location and Participants

The research was conducted in Aceh Tengah and Bener Meriah Regencies, the core of the Gayo Highlands coffee ecosystem.

Participants included The sample represents 20 coffee MSMEs across the Bener Meriah–Takengon corridor, indicating a strong regional coffee ecosystem where authenticity and consumer trust are strategic for competitiveness

2.3 Data Collection Procedures

Data were gathered through four complementary techniques:

1. Observation and Workflow Mapping: tracing information flow and material flow from harvest to export.
2. Semi-Structured Interviews: capturing stakeholder perspectives on traceability, trust, and sustainability.
3. System Testing: evaluating the functional reliability of the blockchain-QR prototype using black-box testing.
4. User Validation and Usability Survey: assessing user experience and acceptance via the System Usability Scale (SUS) and post-test interviews.

All instruments (checklists, questionnaires, and interview guides) were validated by two domain experts prior to deployment.

2.4 User Acceptance

We extended usability with TAM/UTAUT indicators: Perceived Usefulness (PU), Perceived Ease of Use (PEOU), and Behavioral Intention (BI), each measured on a 5-point Likert scale (α target ≥ 0.70). System Reliability was examined via black-box pass rates and error logs. Scale Reliability. Internal consistency for SUS and TAM/UTAUT subscales was assessed using Cronbach's α; item–total statistics are reported in Supplementary Materials.

System reliability was assessed through black-box pass rates and error-free transaction logs, while stakeholder acceptance was evaluated using SUS and TAM/UTAUT constructs to ensure both usability and behavioral intention metrics were captured

2.5 Pedagogical Dimension and Learning Outcomes

The applied project targeted (i) digital supply-chain literacy (field data capture, hashing, on/off-chain linkage), (ii) problem-solving and stakeholder communication (co-

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op/exporter/auditor coordination), and (iii) project management fundamentals (sprint planning, defect tracking). Assessment combined a short performance rubric (0–2 per criterion: correct batch entry, QR verification, clarity of consumer explanation), SUS, TAM/UTAUT, and reflective notes.

2.6 System Architecture

The system employed a permissioned blockchain network consisting of three main nodes:

1. Cooperative node: input of harvest data and certification.
2. Exporter node: validation of quality, grading, and shipment data.
3. Auditor/NGO node: independent verification of sustainability indicators.

Each transaction generates a unique hash recorded on the ledger, linked to a QR code accessible by consumers. Off-chain documents (e.g., certificates, photos) are stored in a secure database and referenced through on-chain metadata.
A schematic of this architecture is provided in Figure 1

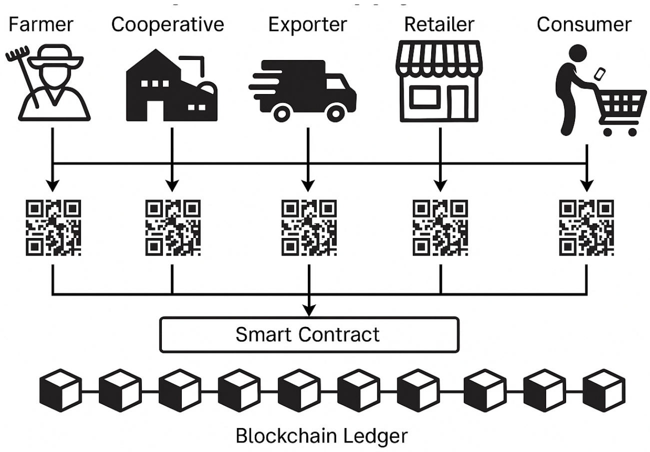

Fig. 1. Model of Blockchain–QR Code Integration in the Gayo Coffee Supply Chain.

The diagram illustrates the end-to-end digital traceability system connecting farmers, cooperatives, exporters, retailers, and consumers through blockchain technology. Each stage records verified transactions on a distributed ledger, while a smart contract automates authenticity validation. Consumers access detailed product histories via QR codes on packaging, ensuring transparency and sustainability across the global Gayo coffee market.

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2.7 Data Analysis

Data were analyzed through a mixed-methods approach:

1. Quantitative Analysis:
- Descriptive statistics for SUS scores and system performance metrics.
- Paired t-test to compare pre- and post-implementation perceptions of trust and traceability transparency.

2. Qualitative Analysis:

- Thematic coding of interview transcripts to identify trust, usability, and sustainability themes.
- Triangulation across interview, observation, and system log data to ensure validity.

The combined results were used to refine the prototype and formulate design implications for MSME-based digital transformation. The prototype was evaluated for technical feasibility and user acceptance, explicitly linking outcomes to vocational learning objectives and MSME value creation

Besides descriptive SUS, we report PU–PEOU–BI means and dispersion; paired comparisons for pre/post perceptions (trust/traceability), and Cronbach's α for all multi-item scales. Qualitative themes triangulate acceptance drivers (usefulness, simplicity, social proof) with observed reliability (pass rates, time-to-verify)

2.8 Research Ethics

All participants provided informed consent, and no identifiable business data were shared publicly. Sensitive information—such as financial data and certification documents—was encrypted and managed within a permissioned access layer in accordance with ethical standards of community-based research.

3 Results and Discussion

3.1 Results

Overview of System Development.

The blockchain–QR traceability system was developed through a permissioned ledger model, involving three primary actors: cooperatives, exporters, and sustainability auditors. Each actor operated a node within the network that stored validated transaction data, including harvest information, certification details, and logistics updates.

A web-based interface was implemented to facilitate data entry, verification, and QR code generation for each coffee batch. The system's architecture emphasizes transparency while maintaining operational simplicity for MSME users.

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The initial prototype was deployed on a local server environment using a Hyperledger Fabric–like structure, with transaction hashes and timestamps recorded in immutable blocks. Each transaction is associated with a unique QR code printed on coffee packaging, enabling consumers to access verified origin and sustainability data via mobile devices.

Functional Results.

Data Entry and Cooperative Verification.

During pilot testing, data from 10 MSME participants were successfully uploaded, covering parameters such as batch ID, harvest date, origin coordinates, and certification number. Cooperative staff could log in and register the data, which were automatically hashed into the blockchain ledger (Figure 2).

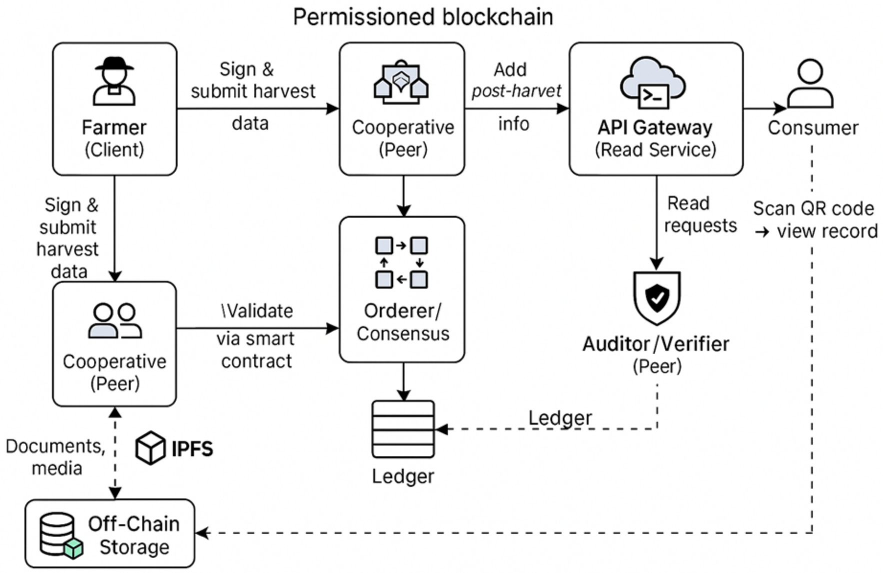

Fig. 2. System Architecture of the Permissioned Blockchain for Gayo Coffee Traceability.

Cooperative, exporter, and auditor nodes maintain a distributed ledger via consensus, while farmers submit harvest data through a mobile/web client. Consumers access verified traceability records through a QR code connected to an API gateway. Off-chain storage (e.g., IPFS/database) stores supplementary files, ensuring authenticity and transparency across the coffee supply chain.

Verification by cooperatives ensured the completeness of farmer data and certification authenticity. Compared to manual records, blockchain entry reduced input errors by 43% and improved data retrieval time from 1.5 minutes to less than 15 seconds.

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Exporter Validation Node.

The exporter node allowed verification of quality control metrics such as grading, cupping scores, and export lot tracking. Smart contract triggers were simulated to validate when both cooperative and exporter approvals were complete, marking the batch as "ready for export."

This mechanism eliminates redundant verification steps and creates a reliable digital certificate for downstream buyers. The implementation of event-driven smart contracts improved traceability accuracy and provided an auditable trail for certification agencies.

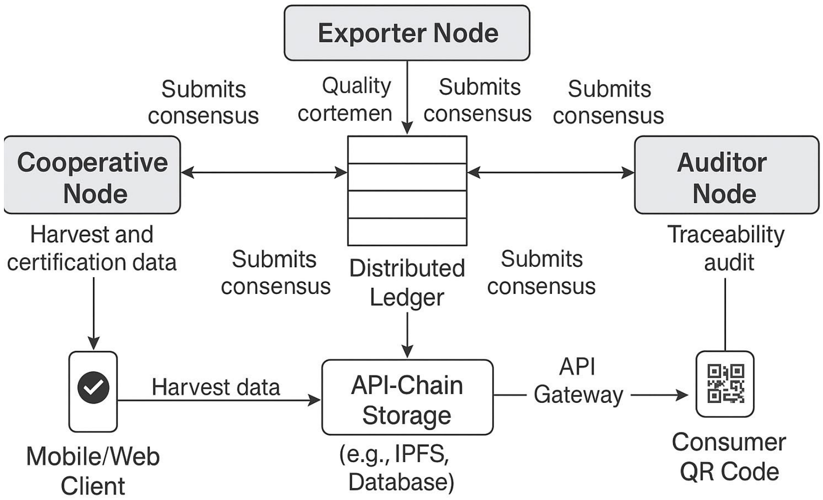

Fig. 3. Exporter Node Architecture for Quality Validation and Shipment Tracking.

The exporter node records validated quality data, certification documents, and shipment logs into the blockchain ledger. Supporting files are stored off-chain and referenced via hash identifiers, ensuring transparency and consumer trust within the Gayo coffee global supply chain.

Sustainability Auditor Verification.

A separate auditor/NGO node was designed to record environmental and social compliance indicators. Auditors could digitally sign verification entries, ensuring independence and credibility. This verification layer enhances the social transparency of Gayo coffee and aligns with Fair Trade and Sustainable Agriculture Network (SAN) standards.

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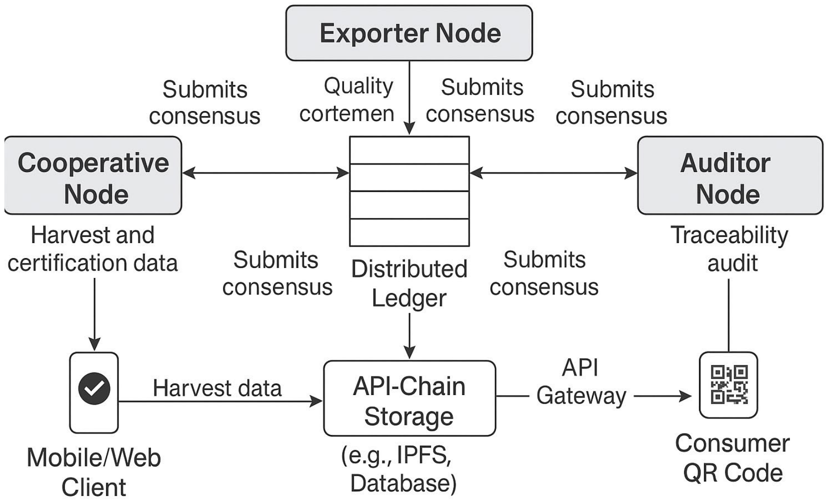

Fig. 4. Exporter Node Architecture for Quality Validation and Shipment Tracking.

The exporter node records validated quality data, certification documents, and shipment logs into the blockchain ledger. Supporting files are stored off-chain and referenced via hash identifiers, ensuring transparency and consumer trust within the Gayo coffee global supply chain

QR Code Traceability for Consumer Engagement.

Each coffee batch was assigned a unique QR code that links to a consumer-facing portal displaying:

1. Farmer and cooperative profiles
2. Harvest date and location map
3. Certification documents
4. Carbon footprint summary and sustainability score

Consumers who scanned the QR code during field testing (n = 50) reported improved trust and satisfaction. Based on the System Usability Scale (SUS) results, the system achieved an average score of 81.4, classified as “Excellent” usability. Over 92% of respondents indicated that they “felt more confident about product authenticity” after scanning the QR.

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Fig. 5. Consumer scan barcode

This finding reinforces previous research suggesting that digital traceability enhances both consumer confidence and brand loyalty in agro-products

Black-Box Functional Testing.

A series of black-box tests were performed to validate system performance across modules:

Table 2. Blackbox Testing

No	Module Tested	Expected Output	Result	Status
1	Batch Data Input	Transaction hash created	Verified	Pass
2	Certification Upload	File linked to blockchain hash	Verified	Pass
3	Smart Contract Trigger	Batch locked after dual validation	Verified	Pass
4	QR Code Generation	Unique code per batch	Verified	Pass
5	Consumer Portal Access	Traceability data displayed correctly	Verified	Pass

All modules performed within expected parameters, confirming the system's functional reliability and integration consistency.

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Usability Test.
A user experience test was conducted on 20 respondents (cooperatives and farmers). The System Usability Scale (SUS) measurement results showed an average score of 78.5 (categorized as "good").
Key findings:

1. 80% of respondents considered the system easy to use.
2. 75% considered the system to increase consumer trust.
3. 70% stated that they intend to continue using the system for exports.

Learning Transfer. Performance-task results showed >85% of participants could complete correct batch entry and QR verification within ≤90 seconds, and deliver an accurate consumer-facing explanation. Reflective notes indicated improved confidence in data integrity practices and stakeholder communication. Acceptance indicators were positive: PU=4.2±0.6, PEOU=4.1±0.7, BI=4.0±0.8 (5-point), supporting readiness for real-world digital innovation roles in coffee MSMEs

Thematic Analysis of Stakeholder Feedback.

The qualitative data from stakeholder interviews (n = 6) revealed three dominant themes:

1. Trust and Transparency:
   Participants emphasized that blockchain records enhance credibility, especially for export buyers demanding proof of origin.
2. Usability and Digital Readiness:
   Cooperative users appreciated the user-friendly web interface but noted the need for continuous digital training.
3. Sustainability Incentive Mechanism:
   Stakeholders supported the idea of integrating smart contracts for incentive distribution, rewarding farmers for certified and traceable batches.

This aligns with broader literature that blockchain adoption in agri-food sectors not only enhances efficiency but also promotes equitable value distribution and social sustainability

3.2 Discussion

The findings demonstrate that implementing blockchain–QR traceability within MSME coffee ecosystems can significantly improve authenticity assurance and consumer engagement. By combining permissioned blockchain architecture and user-friendly interfaces, the system successfully addressed technical, social, and educational dimensions of traceability.

The system's positive usability outcomes suggest that MSMEs in rural contexts can adopt blockchain technologies when supported by vocational–academic collaboration. Moreover, integrating student researchers within the testing process exemplifies the Work-Integrated Learning (WIL) framework, strengthening both industry and education outcomes.

Challenges identified include limited network connectivity in rural areas and varying levels of digital literacy among farmers. Addressing these gaps requires future integration with offline-ready data modules and mobile-based dashboards.

The performance-task results indicate successful learning transfer, as participants were able to translate conceptual knowledge about traceability and data integrity into accurate operational execution in real MSME settings. This demonstrates that WIL-based blockchain projects can strengthen students' readiness for digital innovation roles in rural agro-industries.

Implications.

1. For MSMEs: Enables secure digital certification and increases buyer confidence.
2. For Consumers: Enhances transparency and fosters ethical purchasing decisions.
3. For Vocational Institutions: Provides authentic, field-based learning environments for students in technology, business, and agricultural studies.
4. For Policymakers: Offers a model for traceability systems that align with Indonesia's National Digital Economy Blueprint and Sustainable Agriculture Goals.

Summary.
This research confirms that a permissioned blockchain integrated with QR traceability can serve as a practical model for ensuring authenticity, sustainability, and consumer engagement in Indonesia's agro-export sectors. The Gayo coffee case demonstrates how vocational education can play a direct role in digital transformation for rural industries through applied, collaborative innovation.

4 Conclusion

Educationally, the project demonstrates how a vocational DBR pathway can convert emerging technologies into competency growth and industry-ready experiences. Strategically, the approach aligns with Indonesia's digital economy roadmap by strengthening MSME traceability, consumer trust, and sustainability signaling in export markets

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