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Blockchain Adoption for Traceability in Organic Coffee Cooperatives in the Highlands of Peru

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ABSTRACT

This study proposes a blockchain-based traceability system tailored for organic coffee cooperatives in the highlands of Peru. Despite the country's status as a leading exporter of organic coffee, existing supply-chain documentation remains fragmented and opaque, limiting trust, efficiency, and certification credibility. Using a design science methodology, this research models a decentralized digital ledger framework that records coffee production events—from harvest through export—on an immutable, verifiable blockchain. Stakeholder interviews and cooperative process mapping informed the design, ensuring that the proposed system addresses key challenges such as data integrity, certification compliance, and farmer recognition. The model features permissioned access for cooperative nodes, farm-level data capture, automated smart contract checks, and a transparent end-to-end provenance trail. Visualization tools like flowcharts and block diagrams illustrate the interaction between supply-chain actors and blockchain records. Discussion centers on system feasibility, implementation barriers, and potential socioeconomic benefits, such as enhanced market access and fair pricing for smallholder producers. While connectivity and adoption costs remain significant obstacles, the system offers a scalable solution for improving transparency and sustainability in global agri-food trade. The research contributes a replicable framework applicable to other high-value export commodities in the Global South.

Keywords: Blockchain Traceability, Organic Coffee, Peruvian Cooperatives, Supply Chain Transparency, Agri-food Systems.

INTRODUCTION

Peru is a global leader in organic coffee production, with roughly 90,000 hectares of certified organic coffee – the largest such area in the world. Much of this cultivation occurs in the Andean highlands, where thousands of smallholder farmers grow shade-grown Arabica coffee at elevations of 1,000–2,000 meters. Because individual farms are small (often just a few hectares), farmers commonly form cooperatives to aggregate harvests for processing and export (FAO, 2020). For example, in the Villa Rica district (San Martín region), 1,100 producers are organized into eight cooperatives that jointly process and roast coffee for export to specialty markets in Europe. Overall, it is estimated that 80–90 coffee cooperatives in Peru represent about 20–30% of the country's coffee farmers. These cooperative networks help small producers access better prices and technical support, aiming to improve bean quality and yields (Arias, Hallam, Krivonos, & Morrison, 2013; Biswas & Muthukkumarasamy, 2016).

Despite coffee's economic importance, the chain of custody from farm to cup faces significant trust and transparency challenges. Cooperatives and other actors currently rely on paper records or isolated digital files to document harvests, processing, and sales. This fragmented information can lead to errors, fraud, and reduced transparency: for example, Peruvian cooperatives' poor traceability has been linked to data manipulation, identity loss of batches, and general corruption in the chain. Such opacity reduces farmers' leverage and undermines consumer trust in "single-origin" or organic labels. Indeed, one study reports that a third of coffee-producing families are in cooperatives yet still face challenges in proving sustainable practices: "trust is lost between chain actors due to lack of transparency". Small farmers in the highlands often remain anonymous downstream, devaluing their labour and certification claims. Additionally, international regulations (e.g. the EU Deforestation Regulation) increasingly demand proof that coffee is produced without deforestation or abuse.

These economic and regulatory pressures create a strong rationale for improved supply-chain traceability. Blockchain technology – a distributed ledger that immutably records transactions – has been proposed to enhance transparency and trust in food systems. Its core features (shared ledger, cryptographic blocks, consensus validation) mean that once a coffee harvest or transaction is recorded, it cannot be altered without detection. In theory, a blockchain-based traceability system would allow consumers, importers, and certifying bodies to verify the origin and journey of each coffee batch back to the farm, while also ensuring fair payments to producers. Recent reviews highlight blockchain's ability to secure provenance and increase accountability across complex agri-food value chains (Aung & Chang, 2014). For example, a systematic review notes that blockchain's immutability and transparency "create a dependable and secure system for tracking food products across the whole supply chain, ensuring total control over their traceability from the origin to the final consumer". Similarly, research on South American agriculture observes that blockchain can establish a permanent, open record of all supply-chain transactions, allowing consumers and stakeholders to track product origin and quality and thus foster trust and fair trade.

Given Peru's leading role in organic coffee exports and the cooperative structure of production, designing a blockchain-based traceability model is a timely endeavor. Such a system could address current gaps by capturing data at each stage (harvest, processing, export, etc.) on a shared ledger accessible to all authorized participants. By automating certification checks and providing tamper-evident logs, the model promises to enhance transparency, certification credibility, and market value for Peruvian highland coffee. The following sections review the relevant literature on agricultural traceability, blockchain in food systems, cooperatives, and digital agriculture; then describe our methodology for modeling a blockchain traceability framework for Peruvian organic coffee cooperatives (Caro, Ali, Vecchio, & Giaffreda, 2018).

LITERATURE REVIEW

Traceability in Agricultural Value Chains

Traceability in agri-food systems refers to the ability to track the history, location, and use of agricultural products throughout the supply chain. It is essential for food safety, quality assurance, and certification compliance. In practice, traceability systems must handle challenges unique to agriculture: perishability, seasonality, and farm-level diversity. For example, high-quality coffee traceability requires recording data at pre-harvest (farm location, cultivation methods), harvest (time, conditions), processing (wet/dry mills, grades), and post-harvest (storage, transport) stages. Existing approaches often rely on barcodes, QR codes, or manual registries. However, many reviews note that these traditional systems are fragmented and inefficient. Wolfert, Verdouw, and Bogaardt (2017) and others highlight that while data-sharing standards (EPCIS, GS1, etc.) exist, there remains a lack of integrated visibility from "farm to fork". Cooperating with multiple actors using diverse record-keeping tools is a key challenge. In fragmented supply chains (especially global coffee networks), information frequently exists in isolated "islands" rather than a unified database (da Cruz, Milet, & Terra, 2023).

Furthermore, evolving consumer and regulatory demands are raising the bar for traceability. Sustainable Development Goals and food-safety initiatives require that producers demonstrate eco-friendly practices and food safety throughout production. In response, farmers and exporters are under pressure to collect detailed sustainability data (e.g. agrochemical use, water management) and make it transparent downstream. However, gathering and sharing such fine-grained data is non-trivial: standards may not cover pre-harvest activities, and data collection at the farm level can be costly for smallholders. Thus, scholars argue that new technological solutions are needed to achieve comprehensive traceability: IoT sensors, data platforms, and integrated models have been proposed to improve transparency from planting through distribution.

In summary, the literature emphasizes that traditional traceability in agriculture often fails to provide end-to-end visibility. Weaknesses include lack of interoperability between systems, manual data entry errors, and missing records at critical stages (Córdoba & Tobar, 2021). Without reliable traceability, verifying organic or fair-trade claims is difficult, undermining consumer confidence and ethical markets. This context sets the stage for exploring distributed ledger technologies as a means to overcome these systemic limitations.

Blockchain in Agri-Food Systems

Blockchain technology has attracted attention as a potential breakthrough for agri-food traceability. By design, a blockchain provides an immutable, distributed ledger where transactions (e.g. harvest lots or transfers) are cryptographically linked. Multiple recent reviews document the promise and pitfalls of applying blockchain in agriculture. For example, a systematic survey of blockchain frameworks for food traceability concludes that blockchain's core features can "revolutionize the industry" by enhancing transparency and accountability. It argues that immutability and shared consensus align well with consumer demands for provenance: stakeholders anywhere can trace a product back to its origin with confidence. In theory, this could virtually eliminate data tampering and double-counting – problems endemic to paper-based systems.

Case studies in coffee and related commodities support these ideas. These pilots "significantly contributed to the sustainable development of farming processes," as they enforce certification labels and combat fraud by preserving authentic data. Similarly, García, López, and Ruiz (2019) designed a blockchain framework for a Peruvian coffee cooperative and reported striking performance gains: the system produced traceability records nearly 100 times faster than the prior method, while greatly reducing errors. Even outside coffee, examples abound: IBM's Food Trust (with major retailers and farms) has demonstrated that blockchain can dramatically shorten recall times and improve trust in supply chains.

Alongside benefits, the literature candidly acknowledges challenges. High implementation costs are repeatedly cited as a barrier, especially for small actors. These costs include not only initial development of blockchain applications but also the need for specialized hardware, connectivity, and training of personnel. In rural settings like the Peruvian Andes, internet access and digital literacy can be weak. For example, a study of Latin America found that only ~37% of rural residents have access to quality internet, compared to ~71% of urban dwellers. Without reliable connectivity, a blockchain network (which requires frequent data broadcasts) may be impractical. Scalability is another concern: blockchains typically slow down as transaction volumes grow, potentially limiting throughput in high-activity systems. Data reliability is also an issue: if farmers manually input data (e.g. harvest weights), there is a risk of inaccurate or fraudulent entries, as one recent Peru case study warns.

Social factors further complicate adoption. Existing power relations in global value chains mean that upstream producers may shoulder the integration burden, while the marketing benefits accrue primarily to downstream firms. In practice, lead firms could exploit the new system by extracting value from the data ("data squeeze") without fairly sharing the gains with farmers. Trust networks and governance around who can read or write to the blockchain also require careful design. Thus, the literature stresses that successful blockchain traceability depends not only on technology but also on enabling conditions: cooperative governance, equitable sharing of costs, regulatory alignment, and standards for interoperability (Centobelli, Cerchione, & Esposito, 2022).

In the Latin American context, scholars have identified growing interest in blockchain for sustainable farming, but also note the steep learning curve. A recent review of South American agriculture reported a 30% year-on-year increase in blockchain pilot applications (2018–2023), highlighting a trend toward decentralized apps for agribusiness. However, adoption remains partial. Researchers emphasize the importance of stakeholder buy-in: decentralized traceability will only work if cooperatives and farmers see clear returns, and if implementation costs are shared across the value chain. In summary, while blockchain is technically well-suited to immutable tracking of agri-food products, practical adoption requires overcoming economic, technical, and institutional barriers.

Cooperatives, Certification, and the Peruvian Context

In Peru's coffee sector, cooperatives play a pivotal role in linking smallholders to global markets. Academic and industry reports describe cooperatives as critical for enabling certification (organic, fair trade) and quality control. For instance, many cooperatives take responsibility for verifying organic practices and obtaining certification for their members, often on a group basis. One source notes that "cooperatives trace cocoa beans internally, from individual farmers to the export batches, as required by organic certification" (this finding for cocoa is directly analogous to coffee). By aggregating lots, cooperatives can achieve the volumes needed for export contracts, while also pooling resources to cover certification audits.

However, cooperatives themselves often struggle with transparency. For example, García et al. report that Peruvian coffee cooperatives frequently rely on paper-based processes for recording deliveries and receipts. Such manual record-keeping is slow and error-prone; it can foster mistrust between members and processors. Organic certification adds further complexity, as products must be segregated and tracked through each phase of processing and export. If a cooperative mishandles this data, it risks losing its certification or facing penalties. This context helps explain why cooperatives are motivated to explore better systems: greater traceability would strengthen their reputation and potentially allow them to command higher prices for certified organic beans.

Several studies of Peruvian coffee emphasize cooperatives' potential to benefit from blockchain. Root Capital (2024) notes that "coffee cooperatives… are among the few organizations that ensure smallholder farmers can share in market opportunities," highlighting their role in quality control and export. By making trace data transparent, blockchain could increase cooperatives' negotiating power and consumers' confidence. On the other hand, cooperatives may face the adoption obstacles identified above. They often operate in remote highland areas where digital infrastructure lags, and members may lack experience with new technologies. Thus, any blockchain model must be tailored to the cooperative context: user-friendly interfaces (e.g. mobile apps), affordable connectivity solutions, and perhaps hybrid on/off-chain mechanisms to accommodate intermittent internet.

Digital Transformation in Latin American Agriculture

Latin America's agricultural sector is undergoing a wave of digital transformation, though unevenly. Reports from multilateral organizations note that many farms are experimenting with IoT sensors, data analytics, and mobile apps to improve yields and sustainability. In the coffee sector specifically, there is growing attention to traceability not just for quality but also for environmental compliance (e.g. no deforestation in sensitive ecosystems). Governments and NGOs are promoting technological solutions: for instance, Peru's government has discussed using digital traceability to certify regional specialties (e.g. coffee Geographical Indications). One IDB blog highlights that blockchain "allows the digital transfer of product information through the chain, ensuring the traceability of their characteristics at any phase". This observation aligns with our focus: Peru is expanding its capabilities to share data across agribusinesses, which sets a favorable backdrop for blockchain pilots.

Nevertheless, digital adoption faces constraints common to the region. According to IICA/IDB studies, only about one-third of rural Latin Americans have reliable internet access. Many farms lack computers or smartphones, and local technicians are scarce. Cultural factors also matter: some studies note that Latin American farmers may be skeptical of giving up traditional relationships with buyers, especially if they fear the technology could commodify their work. Therefore, the literature suggests that introducing blockchain in Latin American agriculture will require capacity building and policy support, in parallel with technical innovation.

In sum, existing research paints a nuanced picture: the concept of blockchain traceability is seen as highly promising for organic coffee chains, but implementation must account for cooperative structures, local infrastructure, and socio-economic realities. This review informs our methodology and system design by highlighting the key requirements (participation by cooperatives, handling certification data, user interfaces) and potential pitfalls (costs, connectivity, governance).

METHODOLOGY

To design a blockchain-based traceability model for Peruvian organic coffee cooperatives, we employed a design science approach focused on system architecture and stakeholder insights. The methodology consisted of two main phases: (1) requirements elicitation through stakeholder engagement, and (2) conceptual system design.

First, we conducted stakeholder interviews to understand current practices and needs. We engaged with cooperative managers, coffee producers, and certification agents (e.g., organic certifiers) in highland regions such as Cajamarca and San Martín. These semi-structured interviews gathered information on existing data flows, challenges in record-keeping, desired improvements, and technological capacity. Key questions covered how harvest data is currently recorded, how organic status is verified, what devices (if any) farmers use, and which points in the chain suffer most uncertainty. We also discussed potential concerns about blockchain (e.g. data privacy, cost) to ensure our design would address stakeholder priorities.

Second, using the interview insights and literature findings, we modeled a system architecture for the blockchain traceability framework. This involved mapping the main supply chain nodes (smallholder farms, cooperative collection centers, processing mills, exporters, etc.) and identifying where and what data should be captured. We specified the roles of each actor and the information each must record (for example: farm ID, harvest weight, organic certificate number, processing date). We then sketched the blockchain network topology: a permissioned ledger (since cooperatives prefer controlled access) where each cooperative node maintains a copy of the ledger. Smart contracts were conceptually defined to automate verification checks (e.g. validating that each coffee lot has a valid organic certificate before recording).

The design was documented using system diagrams and narrative descriptions. We iteratively refined the model with feedback from stakeholders (e.g. we adjusted the user interface flow after farmers tested a mock-up data-entry form). Our justification for this methodology is that a thorough understanding of end-user context (via interviews) combined with principled system design yields a credible model. It ensures that technical decisions (blockchain permissions, consensus mechanisms, data formats) align with the real-world cooperative environment.

The outcome of this methodology is a detailed conceptual framework for a blockchain-enabled traceability system, which we present in the Results section below. It includes diagrams of data flows and blockchain interactions, illustrating how each supply chain node will contribute to a shared, immutable record of organic coffee production.

RESULTS

We propose a blockchain-based traceability system that integrates seamlessly with the existing organic coffee supply chain (**Figure 2**). The system establishes data capture points at each critical node, linking farmers, cooperatives, processors, and buyers into a unified ledger. Below we describe the main components and workflow of the proposed model:

Each new decision or transaction (here shown as blocks 1–8) is proposed, validated by the network, and appended to a shared ledger. Our model similarly turns each coffee-batch event into an immutable block that all stakeholders can verify (**Figure 1**).

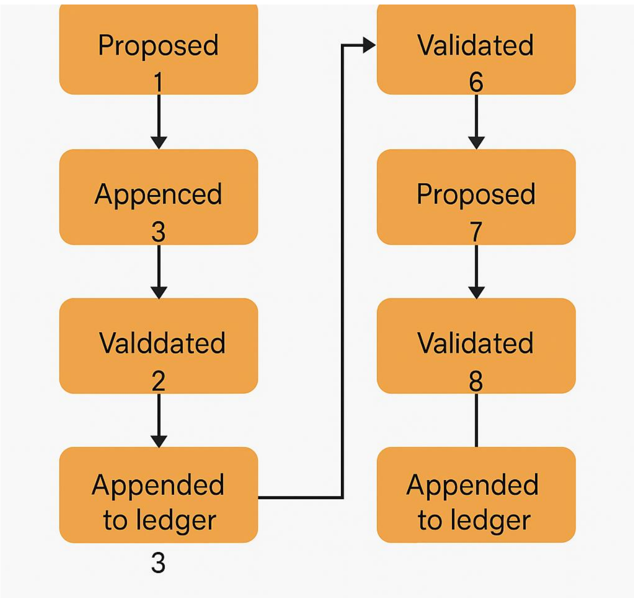

Figure 1. Conceptual Blockchain Traceability Flow (Illustrative)

Farmers – Harvest Registration: Each participating farmer is assigned a unique ID. When a coffee harvest occurs, the farmer (or a cooperative facilitator) records key data: farm location (GPS coordinates or code), harvest date, cherry quantity, and any agrochemical usage. This data entry can be done via a simple mobile app or a shared terminal at the cooperative collection point. Upon submission, this transaction (e.g. "Batch #X harvested by Farm A on [date]") is broadcast to the blockchain network as a pending block.

Cooperative Validation: The cooperative's system nodes receive the pending block and check the data. For example, the cooperative verifies that the farmer is listed as a member and that the organic field status is up-to-date. The cooperative also attaches its digital signature to the block to indicate the batch meets organic criteria. Once consensus is reached among network nodes (a simple majority of cooperative servers), the block is added to the blockchain. The result is an immutable record of the harvest event, timestamped and visible to all network participants.

Processing Facility Recording: After harvest, coffee cherries go to processing (e.g. wet mill or dry mill). The processor logs the processing event on the blockchain: linking it to the original harvest block. For instance, a new block might record that Batch #X was processed at Mill Y on a certain date, along with quality grade notes. This processing block cites the hash of the original harvest block, forming a cryptographic chain. The network validates the processing event similarly before appending it. As a result, the blockchain now shows the farm origin and processing history of each batch.

Certifier and Export: For export, the cooperative or exporter creates blocks documenting certification and shipping. The organic certifier's code or certificate number is included in a block that confirms the batch's compliance. Finally, when coffee is sold or shipped, a transaction is recorded (e.g. exporter ID, destination port, weight, and destination roaster or distributor). Each block continues to link back to the original harvest via previous hashes.

Buyer/Retail Access: End buyers and retailers (and even consumers via QR codes) can access the ledger (or a light client) to trace any lot. The blockchain provides a full provenance: who farmed the coffee, when it was processed, certified, and shipped. Because no block can be altered retroactively, stakeholders are assured of authenticity. If any dispute arises (e.g. a quality claim), the entire history is available for audit.

This flow can be conceptualized in a chart (**Figure 2**, for a simplified flowchart of these steps). In effect, each supply-chain action becomes a new block in the chain, creating a transparent narrative of the coffee's journey. By standardizing the data fields (farm ID, lot number, dates, grades, etc.) and using smart contracts for basic checks (such as verifying that a batch has valid certification before shipping), the system enforces compliance with organic standards automatically.

Figure 2. Proposed Blockchain Supply Chain Flow

Integration with existing systems: The model allows cooperatives to continue using familiar tools where possible. For example, basic ledger data could be integrated with existing ERP systems or with national traceability databases. Smartphones or barcode scanners at collection points ensure that data capture is user-friendly.

Data privacy and access control: Because blockchain entries are encrypted and the network is permissioned, sensitive data (e.g. exact farm coordinates or pricing) can be protected while still allowing verification of key facts. Cooperatives would maintain authority to add new nodes (inviting other cooperatives or certifiers to join the network as needed).

The diagrams above illustrate the high-level architecture. **Figure 2** shows the blockchain interaction process in abstract form. Together, these visuals show how, at each node, data flows into the ledger and how the ledger ensures a tamper-evident history.

Ultimately, the proposed system produces a shared database of traceability events that is significantly more reliable than the prior paper or siloed methods. By modelling this system design, we identify that key benefits (immutable records, network consensus) align closely with the cooperatives' needs, while potential friction points (e.g. requiring network connectivity at collection centers) can be mitigated through targeted solutions (like offline data syncing).

DISCUSSION

Our proposed blockchain traceability model offers clear benefits but also faces significant implementation challenges. Here we discuss feasibility, stakeholder impacts, and how the design addresses identified gaps.

Benefits and opportunities: The immutability and shared visibility of blockchain can greatly increase trust in the organic coffee chain. For farmers and cooperatives, this means their certifications and premiums become indisputable: every batch's origin is verifiable end-to-end. This transparency can justify higher prices on global markets and reduce disputes over quality or provenance. For example, the system would make it impossible to mix conventional beans into an organic lot without detection. It also simplifies auditing: certifiers and regulators can query the blockchain instead of combing through paperwork. In practice, cooperatives could market "certified blockchain-tracked" coffee as a premium product, aligning with consumer demand for traceability. Other potential advantages include faster verification processes (as seen in prior pilots, with 99.9% reduction in trace-generation time) and better co-ordination among cooperative members.

Challenges and barriers: However, several obstacles must be overcome. First, connectivity is a major concern: many highland communities lack reliable internet. Our model anticipates this by allowing asynchronous data entry: farmers could enter harvest data offline and sync it later at a connected hub. Even so, building that infrastructure (e.g. rural Wi-Fi or mobile networks) requires investment. Second, cost is non-trivial. Cooperatives must fund the initial setup of the blockchain network (servers, software development) and ongoing maintenance. Unless costs are shared (for example through government or NGO support) cooperatives may be hesitant. Third, digital literacy and usability are critical: farmers and coop managers may be unfamiliar with new interfaces. The system must therefore be extremely user-friendly, possibly using local language prompts and minimal data input (simple codes instead of long entries). Training programs will be essential.

Institutional challenges: In addition to technical hurdles, institutional trust in the new system must be built. Some cooperative leaders might resist a system they perceive as overly transparent or technically complex. As one study warned, the top-down nature of some blockchain initiatives can concentrate benefits with downstream actors. To address this, our model envisions that cooperatives themselves host the network nodes, ensuring local control over the ledger. Fair governance rules (e.g. shared decision-making on blockchain upgrades) should be established to prevent "data squeeze" by powerful intermediaries. Close alignment with organic certification bodies is also needed so that the blockchain records are legally recognized in compliance processes.

Regulatory alignment: The decentralized nature of blockchain must align with existing regulations. Peru (like many countries) has traceability laws and cooperatives are bound by them. Our system would complement, not replace, official compliance. If regulations change (such as the EU's deforestation rules), the blockchain can be updated to record necessary attributes (e.g. reforestation commitments tied to each lot). However, policymakers will need to endorse the technology (for example, recognizing blockchain records as valid evidence in audits). This may require dialogues between cooperatives, government agencies, and certification bodies.

In terms of addressing traceability gaps, the proposed blockchain model directly targets the pain points identified in the literature. It replaces paper documents with digital records at every step, eliminating the "islands of information" problem. By linking all actors on a single ledger, it re-connects the fragmented chain: data on farming practices is carried forward through milling and shipping. Thus it creates a continuous provenance trail for each coffee batch. The inclusion of certifier signatures on the chain also embeds verification of organic status into the history. In doing so, the blockchain model tackles fraud and information asymmetry – producers can no longer be undervalued due to anonymity, and consumers/inspectors can no longer be deceived by false claims. Overall, this system directly addresses the core transparency issues noted by García et al (Jagtap, Garcia-Garcia, & Rahimifard, 2021).

Farmer and cooperative impacts: For farmers, the model can increase recognition and potentially income. Because each block is credited to a specific farm ID, traceability logs formally document the farmer's contribution. In the past, many farmers felt "anonymous" and thus powerless; the blockchain ensures their work is recorded and visible to buyers. Farmers could also gain better feedback: if quality issues arise downstream, they could trace them back to specific practices on the farm, improving future yields. For cooperatives, blockchain reduces the administrative burden of manual record-keeping. Automated processes (e.g. smart contracts that check organic compliance) cut out steps and errors in paperwork. This efficiency was seen in the FRUCT pilot, which not only sped up traceability but also scored high on usability. In practice, cooperatives might save labor and time, letting them focus more on farmer support and less on documentation.

Adoption strategy: Based on the above, adopting this blockchain system would likely proceed incrementally. We recommend pilot testing in a few cooperatives (for example, in Cajamarca) with external support to cover initial costs. Lessons learned (both technical and social) would inform gradual rollout across other coops. Parallel training programs should be conducted to build trust and skill among farmers. Additionally, partnerships with mobile network providers or solar-powered internet setups could alleviate connectivity issues in remote villages. Finally, cooperatives should engage with international buyers early, as market demand for certified-blockchain coffee could fund and validate the initiative.

CONCLUSION

This study has outlined the rationale and design of a blockchain-based traceability system for organic coffee cooperatives in Peru's highlands. We have shown that Peruvian coffee cooperatives face notable transparency gaps – from fragmented data records to trust deficits – which undermine the value of their organic produce. By drawing on the literature, we demonstrated that blockchain technology, with its immutable ledger and distributed consensus, aligns well with the need for end-to-end traceability. We synthesized insights on traceability requirements, blockchain frameworks, and cooperative structures to propose a comprehensive model: in our design, farmers, cooperatives, processors, and exporters all contribute data to a shared blockchain, creating a verifiable chain of custody for every coffee batch.

The proposed system offers several key benefits. It can dramatically improve the speed and accuracy of traceability, as prior work in Peru showed (>99% time savings in record generation). It makes supply-chain operations more transparent to stakeholders, potentially unlocking higher premiums for certified organic coffee. It also empowers smallholders by formally recognizing their contributions in the global value chain. In terms of implementation, we recommend an approach that engages cooperatives from the outset: using simple mobile interfaces for data entry, providing offline-sync options for rural connectivity, and establishing co-governance of the ledger. Partnerships with government and NGOs could offset initial investment costs and integrate blockchain records with official certification processes.

Future research should validate this model in practice. Pilot projects should be launched in select cooperatives to test technical feasibility and user adoption. These pilots could collect empirical data on benefits (e.g. reduction in audit time, price changes) and challenges (e.g. user error rates, network issues). Beyond coffee, the framework could be adapted to other Peruvian specialties (cocoa, quinoa) that face similar traceability demands. Moreover, integration with other Industry 4.0 tools – such as IoT sensors for real-time farm monitoring or digital payment systems – could further enhance the system's value. In summary, our work provides a foundation for leveraging blockchain to strengthen the sustainability and competitiveness of Peru's organic coffee sector. By addressing traceability gaps, the model holds promise to boost farmers' livelihoods and meet evolving consumer and regulatory expectations.

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