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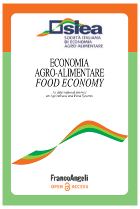

A Proposed Framework for Blockchain Technology in Vietnamese Domestic Pepper Supply Chain Regarding Authenticity and Traceability

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Abstract

In this study, we examined the roles of foreign direct investment (FDI), skilled labour, and technical efficiency in determining the exports of the food and beverage industries in Indonesia. To address this issue, we utilised data from industry micro firms for the period 2010-2015. We applied the maximum likelihood estimation (MLE) technique to the logistic model and the stochastic frontier analysis (SFA). Findings revealed that the food and beverage industries are operating below the possible technical efficiency (TE). However, foreign direct investment, skilled labour, technical efficiency, and industrial concentration assert a significant positive effect on the probability of firms' exports. In the food and beverages sector and the beverages industry, firm size promotes exports; however, in the food industry, firm size has the opposite effect, reducing exports. The imported raw materials have an insignificant effect on the firms' probability of exporting. Interestingly, findings on the mediating roles of technical efficiency and industrial concentration, as well as technical efficiency and firm size, revealed an increasing influence on the probability of exporting. Skilled labour and

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firm size only positively promote exports in the foods and beverages sector and the food industry, but not in the beverages industry. These findings are novel and present an important pathway for policy-making related to the food and beverage industry, potentially shaping future strategies and initiatives in the Indonesian food and beverage sector.

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Introduction

The authenticity and traceability of agricultural and food products are becoming ever more necessary as globalization continues to increase the complexity of food supply chains (Wang *et al.*, 2020). Consumers and food manufacturers face challenges in selecting products that are both healthy and environmentally friendly, while avoiding unsafe or fraudulent food items. Adequate information regarding product brands, authenticity, usage, and preservation is essential.

Using transparency as a foundation, food supply chain traceability enables access to critical and accurate information about the origins and quality of products at any point in the supply chain. However, traditional traceability methods are mostly administrative and lack the use of chemical or biological analytical tools, which limits their reliability (Espiñeira & Santaclara, 2016). Although they allow for tracking product history, they fall short in establishing consumer trust due to the lack of transparency. Therefore, improving traceability systems to ensure both trust and authenticity is increasingly vital in the modern food economy.

1. Background

1.1. *Traceability in food supply chain*

Today, a lot of approaches have been developed and already applied for food supply chain traceability, ranging from simple methods such as traditional paper-based ones to advanced and innovative technologies (Olsen & Borit, 2018). However, less developed and/or even developing countries tend to prefer choosing traditional ones i.e. recording by paper documents rather than using cutting-edge techniques i.e. digital technology to perform traceability in the food supply chain (Islam & Cullen, 2021). Most of Vietnamese farmers are not familiar even with recording documents and exchanging them with wholesalers and/or traders who will buy their products.

This makes it difficult for them to participate in a complex computer or handphone-based system except pepper product companies that have their own farm or under their quality control (Pham & Dinh, 2020). Additionally, few applications have been developed specifically for food traceability since companies prefer to use their internal integrated information system to avoid overspending on an additional fee for external IT systems.

1.2. *Blockchain applications in food traceability*

Blockchain technology has been used to allow traders, retailers and consumers to trace and track the provenance of food products from their origins to stores and restaurants (Ellahi *et al.*, 2024). As a new trend, blockchain technology has much potential to become a realistic technological option to address the challenge of mining and managing information across the food supply chain. A blockchain is a decentralized, distributed, and oftentimes public, digital ledger consisting of records called blocks that are used to record transactions across many computers so that any involved block cannot be altered retroactively, without the alteration of all subsequent blocks (Iansiti & Lakhani, 2017). Blockchain technology can be characterized through five principles: security, peer-to-peer transmission, transparency with pseudonymity, irreversibility of records and computational logic (Andoni *et al.*, 2019; Schiller, 2017).

The first blockchain system applied to food supply chain was developed by Walmart and IBM company. They were running a trial to use a blockchain-backed system for supply chain monitoring for lettuce and spinach – all nodes of the blockchain were administered by Walmart and were located on the IBM cloud (Corkery & Popper, 2018). The results show that one cited benefit is that the system could enable the rapid tracing of contaminated food produce. Some analysts are less convinced that most consumers will be that interested in this traceability system (Gstettner, 2019).

The systems are purely a ‘supply chain’ with information being tracked far beyond the origin and quality of the product, including farming and processing parameters, shipping details, and more. The Internet of Things (IoT) has also been integrated into the blockchain to improve the efficiency of the food traceability system in the hope of building an open and comprehensive network of devices capable of organizing and self-organizing transparent data and resource sharing (Feng Tian, 2016; Madakam *et al.*, 2015). However, there are inherent limitations to the adoption of blockchain in food traceability (Cao *et al.*, 2023). For blockchain to work effectively, all parties and stakeholders must be involved. In addition, the integrity of the data is under the control of the data collector, and an authentication system is required to prevent tampering (Li *et al.*, 2025). The lack of a unified system with clear standards and regulations is a major impediment to adoption (Feng Tian, 2016; Gstettner, 2019). Chemical and biological data of agricultural and food products are valuable information that should be integrated into the blockchain system to avoid human error and interference i.e. administrative information, information assigned to food objects by collectors' purpose. Moreover, as highlighted by recent studies, many misconceptions about the properties of blockchain in the agrifood sector persist, and its successful application requires careful design and governance. For blockchain-based traceability systems to be effective, structural and technological mechanisms such as consistency checking via smart contracts and frameworks for auditing and reliability assessment are essential prerequisites for collaborative blockchain data management (Rampone *et al.*, 2023).

Based on blockchain technology, the consumers and clients can trace and track the origin and journey of products, giving them trustworthy information about how the products were made, transported, and distributed to them (Ellahi *et al.*, 2024). All the information is totally transparent, therefore, blockchain traceability is the ideal tool for gaining consumers' trust in the brands (Dutta *et al.*, 2020). Blockchain is a novel technology that has been gaining a lot of attention and is expected to become the one transforming businesses across different industries including food sectors (Iftekhar *et al.*, 2020; Lukacs *et al.*, 2025). In addition to blockchain technology, various analytical techniques can support food traceability systems. These include mass spectrometry, spectroscopic techniques, and separation techniques that enable the determination of food provenance (Esposito & Pezzolato, 2023). Such analytical methods provide an independent means of verifying traceability systems and help prove food product authenticity (Dou *et al.*, 2023). They also combat fraudulent practices and control adulteration, which are important issues for economic, religious, or cultural reasons.

1.3. *Vietnamese black pepper sector*

Pepper is one of six agricultural products of Vietnam with an export turnover of over USD 650 million per annum capable of competing in the international market. Annually, the pepper output reaches 240,000-300,000 tons, of which 95% of pepper is exported into foreign markets. According to preliminary data reported by the General Department of Vietnam Customs, pepper exports in 2020 reached 288,000 tons of all kinds of pepper. In September 2021, exports reached 15,336 tons of all kinds of pepper, down 2,300 tons, or 13.04 percent down from the previous month and down 2,916 tons, which is a decrease of 19.12% over the same period last year (Vietnam

Trade Promotion Agency Export Promotion Centre, 2020). Vietnamese pepper is widely known in the international market with big brand names such as Vĩnh Linh, Chu Se and Phu Quoc pepper. Vietnam pepper is exported to some major markets such as the USA, German, the Netherlands, India, Singapore, Russia and the Middle East. Like pepper of other exporters, Vietnamese pepper is divided into two types: black and white, of which black pepper accounts for 90% (Economy, 2024). Aiming at keeping the first export position in the world pepper market, Vietnam is actively speeding up the implementation of "cooperation between 4 parties" (Government, Entrepreneur, Farmer, and Scientist) in order to invest and transfer technology of pepper processing to the farmer, enhancing the productivity and quality for products with competitive price (Ly, 2024). In addition, the authenticity and traceability system is really concerning to ensure the Vietnamese pepper brands due to a lot of competition among pepper exporting countries in the region.

Although numerous studies have highlighted the potential of blockchain in food traceability, most existing research has focused on globally traded sectors such as fruits, meat, or seafood (Cao *et al.*, 2023; Ellahi *et al.*, 2024). Evidence from developing countries is still limited, especially where farmers have low digital skills and data systems are not well connected (Islam & Cullen, 2021). For Vietnam's pepper industry, which is a key export but faces problems of quality and authenticity, there are almost no studies on how to apply blockchain effectively. In particular, no research has proposed a model that combines administrative data with chemical and biological data to make traceability more transparent and reliable. This gap shows the need for a new framework that fits the reality of Vietnamese pepper production and also meets international market requirements.

Based on the administrative as well as chemical and biological data gathered from multiple sources and the analysis of a case study, a research is conducted in Vietnam pepper chain with the aim at answering the research question: *How can blockchain resolve to address the traceability and authenticity issues in Vietnamese domestic pepper sector?* The paper will share the findings from the study and propose a new framework using blockchain to improve the traceability as well as authenticity including classify the quality grade of pepper products.

2. Research Methodology

2.1. *Development of traceability framework*

In this research, we identified the potential roles of blockchain technology integrated with rapid analysis instruments, specifically near infrared spectroscopy (NIR), and their ability to be applied to traceability and authenticity systems in Vietnam's domestic pepper sector. The framework was designed through literature review, stakeholder consultation, and process mapping. It includes three layers: (i) data capture (farming logs, harvest, processing, transport, NIR results), (ii) analysis (NIR spectral processing and authenticity classification), and (iii) ledger (a permissioned blockchain to securely record events and generate QR codes for consumer trace-back).

2.2. *Data information and research questions*

Data were collected from multiple sources, including farmer and processor records, pepper samples, NIR measurements, transaction logs from the pilot blockchain system, and stakeholder interviews. The information and data analyses will serve as a foundation to propose a framework that is expected to answer the research question: *How can blockchain technology integrated with NIR be used to address the traceability and authenticity issues in Vietnamese domestic pepper sector?*

2.3. *Pilot project*

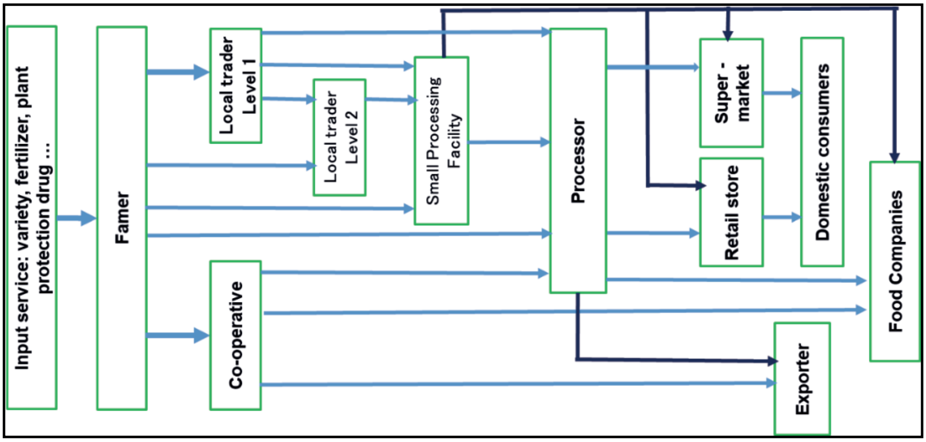
The pilot project implemented the proposed framework in Quảng Trị province. Agricultural logs, harvest activities, processing steps, and transport events were systematically recorded on a blockchain platform. Each transaction was linked with corresponding NIR results for authenticity verification. A QR code label was issued for selected batches, enabling end-to-end traceability demonstration from farm to market. The pilot also tested user adoption and system usability among local stakeholders.

3. Results

3.1. *Vietnamese pepper supply chain*

The Vietnamese domestic pepper supply chain management follows a multi-stage supply chain system consisting of farmers, co-operative and/or local traders level 1, local traders level 2, small processing facilities, pepper processing companies, supermarkets and retailers, and exporters [18]. Figure 1 illustrates in detail the multiple stages involved in the pepper supply chain and their functioning. The primary stage of the pepper supply chain begins with farmers. After pre-processing steps such as cleaning and drying, dry pepper is sold to local trader level 1. The remaining is sold to local trader level 2 and/or small processing facilities or directly to processing companies, either with or without intermediaries. The route depends on factors such as productivity, type of farmers (e.g., large or small landholders), and the capability of their business operations. At the processor stage, pepper is processed undergoes further processing such as re-drying, classifying quality grade, mixing, and storing. After processing, pepper processors sell their products to domestic customers such as retail stores, supermarkets, food companies, and export companies. Other actors in the supply chain sell to retail stores and supermarkets, which in turn sell to domestic consumers. Food companies may purchase pepper from co-operatives or directly from processors. In this supply chain, small processing facilities can also sell their products to retail stores, supermarkets, and food companies.

Figure 1 - Vietnamese domestic pepper supply chain[18]

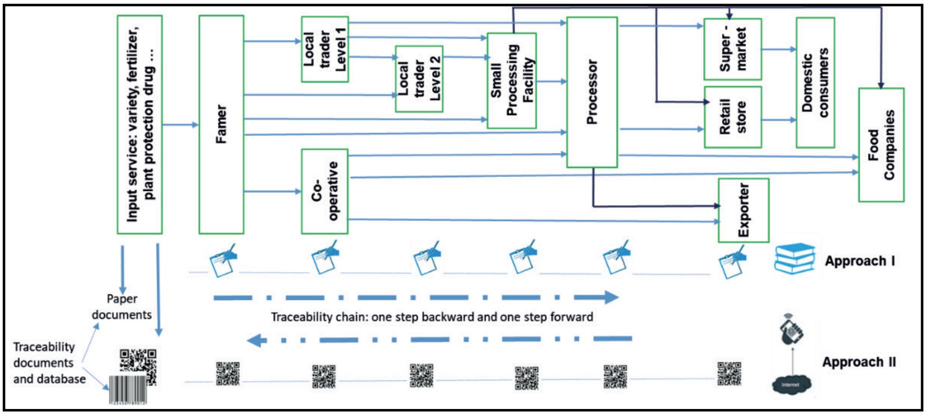


There are generally at least five or six supply chain agents between the farm-gate and the consumer or clients. Compared to supply chains of other agricultural commodities in Vietnam and to pepper supply chains in leading producer countries such as Brazil and India, the Vietnamese model is considerably longer and more fragmented. This extended structure results in several key limitations. First, the length of the chain leads to higher transaction costs, longer lead times, and reduced transparency, making it difficult to trace product origin and ensure consistent quality. Second, weak vertical coordination among actors especially between producers and downstream buyers limits information sharing, price transmission, and incentives for quality improvement. Third, information asymmetry is common, with farmers lacking access to market data, export standards, and demand trends, thereby hindering their ability to adapt production practices effectively. Fourth, the adoption of modern technologies, such as digital traceability systems or logistics optimization tools, remains limited at the farm and early trade levels, reducing overall supply chain efficiency. Finally, the distribution of value along the chain is highly unequal; smallholder farmers, who bear much of the production risk, often receive only a small portion of the final market value. These structural inefficiencies pose significant challenges to the competitiveness and sustainability of Vietnam's pepper industry in the global market.

3.2. *Traditional traceability model*

A traditional pepper traceability system can record the whole circulation process of pepper, from planting, production, processing, warehousing, and to use by consumers (Figure 2). If fraudulent or unsafe pepper is discovered, it can be traced back to its source. However, paper-based traceability is time-consuming, especially when responding to information requests from consumers or clients. Although QR codes or barcodes have been introduced into IT systems to partially digitize traceability, these improvements are still limited in scope. Data in these systems is often manually input, lacks standardized formatting, and is centrally managed, making it vulnerable to

Figure 2 - Traditional traceability model in the Vietnamese domestic pepper supply chain



human error, tampering, or information loss. Moreover, traditional systems do not provide transparency across the entire supply chain, as consumers are typically granted access only to basic or limited details about the product. These systems also cannot confirm if a product is real or fake because they do not use scientific tests, like chemical or biological analysis.

The blockchain-based model proposed in this paper effectively addresses these shortcomings. It creates a decentralized and immutable ledger where all stakeholders in the supply chain directly enter and verify data through cryptographic mechanisms and smart contracts. Every transaction or change is traceable and cannot be altered retroactively, ensuring the integrity of information.

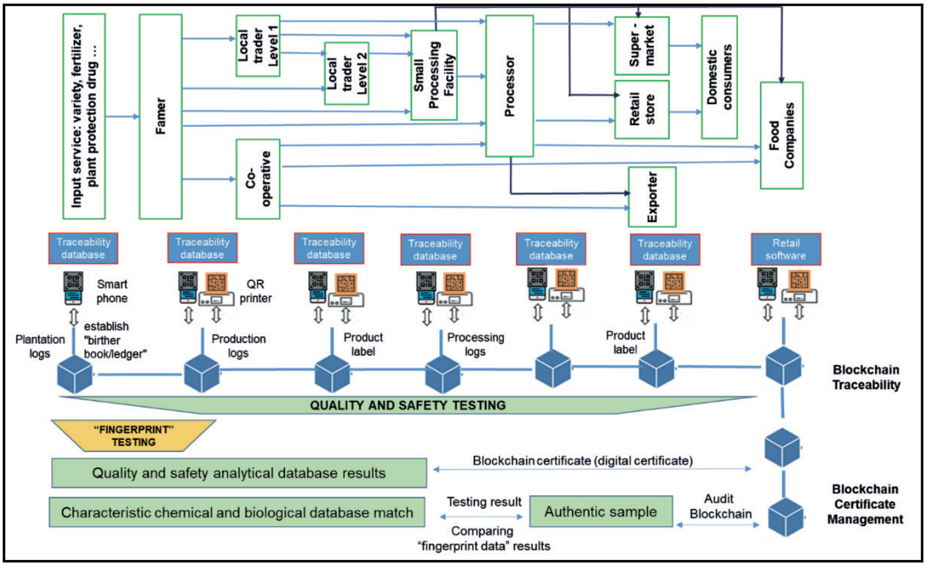
3.3. *Proposed Framework for Traceability and Authenticity System*

3.3.1. Overview of the Proposed Framework

At least two approaches have been developed and already applied for pepper supply chain traceability in Vietnam, ranging from simple methods such as traditional paper-based ones (approach I) to sophisticated technologies (approach II) such as using barcodes or QR codes for recording traceability database. We proposed a new framework for traceability as shown in Figure 3 for the Vietnamese domestic pepper supply chain, making use of blockchain, IoT and smart contracts. The traceability database includes not only administrative data and processing parameters but also data collected from multiple sources using analytical techniques -for example, characteristic chemical and biological data of pepper samples. Each technology has its benefits and limitations and ultimately no individual technology can single-handedly address all the issues surrounding authenticity, provenance and traceability. Therefore, we proposed propose that adopting a framework that integrates multiple technologies into a combined proactive solution could be the key to ensure authenticity, traceability and provenance of pepper products.

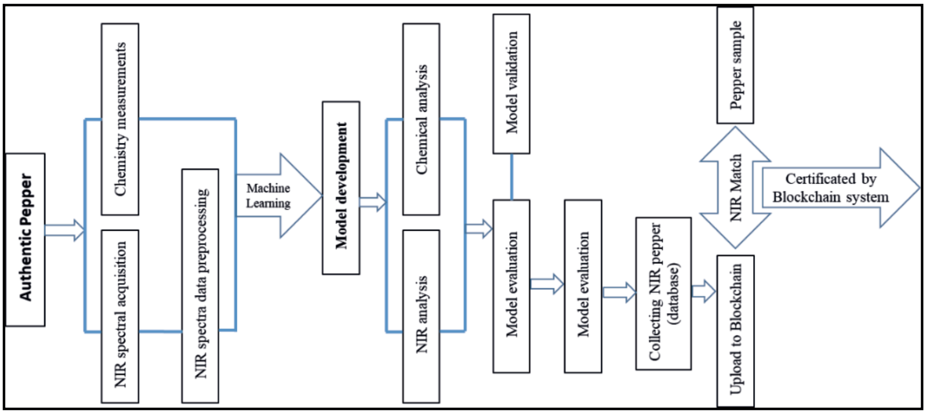
In this traceability system, all supply chain members mentioned in Figure 3, should have to register and provide the administrative information, production/processing parameters by themselves into the system, and match their unique identities and digital profiles stored in the blockchain system. The characteristic chemical and biological data of pepper such as essential oil, piperine, ash, fatty acid content, and DNA were studied and provided by independent analytical laboratories. Characteristic chemical data of authentic pepper from different origin regions were analyzed by spectrometric techniques i.e, such as near infrared spectroscopy (NIRS).

Figure 3 - Propose framework for a blockchain traceability system for pepper supply chain



Machine learning algorithms were used to build a predictive model based on collected 'training data' in order to determine the origin and quality of pepper samples (Figure 4).

Figure 4 - Schematic representation of the procedure for NIR spectroscopy integrated to blockchain



3.3.2. Technical Integration Architecture

The proposed system integrates various technologies into a unified framework to ensure real-time data capture, decentralized verification, and end-to-end transparency across the pepper supply chain. In addition to basic administrative data, supplementary information such as time-lapse footage from digital cameras, weather conditions, and GPS coordinates of farms is continuously collected and uploaded to the blockchain.

The architecture comprises four key technical components. First, **IoT devices and sensors** are deployed at the farm level to monitor environmental parameters (e.g., temperature, humidity, and location) and to capture visual records throughout the cultivation process. This data is transmitted via mobile networks or Wi-Fi to a centralized cloud gateway. Second, **NIR spectroscopy instruments** are used by local traders and processors to rapidly analyze the chemical composition of pepper samples. The resulting spectra are digitized and integrated into the blockchain through dedicated APIs. Third, a **permissioned blockchain ledger** (e.g., Hyperledger Fabric or Ethereum private network) securely stores all hashed data entries submitted by stakeholders along the supply chain, with access and authentication managed through digital signatures and private keys. Finally, **smart contracts** are used to automate transactions between parties, validating criteria such as product weight, moisture content, and chemical parameters before approving data submission or product transfer. Together, these components form a robust and transparent infrastructure that enhances trust and efficiency throughout the pepper supply chain.

3.3.3. Application Across the Supply Chain Stages

The blockchain-based traceability system can be explained in four main stages of a pepper supply chain, namely 1) Farmer: Plantation/At the farm; 2) Intermediaries trader: Procurement/local trader and co-operative; 3) Processing plant: small processing facility and processor; 4) Distribution and consumer/clients: retail store, supermarket and exporter;and at the food factories.

a. Stage 1 – Farmers: Plantation and Production

At the farm level, data about pepper cultivation is recorded using mobile applications and digital cameras. Time-lapse videos document the entire growing process, while farmers input information such as planting date, seed type, fertilizers, and pesticide usage. These records are cross-checked with national standards or certification schemes such as Good Agricultural Practices (GAP) or Organic standards.

After harvesting, the pepper is cleaned, dried to a moisture content of 12–13%, and packed in bags. Each bag is labeled with a QR code or RFID tag containing a unique digital identity. This identity links to a blockchain profile that stores key information including soil and weather conditions, crop variety, planting and harvesting times, GPS location of the farm, and the farmer's personal information. Once the product is ready, a digital smart contract is created for the transaction between the farmer and the next supply chain actor, such as a trader or processor. This contract ensures transparency and automatically logs the product's transfer on the blockchain.

b. Stage 2 – Intermediaries: Traders and Co-operatives

When the pepper arrives at a trader's or cooperative's warehouse, workers scan the product tag to access the data previously uploaded by the farmer. This allows them to verify the origin and production details before accepting the shipment. Information about the trader, warehouse conditions, time of receipt, and product quantity is then added to the blockchain.

To ensure quality and safety, the pepper may undergo rapid testing using Near-Infrared (NIR) spectroscopy, and the analysis results are recorded on the system. Time-lapse cameras may continue to monitor storage conditions. If any issues are found, the data can be traced back to the farm instantly, and corrective actions can be taken quickly. This stage ensures that the product's journey is transparent and verifiable from its origin.

c. Stage 3 – Processors: Small Facilities and Processing Companies

After receiving the pepper, the processor will re-dry it if necessary, classify it by quality grade, mix the batches, and store the product. Information regarding all processing steps is stored on digital product records and updated on the blockchain. At this time, the quality and safety of pepper are also analyzed by the NIR instrument and updated in the blockchain. A time-lapse movie of the entire process will also be recorded. In addition, processing companies will enable QR codes with data such as identifiers, GPS or GLN (Global Location Number), administrative information, etc.

d. Stage 4 – Distribution and Consumers: Retailers, Supermarkets, Exporters

When processed pepper is sent to retailers, supermarkets, exporters, or food factories, each shipment's data continues to be updated on the blockchain. This includes logistics details, storage conditions, and delivery information. Retailers or exporters can scan the QR code on each package to view the full product history.

Consumers – whether domestic buyers or international importers – can access this information by scanning the QR code with a smartphone app. They are directed to a webpage that displays the product's origin, farming and processing standards, transportation details, and even time-lapse videos or lab test results if available.

They will be redirected to a web page with information that answers the following questions about a particular pepper product:

- What farm did the pepper used in this product come from? What agricultural standards (e.g., GAP, Organic, National Standards) were followed during cultivation?
- When and where was the product produced? What processing steps were followed, and how did the product reach its destination? What is the assessed quality of the product? What food safety standards (e.g., ISO, Organic) were followed during processing?
- When did this product arrive at the retailer, supermarket, or exporter, and when did it appear on the shelf or in the warehouse? In addition, consumers and food factories can access time-lapse videos and detailed chemical and biological analyses of the product on this webpage.

However, in fact, in the Vietnamese domestic market, the small retail model is still very popular next to supermarkets, convenience stores, and retailers. These small grocers cannot afford standard technology systems, even POS systems that scan QR codes on purchased products to update their status; while smartphones have become very popular gadgets. As a result, this feature is currently impractical for the entire domestic pepper supply chain. However, it is well-suited for export markets, where importers may require full traceability – especially during disruptions such as the COVID-19 pandemic. If scanning systems and digital infrastructure become standardized across the food sector, this model could eventually be expanded to apply to not only pepper but also other food supply chains and consumer products.

3.4. *Empirical Validation and Initial Implementation Results*

To evaluate the feasibility and effectiveness of the proposed blockchain-based traceability framework, a pilot implementation was carried out in collaboration with a pepper cooperative in Vinh Linh district, Quang Tri province, one of the major pepper-producing regions in Vietnam.

Figure 5 shows the automated blockchain data registration module, where each transaction is digitally signed and permanently recorded. Smart contracts validate each step automatically.

Additionally, Figure 6 presents the user log management interface, which helps supervisors monitor who entered what data and when ensuring traceability and accountability in human data input.

Figure 5 - Blockchain transaction logging and validation interface

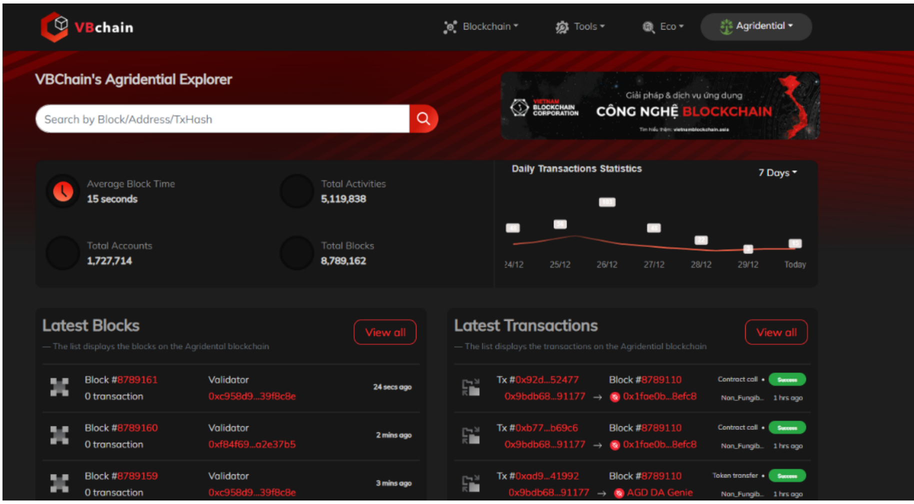


Figure 6 - Data transparency and personnel accountability screen

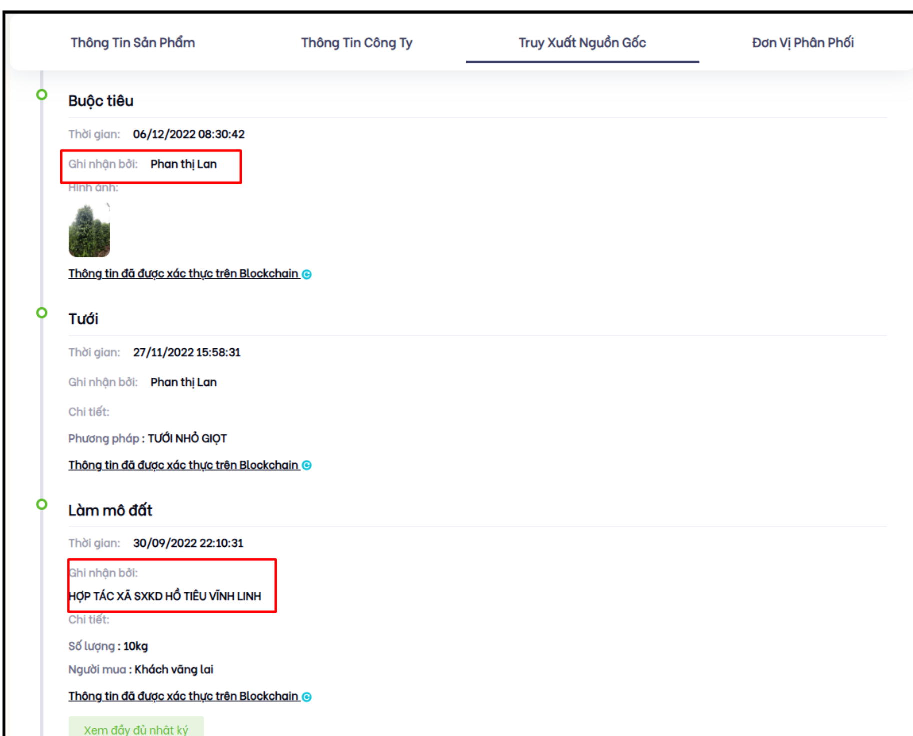
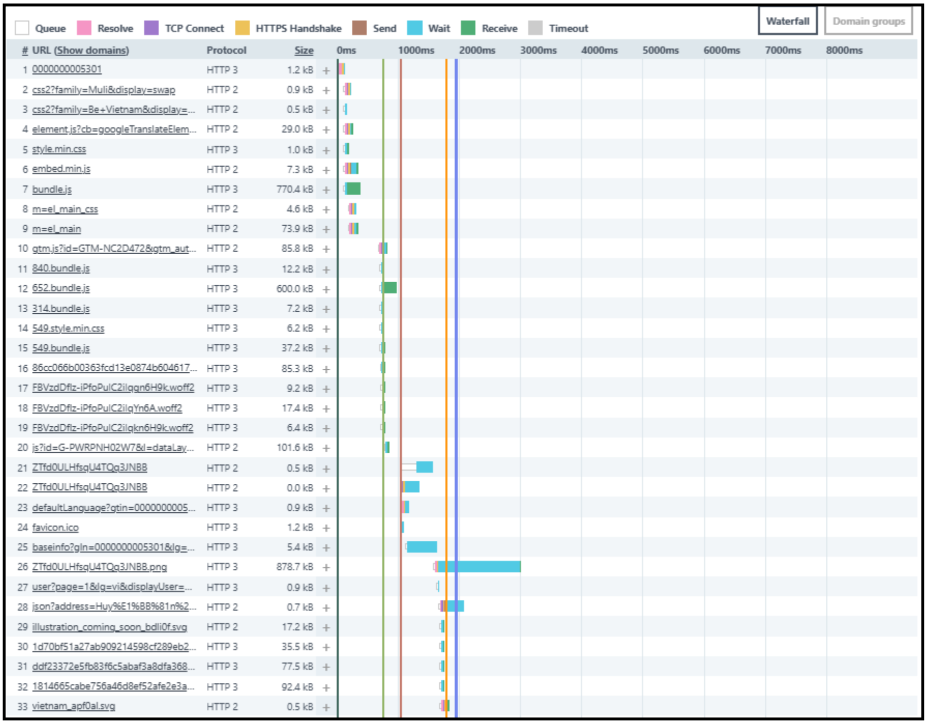


Figure 7 - Test results of the product traceability research site



The pilot system demonstrated strong performance and reliability, achieving an average transaction throughput of 520 tps, with a maximum of 1000 tps, a transaction confirmation time of 1.5 seconds, and synchronization latency of less than 3 seconds. During the testing phase, no occurrence of transaction failures was documented. Beyond its performance, the implementation ensured high security with no detected vulnerabilities, accurate and instant synchronization of records across the blockchain, and compatibility with existing devices and software. The framework demonstrated scalability and extensibility, exhibiting the capacity to accommodate elevated transaction volumes without compromising efficiency.

Building on the pilot results, the study compares traditional and blockchain-based traceability. In Vietnam, traditional systems are centralized and paper-based. They depend on intermediaries and fragmented manual records. Transparency is limited, and a traceability request may take 48-72 hours to process. These weaknesses reduce both efficiency and data reliability. Blockchain offers a different approach. It uses a decentralized and immutable ledger that enables near real-time traceability. The system improves transparency, builds consumer trust, and connects multiple stakeholders. Compared with conventional methods, blockchain requires higher initial investment, mainly related to server setup and ongoing system maintenance. Over time, however, it reduces redundant verification and increases confidence in product information. More data and longer trials are still needed to validate the model and support further research. Even so, blockchain-based traceability is particularly relevant for enterprises seeking access to high-demand export markets such as the European Union and the United States.

These results strongly demonstrate the framework's readiness for practical deployment across both domestic and export-focused pepper supply chains. Future development will focus on enhancing system intelligence through AI-powered data analytics for real-time quality prediction, fraud detection, and supply chain optimization. Additionally, the platform will be extended with multilingual user interfaces to support ethnic minorities and international stakeholders, as well as integration with national certification databases (e.g., VietGAP, Organic Vietnam) to ensure seamless compliance verification. The long-term vision is to evolve this framework into a modular, open-source platform that can be adapted for traceability in other key Vietnamese agricultural products such as coffee, rice, and cashew nuts.

Conclusion

In this paper, a framework for a blockchain system was proposed, designed to ensure traceability and authenticity within the Vietnamese domestic pepper supply chain. Employing this system in the pepper supply chain offers several benefits: it ensures integral traceability and authenticity, fights fraud, and minimizes system errors. Beyond transaction records, the framework also integrates supplementary data such as time-lapse videos and chemical or biological analyses, which further enhance product verification. The novelty of this study lies in introducing one of the first blockchain-based models specifically designed for the Vietnamese pepper industry, with the unique integration of chemical, biological, and multimedia data. Nonetheless, the framework remains conceptual, and its implementation may face challenges, including high infrastructure costs, limited digital literacy among farmers, and scalability issues across larger supply networks.

Another benefit of blockchain is the elimination of human errors such as those made by farmers, traders and conventional pepper producers in Vietnam in the circulation of pepper. Consumers and clients now have reliable support tools to prove the traceability and authenticity of pepper products, especially black pepper products with high commercial value, to regain their confidence. With sensors, digital cameras, analytical equipments and smart contracts are integrated into the system, businesses can save significant time and costs for human resources or intermediaries to control the quality, safety and traceability of their products. Furthermore, processors can be more assured that the standard procedures will be strictly followed by farmers or producers since this traceability system can trace back to a particular batch of pepper to its originating farm.

Regarding administrative management, the government can rely on the proposed traceability solution. This transparent, convenient, and, more importantly, realistic system can address pepper safety issues and fraud with limited risks of human error and tampering during information exchange, which is particularly crucial as competition in the pepper market increases among pepper-exporting countries. Future work will focus on implementing pilot projects and developing advanced technologies such as IoT and AI to enhance real-time monitoring, anomaly detection, and data integration. In addition, future studies should conduct a deeper comparison between the costs and benefits of traditional manual practices and the adoption of the proposed blockchain-based system, thereby providing more practical insights for stakeholder.

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