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REGULAR ARTICLE

Traceability in the supply chain of specialty coffee small producers through QR technology in Colombia

Helmer Paz-Orozco[1,2]; Isabela Antunes de Souza Lima[3]; Yesid Anacona-Mopan[1], Irineu de Brito Junior[3], Ana Luna[4], Mario Chong[4*]

[1]Corporación Universitaria Comfacauca, Cauca, Colombia.
[2]Universidad Nacional Abierta y a Distancia, Cauca, Colombia.
[3]São Paulo State University, São Paulo, Brazil.
[4]Universidad del Pacífico, Lima, Peru.

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Abstract

The global coffee industry faces pressing sustainability challenges, including volatile market prices, low wages, labor shortages, and limited technological adoption, which threaten the viability of small producers, especially in Colombia. In this context, ensuring traceability in the coffee supply chain emerges as a crucial strategy to promote transparency, fairness, and sustainability. This study aims to develop and test a cloud-based traceability system utilizing QR codes in the Colombian specialty coffee supply chain, with a focus on its implementation process and practical implications for small-scale producers. To achieve this, the research adopts a case study methodology, combining direct observations and interviews with nine smallholder coffee producers in Cauca. A cloud-based traceability tool was developed and tested to track the movement of coffee lots along the supply chain, from farmers to consumers. The results demonstrate that the system enhances data entry accuracy, facilitates real-time access to information, and fosters trust among stakeholders. Moreover, it facilitates the documentation of product origin, quality, and sustainability attributes, reducing risks of fraud and improving market access for producers. The study concludes that QR-based traceability is a cost-effective and scalable solution for small-scale producers, contributing to more sustainable and transparent agri-food supply chains.

Keywords

Digital Traceability; QR Code Technology; Cloud Technology; Coffee Supply Chain; Sustainable Supply Chain.

Introduction

The global coffee industry is facing increasing scrutiny for its sustainability performance due to challenges such as volatile market prices, labor shortages, low wages, and insufficient technological investment. These structural problems compromise the economic viability of coffee cultivation, especially for smallholder farmers in developing countries (Dietz et al., 2018; Kath et al., 2020). Colombia, as one of the world's leading coffee producers, is particularly vulnerable to these dynamics. Coffee plays a pivotal role in the country's rural economy, generating over 631,000 jobs annually and supporting approximately 60% of the rural population (Anacona-Mopan et al., 2024; Bettín-Díaz et al., 2022; Trollman et al., 2022).

Despite its importance, the Colombian coffee sector continues to experience persistent inequities in value distribution. Producers receive a minimal portion of the final product's revenue, while consumer countries concentrate the added value through branding, roasting, and retail (Ponte, 2002). This situation places coffee growers in a position of economic and social vulnerability. Moreover, market instability exacerbates their precarity; for instance, the average price of Arabica coffee futures reached USD 1.85 per pound in March 2024, influenced by climate variability and exchange rate fluctuations (ICO, 2025).

These challenges are further intensified by the growing complexity of global supply chains, which involve multiple actors, from farmers and cooperatives to exporters, roasters, and retailers. Managing these networks efficiently and transparently has become critical to ensuring quality, authenticity, and competitiveness (Dannoun, 2022). In this context, traceability systems emerge as key tools to enhance transparency, optimize operations, and strengthen trust across the supply chain (Aung & Chang, 2014; Ma et al., 2022).

For specialty coffee in particular, traceability is not only a commercial advantage but a requirement to meet consumer expectations regarding quality, origin, and ethical production practices. Detailed information on origin, processing methods, and sustainability attributes enhance consumer engagement, enabling producers to capture added value. However, collecting and managing such data remains a significant challenge in the Colombian context, where agricultural operations are predominantly manual and rely on producers' experience (de Assumpção et al., 2025; Dionysis et al., 2022).

Moreover, the absence of robust traceability mechanisms creates opportunities for fraud, such as mislabeling non-origin coffees as premium specialty products. These practices

*Corresponding authors
E-mail address: m.chong@up.edu.pe

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undermine market integrity and reduce incentives for producers to invest in quality and sustainable practices. In this scenario, implementing digital traceability tools that enable real-time, verifiable tracking of coffee lots becomes essential to ensuring fair trade and promoting social and economic sustainability in coffee-producing regions (Cortés et al., 2019; Saberi et al., 2019).

Although digital technologies such as blockchain, RFID, and QR codes are increasingly being explored for traceability, many existing systems remain difficult to implement in practice, especially in regions with limited infrastructure or technical capacity (Karlsen et al., 2013). QR code-based systems, when combined with cloud technology and mobile devices, represent a low-cost and scalable alternative for data management and traceability, particularly suited for smallholder contexts (Kim & Woo, 2016; Shou et al., 2021).

In Colombia, most small coffee producers lack access to advanced digital tools or integrated systems to manage supply chain data. Nonetheless, initiatives that simplify technological adoption and integrate local practices may provide opportunities to enhance the visibility and value of their products. By enabling direct communication between producers and consumers, traceability systems can facilitate fairer value distribution, enhance market access, and promote social equity throughout the supply chain.

The present study focuses on the economic and social dimensions of sustainability, particularly on transparency, producer income, and market fairness. While environmental aspects are relevant in the broader discussion, they are not the primary focus of this investigation. This approach aligns with global sustainability goals, especially SDG 12 (Responsible Consumption and Production), which encourages traceable and ethical supply chains, and SDG 8 (Decent Work and Economic Growth), which emphasizes fair remuneration and inclusive market participation.

Given this context, this study aims to develop and test a cloud-based traceability system utilizing QR codes in the Colombian specialty coffee supply chain, with a focus on its implementation process and practical implications for small producers. A case study methodology was employed, involving direct observation and interviews with smallholder producers in the Cauca department. The project involved the pilot testing of a digital tool that enabled data capture along the entire supply chain, from the farmer to the final consumer.

By analyzing the tool's application in a real-world setting, this study contributes to both academic and practical discussions on how digital traceability can enhance transparency, promote fair trade, and improve supply chain governance. Additionally, it provides insights into the barriers and opportunities for small producers in adopting such technologies, highlighting lessons that can inform broader efforts to promote sustainability in agri-food systems.

For many years, traceability in the food supply chain has been achieved through enterprise resource planning systems that enable the connection between supply chain data and business processes. However, these systems are costly and unsuitable in an ever-changing global supply chain with multiple stakeholders. Achieving traceability in the supply chain of origin products requires a solid understanding of the key concepts. In this context, an overview of traceability in the supply chain and coffee supply chains will be briefly presented (Crockett et al., 2018; Hassoun et al., 2024).

Traceability in the supply chain

The importance of traceability systems in promoting sustainability has been widely discussed in the literature, particularly with their ability to increase accountability and reduce fraud in supply chains (Bager & Lambin, 2020). QR codes, RFID, and blockchain-based solutions have been explored in various industries, yet their application in specialty coffee supply chains remains underdeveloped (Mejías et al., 2019).

Additionally, traceability systems enable producers to meet the growing consumer demand for ethically sourced products, strengthening their market position and financial resilience (Dietz et al., 2018). As consumers become increasingly aware of the social and environmental implications of their purchasing decisions, traceability systems serve as a strategic tool for reinforcing trust and transparency in supply chains.

Considering the importance of developing traceability systems for food products, several efforts have been presented in the literature, highlighting QR code technology as a high-performance and low-cost alternative for food product traceability. For instance, traceability models for vegetables have employed QR codes as information carriers to monitor cultivation, storage, processing, and transportation, while web services technology was used for information exchange (Ligar et al., 2022; Shuyi Qiao et al., 2013).

Similarly, RFID has proven effective in enhancing traceability. RFID tags have been applied to fruit products, and when integrated with personal digital assistant devices, have created a semi-automated traceability platform that significantly reduces the time needed for data analysis and management. RFID technology has also demonstrated positive results within the live fish supply chain. RFID technology has also been used with QR codes to enhance the identification and registration of logistical information on wheat flour packages, as well as facilitate information exchange within packaged food supply chains (Gandino et al., 2009; Li et al., 2017; Yu-Chia Hsu et al., 2008).

Despite the growing interest in fresh produce traceability systems, integrated IoT-based solutions remain scarce and are still in the relatively early stages of development (Anagnostis et al., 2020). Despite this, various sensor technologies incorporated into IoT systems support every stage of the food supply chain, providing a more effective way to record and exchange useful information. These technologies include, for example, barcodes, RFID, QR codes, and wireless sensor networks (WSN) (Demestichas et al., 2020).

On the other hand, cloud technologies can contribute to the better identification, location, and tracking of product status in real-time. Statistical analysis techniques can be contrasted with data from publicly available reports, such as those provided by Google and Apple. This can streamline the retrieval, analysis, storage, and connectivity of valuable data throughout the supply chain, which is crucial for the traceability of perishable products to ensure compliance with safety standards (Solis Pino et al., 2022; Verdouw et al., 2016).

Lastly, a proposed Food Trade System using Consortium Blockchain (FTSCON) is proposed to enhance transaction security and trust. The findings indicated that while the system could boost traders' profits, its real-world implementation is challenging without adequate technological infrastructure. also developed a blockchain-centric agricultural supply chain system based on a dual-chain architecture: a “user information chain” and a “transaction chain.” This architecture proved to have the potential to significantly improve the platform's reliability and the system's overall efficiency (Mao et al., 2019).

As digital traceability solutions evolve, technologies such as blockchain and IoT have been increasingly adopted to enhance supply chain monitoring. The role of technology as a driver of social, economic, operational, and sustainability improvements reinforces the idea that integrating digital traceability into agricultural supply chains can strengthen consumer trust, reduce fraud, and improve supply chain resilience (Khanna et al., 2022).

In addition to the technological aspects of traceability, it is important to understand its role in promoting sustainability within supply chains. The concept of sustainability is commonly structured around three pillars: environmental, economic, and social (Geissdoerfer et al., 2017; Ghisellini et al., 2016).

While environmental sustainability emphasizes reducing ecological impacts, economic and social dimensions focus on income distribution, decent working conditions, and equitable market access. In the case of Colombian smallholder coffee producers, the challenges are primarily economic and social, due to power asymmetries in the value chain and dependency on intermediaries (Dietz et al., 2018.

Traceability in the coffee supply chain

In some companies, traceability is implemented as a tool to ensure and verify the sustainability of the supply chain; nonetheless, only a very small percentage of food products can be traced to sustainability attributes. In the coffee supply chain, blockchain technologies have been assessed in various scenarios using different methodologies.

An exploratory study was proposed to explain how to implement blockchain technology for a coffee supply chain through a proof of concept on Hyperledger Fabric, an open distributed accounting platform. This approach identified feasibility and implementation challenges, generated feedback, and demonstrated a method for tracking product origin using extended accounting technology.

Similarly, we analyzed the tasks of each actor in the supply chain to design a blockchain-based traceability system that enables access to information from agribusiness to consumers, from farm to café. The methodology included use case diagrams, actor relational analysis, feature selection, and cosine similarity algorithms. The final traceability system successfully met the requirements for real business processes in coffee supply chains.

Likewise, the potential of blockchain technology to enhance sustainability in coffee supply chains by increasing traceability and transparency. While their pilot project demonstrated some benefits of blockchain, they concluded that its true contribution lies in improving visibility and transparency rather than directly promoting sustainability (Anacona Mopan et al., 2023; Bager et al., 2022; Kolk, 2012; Pradana & Djatna, 2020).

While transparency is a fundamental component of sustainable supply chains, its effectiveness is further amplified when combined with strong stakeholder collaboration. cooperation between suppliers, manufacturers, and retailers enhances both traceability and sustainability outcomes, and transparency efforts alone may be insufficient unless supply chain actors actively engage in cooperative initiatives. This perspective underscores the importance of fostering partnerships within agricultural supply chains to ensure that traceability mechanisms translate into meaningful improvements in sustainability and operational efficiency (Garcia-Torres et al., 2024).

The circular economy framework encourages waste reduction and resource optimization (Ghisellini et al., 2016). In coffee production, traceability can facilitate the repurpose of coffee byproducts, such as husks for biofuel and spent grounds for composting, thereby promoting both environmental and economic sustainability. In coffee production, traceability can facilitate the repurposing of coffee by-products, such as husks for biofuel production and spent grounds for composting, thereby promoting both environmental and economic sustainability (Cortés-Macías et al., 2022).

A well-structured traceability system is not only beneficial for improving supply chain efficiency but also aligns with the principles of a circular economy. The integration of Industry 4.0 technologies, such as IoT and blockchain, can help companies committed to social and environmental causes strengthen consumer trust while simultaneously mitigating resource loss (Kersten et al., 2024).

Moreover, various applications of QR technologies have been implemented at different stages of the coffee supply chain. Reported an overall QR code scanning rate of 4.22%, with consumers rating QR codes highly regarding perceived usefulness, product sustainability, and future use preference. QR codes with a suggestive appeal obtained more scans than those lacking such features. This highlights the potential for companies to use technology-based marketing innovations to communicate sustainability-related product information and promote sustainable consumption effectively (Bashiri et al., 2021). Concerning the dimensions of the specialty coffee experience, the drivers of customer visits explored and their intentions to return to urban cafes using QR code traceability.

The findings indicate an increase in consumer sophistication and engagement. Investigate the rapid creation of visually appealing and robust QR codes for the coffee supply chain using advanced deep-learning algorithms. Their framework can embed color images into QR codes in seconds with minimal decoding errors, achieving similar qualitative results to optimization-based methods but three orders of magnitude faster (Kwame Opoku et al., 2023; Pena-Pena et al., 2022).

QR codes have also been identified as a useful tool that can bridge this information gap by providing consumers with sustainability-related product information at the point of purchase. Nevertheless, the literature offers little insight into the factors influencing consumers' intention to use QR codes to obtain sustainability-related product information in everyday consumption decisions (Li et al., 2017; Qian et al., 2017).

Methods and Procedures

This research employs a qualitative case study approach, grounded in participatory design and field testing. The authors were directly involved in developing the traceability system, from designing data collection forms to implementing QR code identifiers and cloud-based data storage. Fieldwork included technical training, testing of the digital tool with coffee producers, and iterative feedback sessions to refine the platform.

This research proposes a methodology for effectively implementing a traceability system through a real case, employing IoT, cloud support, and QR codes to build a traceability tool within a structured framework. Furthermore, this research will demonstrate the real-world applicability of this technology within the coffee supply chain, where coffee is transported through various stages. The study is structured into two phases, which are presented below.

Fase 1: Analysis of the Colombian coffee supply chain: The study is carried out along a coffee supply chain involving different coffee farmers in Colombia. The coffee supply chain includes seven main nodes, each involving different actors, from coffee cherry production through primary processing to manufacturing (roasting, blending), retail and wholesale, and final consumption (see Figure 1).

In the case study, supply chain actors use a cloud-based tool with QR codes on intermediate and final products to track movements along each step of the value chain. This tool records and verifies each transfer of bags of coffee between value chain actors. The actors upload to the cloud the data normally transferred along the value chain, including bills of lading, certification documentation, photos and information, coffee prices, weights, contents, types, regions, farmers, cooperatives, roasters, and other relevant actors.

On the other hand, it is essential to understand the various elements of the Colombian coffee supply chain and their interconnection. Therefore, the relationship between the history of Colombian coffee, the production process, customers, economic, financial, and social aspects, associations, state policies, international policies, management indicators, decision-making levels of the various actors, endogenous and exogenous variables, and information systems was analyzed (see Figure 2).

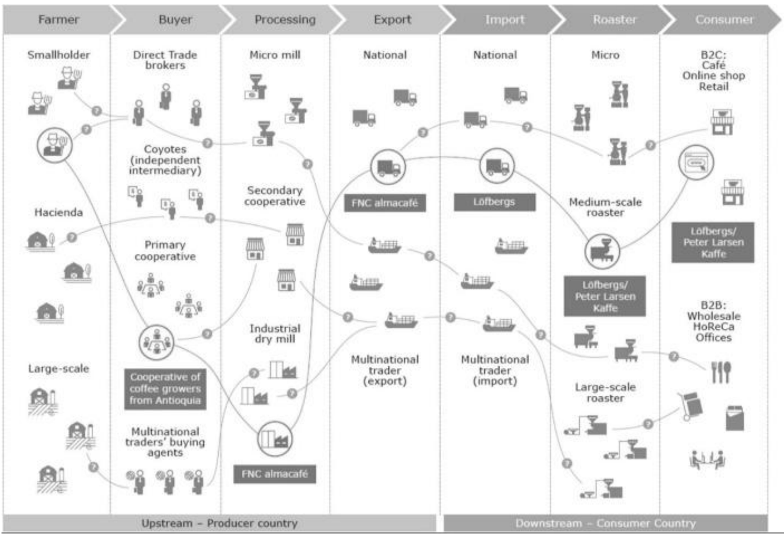

Figure 1. The coffee supply chain described by (Anagnostis et al., 2020)

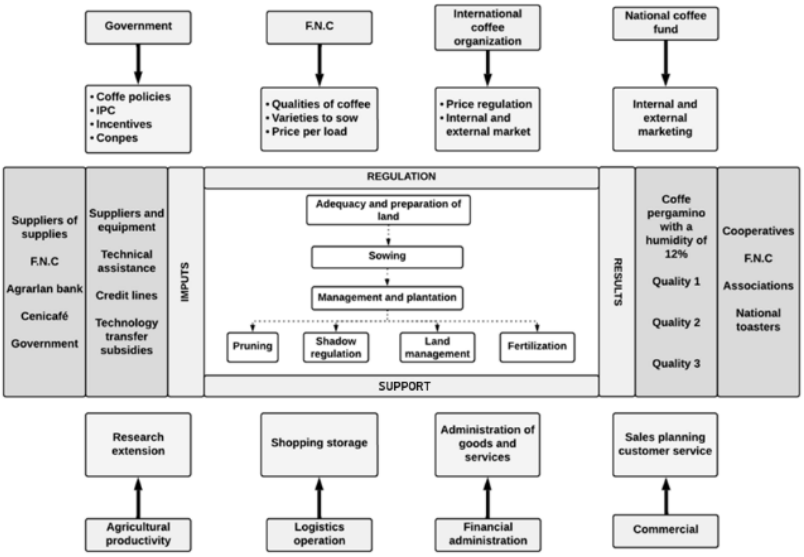

Figure 2. Characterization of the coffee supply chain

Phase 2: Analysis and design of traceability system:

For the identification phase, an area analysis was carried out through a pilot test of the tool with nine Colombian specialty coffee producers (see Table 1). These producers, selected for their cup profile above 80 points, provided two bags of specialty coffee each, equivalent to approximately 140 kg per farmer.

Table 1. Coffee producers selected for the pilot test

Type of coffee	Location	Cup profile
Typical	Timbio	82,50
Bourbon	Piendamo	89,90
Maragogipe	Cajibio	85,70
Subordinate	Cajete	84,30
Cockatiel	Timbio	80,70
Castle	Cajibio	90,10
Maragogipe	Piendamo	83,56
Subordinate	Piendamo	89,74
Typical	Timbio	88,72

As supply chain actors conducted their transactions, information was collected, data was entered into the tool, and the process was documented. At each stage, stakeholders were encouraged to add necessary information and provide feedback on the process and potential areas for improvement. For the pilot, all processes were executed normally, with coffee sent along the chain to the final consumer. Figure 3 illustrates the complete flow of information between the actors involved in the supply chain, detailing all the steps from the farmer to the consumer.

Table 2 provides an overview of the information collection process, the separation of the physical coffee flow from the digital information entered and subsequently stored in the cloud, and the link between the two.

A two-part system has been designed, processing and traceability (see Figure 4). In processing, the information is recorded and managed, including the coffee grower's data and the evaluation of the coffee, which are uploaded to the cloud. From this information, QR codes are assigned to the coffee lot. The traceability system is linked to the database, allowing customers to access detailed information about coffee by scanning the QR code. This enables them to view the full traceability and details of the coffee they want.

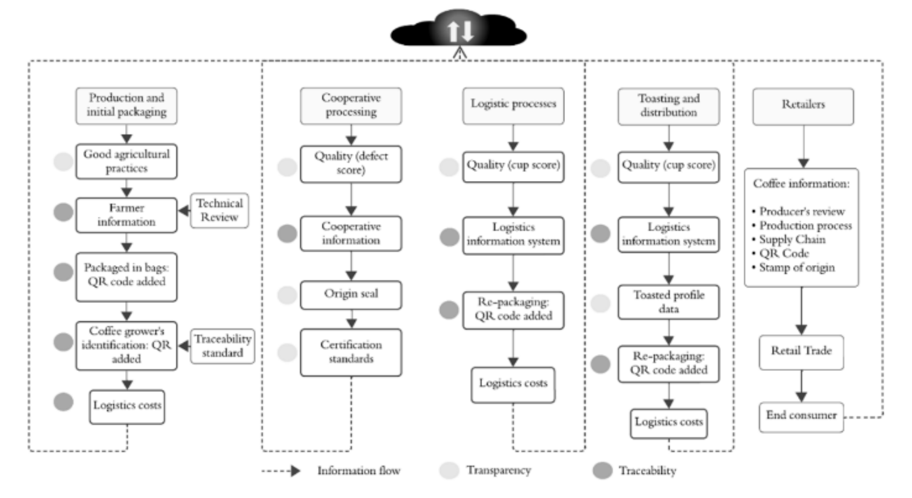

Figure 3. Coffee supply chain information flow via QR code.

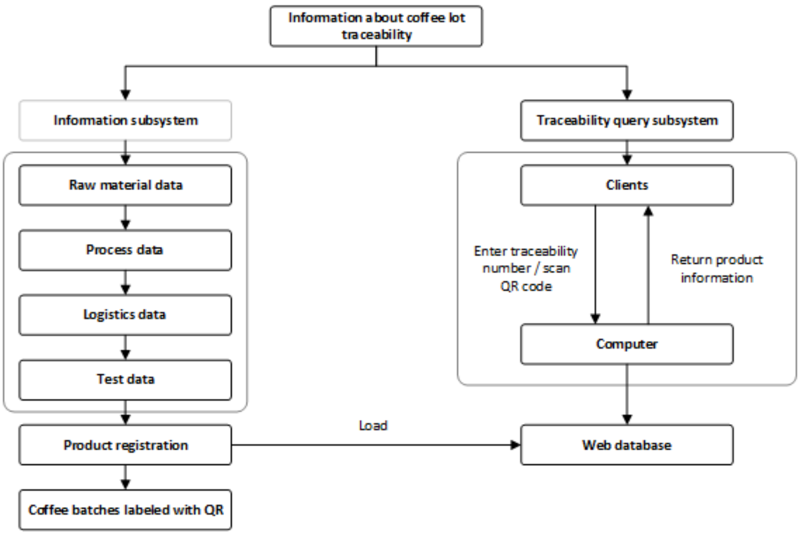

Figure 4. Structure of the coffee traceability system.

Table 2. Detailed description of the coffee supply chain stages and specific data entry for the traceability tool.

Stages	Description
Farmer	Create a profile and enter personal and farm data. Wet mill cherries into parchment coffee and dry on African beds or concrete patios. Sort, pack in jute bags (40-50 kg), and add a QR code. Deliver to cooperative purchase points.
Cooperative	Purchase coffee directly from the farmer, checking sample quality to determine pricing. Enter price, quality, and storage data. Arrange transport and send it to FNC's dry mill. Record shipment and delivery details.
Intermediary	Check coffee quality (defects, size, cupping) before milling for pricing. Mill the coffee in dry mills. Test quality, characteristics, and a cup of coffee before and after processing.
Intermediary	Specify the desired quality and characteristics and receive a sample for test roasting.
Intermediary	Grind and grade coffee for green coffee. Add QR code to bag, upload processing conditions, certifications, batch, and warehouse numbers.
Intermediary	Store, prepare, and send bags for transport to the roaster. Upload delivery details and inventory metrics.
Roaster	Check quality (coffee cup). Roast, blend, package, and add the final QR code, then prepare for retail. Upload delivery, roasting, and quality data.
Consumer	Scans the QR code to obtain information about the product, including details on origin, price, quality, certifications, sustainability indicators, and the farmer's story.

Study area: To apply the methodology developed in this research, the municipality of Popayán was selected, which has a territorial extension of 512 km² located in the department of Cauca (Figure 5). This area was selected due to its accessibility to information and its significant representation of Colombian coffee production. According to the most recent data, it is the fourth-largest coffee-producing region in Colombia, accounting for approximately 10% of the total land allocated to coffee cultivation (Anagnostis et al., 2020).

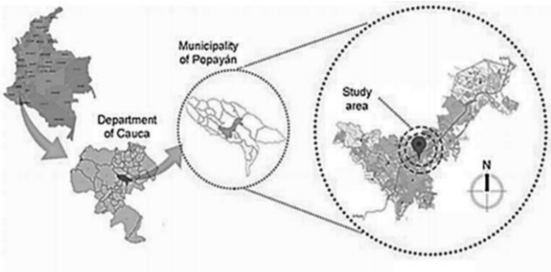

Figure 5. Geographical location of the study

Results

The pilot test yielded several interesting results related to traceability and transparency in the different steps of the supply chain. Figure 6 summarizes the main results of applying the event-based traceability model, illustrating how the different actors along the coffee supply chain contribute information to the tool.

The pilot project successfully transferred the information introduced on coffee quality, sustainability practices, and certification standards from the individual farmer along the value chain to downstream actors (including consumers). An example of the information transmitted through the traceability system is shown below. All information regarding the origin of the coffee, including the producer's details, is registered as shown in Table 3. Coffee sample number 2510 was produced by Floralba Muelas Otero, a member of the AMUCC Association. The coffee is grown on the farm “Las Veraneras, Lote 4 Soca” at an altitude of 2000 meters in the department of Cauca. The variety is Castillo, and the process used was demucilaging. The harvest took place on 28/05/2021. The batch was fermented for 12 hours, and a total of 100 kg was processed. The farm is in La Cabaña, and the producer's contact is floralbamo56@gmail.com, phone 3106500000.

Table 4 shows a series of metrics related to the quality and classification of a coffee lot; a sample is briefly described below as an example. The initial weight is 250 g, with a humidity of 12% and a density of 720 g/L. After the threshing process, the weight is reduced to 209.3 g, with 3.4 g of defects and 205.2 g of excellent coffee. The granulometric classification details the size distribution of the beans, with 28.7% retained in the N17 mesh and 55.1% in the N18 mesh, totaling 100%. Moisture is maintained at 12%, and density at 720 g/L. Shrinkage is 16.3%, with 82.1% of Excelso coffee and a factor of 85.3. Defects include borer (1.1%), broken beans (0.4%), unripe (0.2%), and vinegar (0.1%), with no other defects reported. The final classification of the coffee includes categories such as Supremo and Premium, reflecting the quality of the lot.

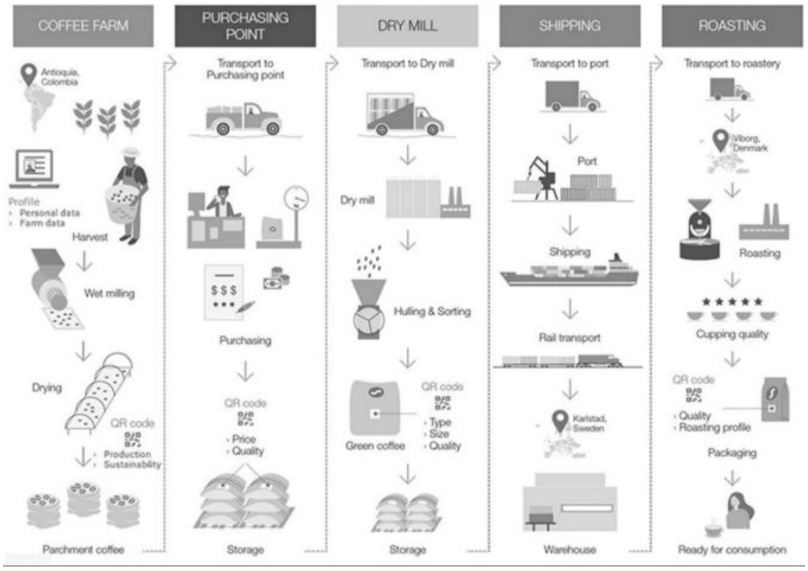

Figure 6. Supply chain case study for pilot implementation, by (Bager et al., 2022).

Table 3. Information on the origin of coffee

Coffee Information					
Producer	Floralba Muelas Otero	**Association**	AMUCC	**Sample number**	2510
Document	1061852963	**Coffee area**	2	**Variety**	Castle
Farm	Las Veraneras Lote 4 Soca	**Farm height**	2000 a.s.l.m.	**Process**	Demucilaging
Municipality	Department Cauca	**Phone**	3106500000	**Fermentation hours**	12
	Location The Cabin	**Email**	-	**Kg per lot**	100

Table 4. Information on the physical characteristics of coffee

SAMPLE DATA			
AW	*Hulled (g)*	*Defects (g)*	*Excellent (g)*
0.68	209.3	3.4	205.2
GRANULOMETRIC CLASSIFICATION			
N.16	*N.17*	*N.18*	*Total*
19.4	58.7	112.7	204.6
9.50%	28.70%	55.10%	100%
EUROPE	SPECIAL	SUPREME	PREMIUM
RESULT OF PHYSICAL ANALYSIS			
Loss %	*Excellent %*	*Factor*	
16.30%	82.10%	85.3	
DEFECTS		1.60%	
Type	*Weight (g)*	%	
Borer beetle	2.2	1.10%	
Broken	0.9	0.40%	
Unripe	0.4	0.20%	
Vinegar	0.2	0.10%	
Others		0.00%	

Observations: Parchment sample of a homogeneous color, free of contaminating odors, moisture of 12% within the range required for processing and storage, good shrinkage and good threshing yield, excellent yield factor, 1.6% defects represented by mainly sprouted kernels, some broken, immature, and vinegar. It is recommended to control the coffee borer beetle and check the condition of the milling equipment.

Sensory analysis results are also recorded, as illustrated in the radial graph in Figure 7. Attributes such as fragrance, flavor, acidity, and body received scores of 7.63, 7.63, 7.56, and 7.56, respectively. Meanwhile, uniformity, clean cup, and sweetness achieved a perfect score of 10, culminating in an overall score of 83.07. The sensory profile includes fragrance, and aroma notes of herbal pea, watermelon, panela, spice, tobacco, hazelnut, and chocolate; a bitter, fruity, slightly woody, and citrusy chocolate flavor; and a residual taste of bitter chocolate, herbaceous notes, and a lingering citrusy lemon zest. The acidity is bright and citrusy, and the body is medium, resulting in a clean, even, and balanced cup.

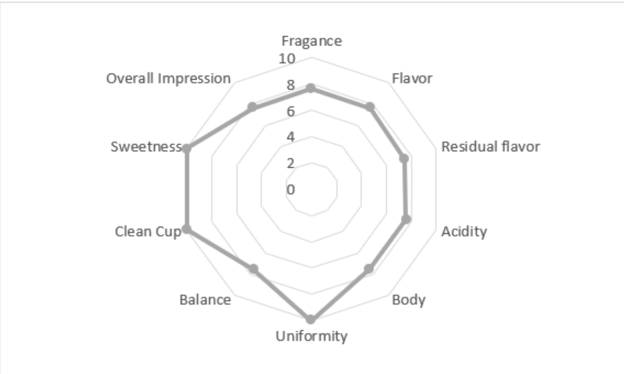

Figure 7. Radial graph of sensory analysis

The code used for coffee traceability (see Figure 8) is designed to track logistical information throughout the supply chain at any point. The coffee grower can quickly obtain detailed information about his product, such as storage time, type of coffee, and number of bags. At the same time, the end buyer will be able to know where the coffee has come from, how it has been handled throughout the supply chain, and the quality of the coffee they are buying.

On the other hand, farmers are identified through a card. This card contains a QR code that allows them and their coffee lots to be recognized and accredited as producers (see Figure 9). The information generated throughout the supply chain is linked to a unique identification number, reducing data collection errors and improving productivity.

Figure 8. Product identification with QR code. (a) Coffee sample with a QR code printed on the surface; (b) an amplification of the QR code; (c) product information stored in the QR code.

Figure 9. Coffee farmer card

The pilot project successfully transferred information entered by individual farmers regarding coffee quality, sustainability practices, and certification standards along the value chain to downstream agents, including consumers (see Figure 10). In addition, the pilot application revealed that industry players along the supply chain (cooperatives, mills, roasters, etc.) have specific information systems in place to manage transactions and the flow of goods. The cooperative already uses a digitized system that collects most of the relevant information, including records on price, quantity, characteristics, and quality (yield factor and defects) of the coffee. Therefore, implementing a system based on QR codes and cloud storage facilitates the exchange of data to a central database.

Figure 10. Final product presentation

Discussion

The QR-based traceability system effectively linked intermediate consumers and supply chain participants. However, its success relies on the accuracy and completeness of the data provided by supply chain agents. As these agents introduce price information, greater cost transparency is achieved, allowing stakeholders to track upstream prices and the relative share received by different participants. Nonetheless, under the current framework, it remains difficult to separate specific cost components, such as transportation, making it possible to observe only price variations rather than actual profit margins.

In terms of traceability, a QR code and cloud-based system can be effectively implemented in agri-food supply chains, enhancing transparency and data accessibility. This system improves stakeholders' knowledge of product origins and characteristics, as detailed information about farmers and production practices can be transferred along the supply chain. Additionally, it streamlines data exchange through centralized storage. However, standard operating procedures that involve product mixing pose challenges, as they prevent tracking of individual coffee bags. While the lower end of the supply chain demonstrates sufficient digitalization, significant barriers persist at the farm level, where most sustainability-related data must be collected. Although all farmers in the region have access to electricity and telephone networks, not all possess smartphones, limiting real-time data input (Mehrabi et al., 2020).

The implementation of QR-based traceability significantly enhanced supply chain transparency, ensuring that only certified coffee reached consumers. This increased accountability, particularly in preventing fraud and mislabeling. Additionally, data collected through the system facilitated improved waste management by identifying opportunities to repurpose coffee by-products. Producers were able to diversify their revenue streams by selling coffee husks for biomass energy production or composting.

Digital traceability also contributed to fair trade practices, enabling farmers to access premium markets and secure better prices directly. By reducing reliance on intermediaries, direct producer-to-consumer traceability increased farmer profits. Furthermore, the system's scalability suggests potential expansion to other agricultural commodities, such as cocoa and spices.

Beyond increasing transparency and ensuring food safety, digital traceability has the potential to reshape power dynamics within supply chains. By providing verifiable data on product origin and quality, small coffee producers gain stronger bargaining power, improving their ability to negotiate fairer prices and expand market access. This reduces dependency on intermediaries, a factor that has historically disadvantaged producers (Dietz et al., 2018). Additionally, as consumers become more conscious of the social and environmental impact of their purchases, companies face increased pressure to adopt responsible sourcing practices, ultimately fostering greater equity within the coffee supply chain (Kath et al., 2020).

While digital traceability systems offer substantial benefits, their long-term success depends on aligning technological advancements with industry-specific regulatory frameworks. Transparent governance policies and equitable value distribution mechanisms are essential to ensuring that all stakeholders, particularly small-scale producers, can effectively participate in and benefit from these digital solutions.

The adoption of QR code-based traceability not only enhances transparency but also supports the principles of a circular economy. By accurately tracking coffee lots from production to final consumption, the system facilitates the identification and repurposing of by-products such as coffee husks for biomass energy and spent coffee grounds for composting or bioplastics. This reduces waste and extends the life cycle of materials, reinforcing sustainability goals within the coffee supply chain (Ghisellini et al., 2016).

Beyond improving transparency and reducing fraud, the adoption of QR code-based traceability contributes directly to SDG 12 by enabling consumers and businesses to make informed purchasing decisions. The ability to track and verify sustainability practices along the supply chain fosters accountability and encourages responsible sourcing. Additionally, this system supports SDG 13 by enabling the identification and repurposing of coffee byproducts, thereby reducing waste and minimizing the environmental footprint of coffee production.

Empirical studies suggest that digital traceability improves supply chain efficiency, resulting in measurable reductions in waste and resource consumption. For example, (Cunha et al., 2010) report a 30% decrease in supply chain waste due to improved inventory accuracy and demand forecasting. Within the coffee industry, precise tracking of coffee lots optimizes logistical planning, reducing unnecessary transportation and storage, which in turn lowers carbon emissions. Additionally, the ability to trace agricultural inputs, such as fertilizers and pesticides, promotes more responsible resource use, further minimizing the environmental footprint of coffee production (Ruiz-Garcia & Lunadei, 2011).

Compared to conventional traceability methods, such as RFID and blockchain-based solutions, QR codes provide a cost-effective and scalable alternative, particularly for small producers with limited access to digital infrastructure. While RFID enables real-time tracking, its high hardware and maintenance costs make it less viable for smallholder farmers. Blockchain, though offering data immutability and enhanced security, presents barriers related to implementation complexity and high costs (Mejías et al., 2019). By integrating QR codes with cloud-based storage, this study presents an accessible and efficient solution that enhances traceability while minimizing financial and technological constraints.

Despite these advantages, large-scale adoption of QR-based traceability still faces several challenges. Successful implementation requires that small producers have access to mobile devices and stable internet connectivity, which remains a limitation in regions with underdeveloped infrastructure. Additionally, the introduction of new technologies often encounters resistance, particularly among farmers with limited digital literacy or those hesitant to deviate from traditional practices. Moreover, integrating QR code traceability with existing supply chain systems demands further investment and coordination among stakeholders, which may not always be feasible for smallholder farmers (Mehrabi et al., 2020). Overcoming these challenges will require targeted policy interventions, capacity-building programs, and financial incentives to support the transition toward digital traceability in agriculture.

Conclusion

This study contributes to both theoretical and practical discussions on sustainable supply chain management by demonstrating how QR code-based traceability systems enhance transparency, efficiency, and social equity. The findings expand the understanding of how digital traceability supports circular economy principles, particularly in agricultural supply chains. From a practical perspective, the study presents a scalable and cost-effective solution for small producers, improving compliance with sustainability standards while creating economic opportunities.

Traceability is gaining increasing relevance within the coffee supply chain. Recent advancements, such as RFID standards, have been recognized as innovative solutions that provide fast, accurate, and real-time data integration. These technologies have captured growing interest from both companies and researchers. Additionally, international traceability regulations now require companies to track products at least one step forward (from customer to supplier) and one step backward (from supplier to customer) along the supply chain.

The integration of QR codes and cloud technology enables upstream supply chain participants to access real-time information on coffee quality, allowing for better monitoring and evaluation throughout the product's journey. At the same time, end consumers can easily trace the origins of products, gaining insight into sourcing and production practices.

However, in Colombia, the adoption of traceability technology in the coffee sector remains limited. Companies often hesitate to invest in such systems due to high initial costs and delayed financial returns. Furthermore, technical challenges, such as insufficient infrastructure on farms, continue to hinder widespread implementation. While these obstacles persist, viable solutions exist, and the long-term benefits of digital traceability are expected to increase as the industry progresses.

This study reinforces the role of digital traceability, based on QR codes, as a tool to align global coffee supply chains with sustainability goals. By improving efficiency, reducing fraud, and supporting circular economy practices, digital traceability contributes to sustainability by enabling the repurposing of coffee by-products, such as husks and spent grounds, while ensuring fair compensation and strengthening ethical trade practices. By enhancing transparency, QR code-based systems empower consumers to support ethical and environmentally responsible production, aligning with SDG 12.

Additionally, the integration of circular economy practices, such as repurposing by-products, contributes to SDG 13 by mitigating waste and reducing carbon emissions. Future research should investigate the scalability of this approach in other agri-food sectors, thereby facilitating broader adoption of digital traceability for sustainable development.

While this research highlights the advantages of QR-based traceability, further studies are needed to explore its integration with emerging technologies such as AI-driven predictive analytics and blockchain-based authentication. Future research should also examine how these technologies can enhance data security and facilitate the widespread adoption of these technologies across various agricultural sectors. These advancements will be crucial for maximizing the long-term impact of digital traceability on supply chain sustainability.

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