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Blockchain is not a silver bullet for agro-food supply chain sustainability: Insights from a coffee case study

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ABSTRACT

Information sharing lies at the core of most governance interventions within agro-food commodity supply-chains, such as certification standards or direct trade relationships. However, actors have little information available to guide sustainable consumption decisions beyond simple labels. Blockchain technology can potentially alleviate the numerous sustainability problems related to agro-food commodity supply-chains by fostering traceability and transparency. Despite significant research on blockchain, there is limited understanding of the concrete barriers and benefits and potential applications of blockchain in real-world settings. Here, we present a case study of blockchain implementation in a coffee supply-chain. Our aim is to assess the potential of blockchain technology to promote sustainability in coffee supply chains through increased traceability and transparency and to identify barriers and opportunities for this. While our pilot implementation clearly illustrates certain benefits of blockchain, it also suggests that blockchain is no silver bullet for delivering agro-food supply chain sustainability. Knowledge on provenance and transparency of information on quality and sustainability can help trigger transformation of consumer behaviour, but the actual value lies in digitising the supply chain to increase efficiency and reduce costs, disputes, and fraud, while providing more insight end-to-end through product provenance and chain-of-custody information. We identify a need to understand and minimize supply chain barriers before we can reap the full benefits of digitalization and decentralization provided by blockchain technology.

1. Introduction

In recent years, the global coffee industry has come under increasing scrutiny for its sustainability performance (Bager and Lambin, 2020; Panhuysen and Pierrot, 2018, 2020). The coffee market is characterized by low and volatile market prices, and production suffers from labour shortages, low wages, and lack of investment in productivity-raising technology and knowledge (e.g., through farmer outreach and training), reducing the economic sustainability of coffee farming. Social problems include, inter alia, poverty, inequality, and occurrences of child or forced labour in coffee production (Dietz et al., 2018b; Kath et al., 2020; Panhuysen and Pierrot, 2014). Coffee's environmental challenges relate to direct ecosystems impacts, primarily through conversion of natural vegetation to coffee plantations (Ango et al., 2020; Meyfroidt et al., 2013; Pendrill et al., 2019), and resulting losses of ecosystem services and pollution (Cerda et al., 2017; De Leijster et al., 2021; Pico-Mendoza et al., 2020). The use of non-renewable resources (e.g., fertilizers and fossil fuel use) and the combined pressure of climate change and pests and diseases further add to the coffee sectors' environmental impact (Bunn et al., 2015; Kath et al., 2020; Ovalle-Rivera et al., 2015; Pham et al., 2019).

The lack of functioning institutions in several coffee producer regions to protect, for example, workers' rights or the environment have raised pressure from consumers and civil society (Dauvergne, 2017; Giovannucci and Ponte, 2005; Linton, 2008). As a reaction, multinational corporations have increasingly turned to various private governance mechanisms to address sustainability challenges. These include voluntary sustainability standards (VSS)—expressed in labels and certification schemes, such as organic, fair trade, and Rainforest Alliance—codes of conduct, roundtables, public-private partnerships, direct trade relationships, corporate social responsibility programs, and corporate pledges (Bager and Lambin, 2020; Lambin and Thorlakson, 2018;

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Thorlakson et al., 2018).

Coffee supply chains involve a high number of actors—small-scale farmers, cooperatives and middlemen, exporters, logistic and transport companies, roasters, and retailers—and cannot be easily segregated, as commodities from hundreds or thousands of producers are mixed during processing steps, obscuring any information from previous supply chain stages. The farming sector alone involve over 100 million people, in over 80 tropical and sub-tropical countries (Levy et al., 2016). The diffuse and often largely informal supply chains also cut across national jurisdictions and exhibit large power imbalances between the primary producers (often smallholder farmers) and large multinational corporations (Dallas et al., 2019; Gereffi et al., 2005). Information sharing along the value chain—from the producer via the intermediates and retailers to the end-user—on processes and standards lies at the core of most of these governance interventions. However, downstream actors have little information available to guide consumption decisions and mostly rely on various eco-labels for sustainable choices (Grabs, 2017; Lambin and Thorlakson, 2018). In addition, most standards do not preserve much information beyond the label itself, rendering it difficult for consumers to send a signal through the value chain to the producers. This is further complicated by the opaque nature of most standards and governance approaches and the complexity of coffee supply-chains.

Ensuring that sustainability information at all stages, from farm to consumers, passes unmodified through the supply chain is onerous, costly and entails risks of fraud (Gardner et al., 2019; Kim and Davis, 2016; Mol, 2015). One proposed solution to this problem has been the introduction of distributed ledger technologies (DLTs), such as blockchain (Antonucci et al., 2019; Tripoli and Schmidhuber, 2018). Blockchain technology has recently seen significant media attention and hype, especially focusing on cryptocurrencies like bitcoin. Blockchain is associated with the potential to disrupt current business models, facilitate new ways of conducting business, and enable transparency and traceability across various sectors from banking, finance and insurance (Beck, 2018; Chen, 2018) to medicine and pharmaceuticals (Bocek et al., 2017; Swan, 2018), renewable energy (Brody, 2018; Ellis and Hubbard, 2018), carbon finance (Dodge, 2018; Jackson et al., 2018), nature protection (Howson et al., 2019) and global supply chains (Gonczol et al., 2020; Saberi et al., 2019).

Throughout agro-food supply chains, blockchain supposedly provides ample opportunities for addressing sustainability issues (Antonucci et al., 2019; Sylvester, 2019; Tian, 2016). Many large-scale corporations already experiment with blockchain, including Dole, Driscoll's, Nestlé, and Walmart, while technology firms use it in combination with sensors to track agro-food and pharmaceutical supply chains (Tripoli and Schmidhuber, 2018). IBM and Microsoft are two of the main actors, but smaller developers such as Bext360 are also providing blockchain solutions for agro-food supply chains.

While blockchain can potentially alleviate some of the sustainability problems currently facing coffee supply-chains, a key question is how this theoretical potential translates into concrete impacts when implemented in real-world agro-food supply-chains. Despite growing interest in and significant research on blockchain within computer science, and the proliferation of various blockchain-related applications, there is limited understanding of blockchain's concrete benefits and potential applications across sectors. Several conceptual studies (Behnke and Janssen, 2020; Kouhizadeh and Sarkis, 2018; Saberi et al., 2019), discussion papers (Francisco and Swanson, 2018; Gonczol et al., 2020; Schahczenski and Schahczenski, 2020) and literature reviews (Antonucci et al., 2019; Wang et al., 2019) assert the theoretical potential for blockchain technology to revolutionize supply-chain management, but empirical studies of blockchain technology's potential applications are few, especially in agro-food supply chains. This also implies that the blockchain literature has had a primarily technical focus, lacking a socio-technical systems perspective (Köhler and Pizzol, 2020) that can facilitate an understanding of challenges and real-world implications of implementing blockchain as a solution to sustainability challenges in agro-food supply chains.

This paper aims to fill this gap by testing the real-world applicability of the technology and identifying challenges and potentials for blockchain-enabled acceleration of sustainability in coffee supply chains. More specifically, we assess how value chain characteristics affect the adoption, implementation, and operability of the blockchain model in terms of: (1) traceability, through the collection and transfer of information across the different steps of a coffee supply-chain (such as milling, roasting, etc)., and (2) transparency, indicated by the veracity of pricing, quality and sustainability information that is made available to downstream actors. We do so through a case study of blockchain implementation in a coffee supply chain involving producers in the Colombian department of Antioquia and the Swedish coffee importer and roaster Löfberg Group, through its Danish subsidiary-roaster Peter Larsen Kaffe. The next section gives a brief introduction to blockchain technology, including current applications in coffee supply chains, and outline the key challenges for blockchain technology to improve traceability and transparency that we assess in this paper. We then describe our methodology, which involves building a "minimum viable product" version of an event-based blockchain model, undertaking fieldwork along the supply chain, and running a pilot test of the model. The results section describes the implementation of this model. Based on insights from this pilot, we end with a discussion of the potential of blockchain technology to address broader sustainability-related questions within agro-food supply chains, before offering conclusions and perspectives for future research.

2. Background – blockchain and coffee supply chains

Blockchain is a specific type of database, which is managed and fed by a network of distributed ledger technologies, which records all transactions, enabling decentralization, verification, and immutability (Pavlić Skender and Zaninović, 2020). The data input can be financial information and product characteristics, for example, and include both text, numbers, and pictures. The data can be extracted from transactions processes or collected automatically by various technologies, such as IoT-devices or satellites. Data is added to the blockchain in sequentially linked 'blocks' with a unique ID called a 'hash', a cryptographically unique value created by an algorithm, and a pointer to the hash of the previous block. The immutability of the data means that it cannot be overwritten, allowing a full view of historical transactions (Gammelgaard et al., 2019; Sylvester, 2019). The main benefit in agro-food commodity supply chains is that it adds a digital layer to a physical commodity flow, as supply chain-related information and metadata, e.g., on transactions, processes, or growing conditions is stored on the blockchain (Tröster, 2020). Fig. 1 illustrates the basic principle of blockchain for a coffee supply chain.

Blockchain applications are already coming to life in coffee supply chains. Along with several multinational coffee companies, Farmer Connect has developed the app "Thank My Farmer", based on IBM's blockchain, to connect coffee farmers to consumers, who can track and trace the coffee, learn about the specific stakeholders, see different sustainability projects near or on the coffee farms, and support the projects through in-app donations. In collaboration with Microsoft, Starbucks' 'Bean to Cup'-project also works on implementing blockchain, focusing on consumers' ability to trace coffee and showcase producers (Starbucks, 2018).

Both initiatives focus primarily on improving *traceability* of coffee supply-chains, providing consumers (and other supply-chain actors) with provenance information. The potential to offer fast and complete traceability along supply chains, allowing actors to identify and examine agro-food products' movements from input and practices to transportation, storage, and processing is one of the main selling points for blockchain (Tripoli and Schmidhuber, 2018). However, to improve sustainability in coffee supply-chains, traceability is not enough: actors also need information on sustainability impacts and outcomes across the

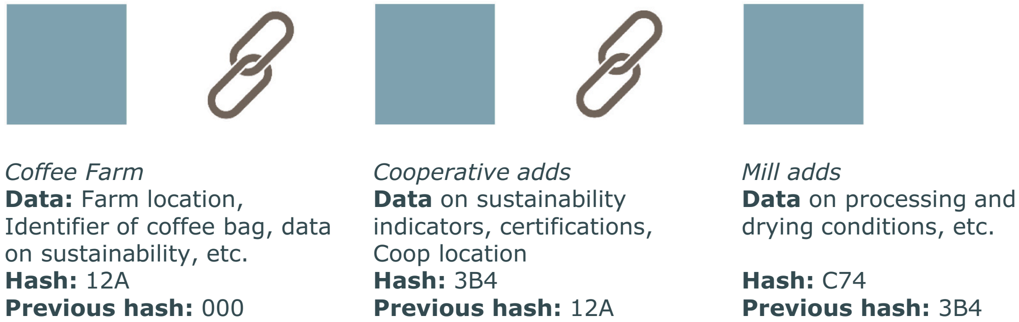


Fig. 1. The basic principles of a blockchain for a hypothetical coffee supply chain.

supply-chains, such as the transfer of price premiums to farmers or the application of environmentally-friendly agronomic practices.

Currently, the consumer price premium frequently fails to sufficiently reach upstream producers, reducing the ability of certifications to overcome the low economic value of many agro-food commodities (COSA, 2013; Minten et al., 2018; Mitiku et al., 2017). iFinca, a Colombia-based company founded on blockchain technology, whose app connects farmers and consumers, aims to address this by securing reasonable payments to the farmers. Their website (www.ifinca.co) includes information on prices paid to farmers they work with, which at around 2.50–3.00$/lb. is significantly above average world market price, but their model is limited to specialty coffee (thus reducing mass-market potential).

Traceability further needs to be supplanted by *transparency*. Currently, transparency is hampered by transactions in most agro-food supply chains being slow, paper-based, labour-intensive, insufficiently audited, fraud-prone, and generally inefficient (Albersmeier et al., 2009; Stupak et al., 2021; Wildt et al., 2019). Additionally, the large number of intermediaries and frequent product mixing means that downstream actors often have limited insight beyond first-tier suppliers. Theoretically, blockchain can reduce these risks by providing documentation, transferring farm-specific knowledge and audit information downstream (Leong et al., 2019), enabling transparency and accountability of transactions and prices. This provides actors with unique information and negotiation leverage, e.g. allowing actors to pressure for more evenly distributed profits to ensure producers receive fair prices (Pavlić Skender and Zaninović, 2020). It further allows all actors to reap efficiency gains due to alignment of data and near real-time data sharing, to sell products at higher values, given consumer demand for transparency and other sustainability characteristics, and to reduce administrative costs. Finally, it provides incentives for farmers to apply sustainable or costly farming-methods currently not rewarded by the market (beyond certifications) by documenting and tracing this from farm to final consumer (Tripoli and Schmidhuber, 2018). As such, a DLT-based system provides a platform for traceability and transparency across the coffee value chain to facilitate provenance and ensure the authenticity of the coffee i.e., validating the chain-of-custody, price, certification, quality, sustainability performance, and other characteristics of the coffee.

However, there are two main challenges to realizing this theoretical potential: linking digital records to physical assets that undergo several transformations along the supply chain and ensuring the validity of data entered into the digital ledger (Howson, 2020; Köhler and Pizzol, 2020; Schmidt and Wagner, 2019). To ensure traceability, it is not enough that the digital records are tamper-proof, these digital records must be uniquely linked to the physical products and their identity must be preserved across the supply-chain (Tripoli and Schmidhuber, 2018), which may involve steps where products are processed or mixed with other products, without the possibility of fraud. For transparency, blockchain solutions are susceptible to the ‘garbage in-garbage out’ problem (Howson, 2020), implying that precautions must be taken to make sure that the data entered into the blockchain is of high quality and trustworthy (Köhler and Pizzol, 2020).

3. Methods

The research for this paper has been part of a transdisciplinary, case-based research project, whose project team includes three universities, a private coffee company, and a consulting firm. The objective was to assess the potential of blockchain technology to accelerate sustainability in bio-based supply chains and demonstrate real-world applicability of this technology. As part of the project, we developed an event-based blockchain system for the coffee supply chain case and tested this in a fully operational pilot, where coffee was transferred along the supply chain. This paper reports the project’s outcome with regards to transparency and traceability. We report on the model development and computer science-aspects in Bager et al., (2022), focusing here on the supply chain-related aspects and “real-life” outputs. In addition, Singh et al., (2022) provide insights into the drivers and obstacles that coffee producers face regarding blockchain adoption. The project ran from January 2019 to September 2021, with fieldwork taking place in Colombia in January–February and November–December 2020 and in Denmark in April 2020 and August 2021, while the pilot test took place from December 2020 to August 2021. Due to the Covid-19 pandemic, we extended the pilot phase and scaled-down in-person interviews.

In this section, we describe the process and methods for this paper more specifically. We applied a mixed-methods approach, drawing on methods from computer science and geography, respectively. Table 1 describes the project’s five distinct research phases. This paper is the centrepiece of the scientific project outcomes, therefore stretching across project phases. We relied on semi-structured interviews with individual value chain actors as well as focus groups to understand current actor behaviour within the supply chain and their approach to digital innovation (i.e., blockchain). We also applied other methods, such as transect walks and participant observation to experience how actors currently handle coffee transactions, record data, and interact with existing systems. To analyse the data, we transcribed and coded interviews and used qualitative analysis to assess the implications of implementing a blockchain system.

During the scoping and design of this research, we identified transparency and traceability as central themes to the research and further selected dimensions and their indicators, both as prerequisites for the blockchain model, as well as to code the interviews. All indicators were selected by project participants. Ecological and social/economic sustainability indicators correspond to similar indicators in several coffee VSS, such as Rainforest Alliance and Fairtrade (see also (Dietz et al., 2018a)). For a summary of the indicators used, see Table 2.

3.1. *Empirical setting*

The empirical study takes place along a coffee supply chain involving

Table 1
Summary of activities and methods for this paper. The third phase is dealt with in Bager et al., (2022), yet listed for the sake of completeness, as the model development is prerequisite for the pilot test.

Project phase	Activities	Data collection methods for this paper
1. Identification and Preparation	• Mapping the supply chain to identify key stakeholders, general characteristics and potential challenges	• Semi-structured interviews with key informants (Galletta, 2013)
2. Fieldwork and data collection	• Collecting data upstream (Antioquia, Colombia; January 2020) and downstream (Central Jutland, Denmark; April 2020, August 2021) • Upstream key stakeholders included coffee producers in Heliconia and Titiribi, the cooperative of coffee producers in Antioquia, and the exporting arm of the National Federation of Coffee growers in Colombia (FNC) Almacafé. • Downstream stakeholders include employees from Löfbergs Group and Peter Larsen Kaffe: Chief officers for purchasing, and innovation and circular transformation at Löfbergs, master roaster, and marketing and communication staff at Peter Larsen Kaffe.	• Semi-structured interviews with 5 coffee producers (1 female, 4 male), 2 cooperative staff at purchasing points (1 female, 1 male) • 3 focus groups, 2 with 6 cooperative staff (2 female, 4 male) and one with four staff from Almacafé (1 female, 3 male) • One transect walk (Kanstrup et al., 2014) at Almacafé (coffee mill) • Participant observation (Spradley, 2016)
3. Model development and testing	• Development of blockchain application • Datasets and prototypical implementation for this study can be found in the GitHub repository for the project: https://github.com/diku-dk/coffeechain.	• Model development is not reported in this paper; see Bager et al., (2022) for further details.
4. Pilot test	• Identification of coffee producers for pilot (November 2020 – January 2021) • Pilot test of the application along the entire supply chain from point of production through to final roasting, procuring and then following the physical product throughout all transactions and transformations. (March 2021–June 2021)	• 6 semi-structured interviews with coffee producers (1 female, 5 male) involved in pilot test • 2 semi-structured interviews with cooperative staff at purchasing points (1 female, 1 male) • Transect walk at mill (Almacafé) and interview with 2 staff (male) • Transect walk at roaster and interview with three Löfberg/Peter Larsen Kaffe staff (male)
5. Assessment and Evaluation	• Adjustments to application based on findings • Data analysis	• Interview coding and subsequent qualitative analysis

Table 2
Key dimensions and indicators used in study.

Dimension	Indicator
Quality	Cupping score, defect score, variety
Certification	Fairtrade, 4C
Pricing	Price paid per kg coffee for each transactions
Environmental sustainability	No deforestation
	Planting of canopy cover on farm land (agroforestry system or shade trees)
	Safe handling and application of chemicals, including use of Personal Protective Equipment (PPE) for application of agrochemicals
	Safe storage of chemicals
	Water treatment system
	Renewable energy, e.g. solar panels
Social / Economic sustainability	Payment of premiums to producers (as regulated by the market or set by the standard-setting body)
	Use of premiums (by the management of a cooperative or estate according to communal development or work plans approved by an inclusive general assembly)
	Provide workers with legally binding written contracts
	Pay equal to or greater than minimum wage
	Reliable and transparent payment systems

the cooperative of coffee growers from Antioquia, Colombia ("Cooperativa de Caficultores de Antioquia", referred to as "the cooperative" throughout the paper), Colombia's national coffee association ("Federacion National del Café", FNC), and the Löfbergs Group, particularly Peter Larsen Kaffe. The coffee supply chain includes seven main nodes, each involving different actors; from coffee cherry production over primary processing to manufacturing (roasting, blending), retailing and wholesale, and final consumption (Fig. 2).

The supply chain used for this case study is just one of several different coffee supply chains, but we developed the model to handle a generic coffee supply chain, rather than tailoring it to this specific case; see further details in Bager et al., (2022). In our use case, supply chain actors use a blockchain-based application with QR-codes on intermediary and final products to trace the movements along each step of the value chain. The DLT records and verifies each transfer of coffee bags between value chain actors. Actors upload the data normally transferred across the value chain, including contracts, bills-of-lading, certification documentation, photos, and "generic" information, including price of goods, weight, content and type, region, and farmer, to the application. Farmers, the cooperative, roasters, and other actors involved also each created a profile and user in the system.

3.2. Implementation of blockchain model pilot

We conducted the pilot test of the blockchain application with six coffee producers that each provided two exportable bags (i.e., circa 140 kg of coffee per farmer). While the supply chain actors conducted their transactions, we observed, collected information, entered data into the application, and documented the process. At each stage, we asked actors to try to add information and solicit feedback on the process and potential improvements. For the pilot, all processes were conducted as normal, meaning that we shipped physical coffee along the chain and paid for the final batch of coffee delivered by the roaster. We did not involve actors that are not directly related to the coffee supply chain, e.g., port authorities, in the pilot implementation, meaning that information on, for example, import or export and shipping is provided by the importer or the exporter. Table 3 provides a full description of all steps in the supply chain from farmer to consumer. Fig. 3 provides an overview of the information collection and the separation of the physical flow of coffee from the digital information entered and subsequently stored on the blockchain as well as the link between these.

Due to the scale of operations, we made two modifications to the conventional supply chain practices to ensure project objectives: procuring separate bags for the coffee logged on the blockchain and changing the mill to a micro-mill. Normally, product mixing occurs at purchasing points (PP) and at the mill dry. At the PP, the cooperative does not store coffee separately for each farmer. Individual tracking of bags on the application (using QR-codes) alleviates this. At the mill, the current scale of operations does not permit provenance to farm, as coffee is stored in huge silos containing coffee from several hundreds of farmers, which is only distinguished by certification standard and region. To overcome this obstacle, for our pilot implementation the blockchain coffee was processed at the closest micro mill located in Bogota, partly by hand (as even this mill was too large to handle the small quantities of our pilot implementation).

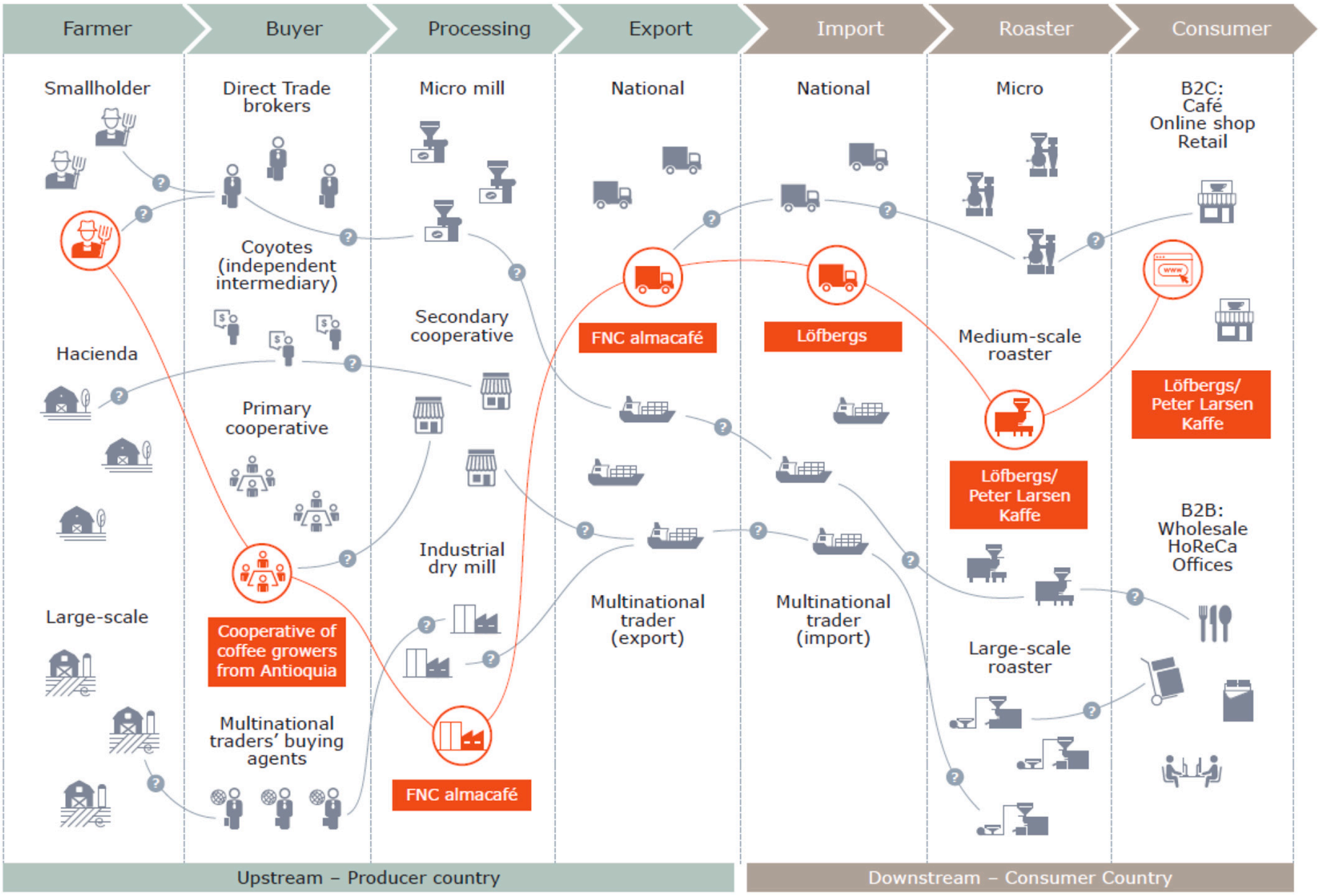


Fig. 2. The seven nodes in the coffee supply chain: farming (coffee bean cultivation, harvesting, and wet processing), buying (coffee point purchasing and quality control), processing (hulling, milling and sorting), export (customs, international transport), import (customs, local transport), secondary processing (roasting, blending, and packing), and retail and consumption (business-to-business (B2B) or business-to-consumer (B2C)). Each column describes the different actors, which can typically be found at this node. The red line indicates the supply chain make-up for this case study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4. Results

The pilot test yielded several interesting outcomes related to traceability and transparency across the various steps in the supply chain. Fig. 4 summarizes the key results of the event-based blockchain model implementation, displaying how information is added to the blockchain by different actors across the coffee supply-chain.

On traceability, it is possible to establish a system suitable for agro-food supply chains and make it work: the implemented blockchain model established a chain-of-custody, including time of transactions, and connected coffee to specifics lots and farmers (Fig. 4). This increases supply chain actors' knowledge about product origin and related characteristics, as information pertaining to farmers could be transferred across the supply chain. However, this traceability came at a cost, as standard operational procedures entail product mixing and thus do not cater for handling individual coffee bags. At the purchasing point, coffee is kept in second-hand bags and stored in a simple warehouse, separated according to certification scheme. The lower-grade-coffee is repacked from the jute bags to silos. Separate handling of coffee per producer is in theory possible but would require a more elaborate storage system, which implies additional effort from the local staff. With 60 silos and a total storing capacity of 24,000 tons, the dry mill in Medellin is laid out for large-scale operations. The coffee is stored in silos according to certification and region. In the automatic sorting process (by size, weight, density and colour), the beans from the same 400-tons-silo get further mixed. Therefore, the size of the current milling setup makes traceability to farm impossible.

Another challenge encountered in the pilot implementation relates to ensuring mass conservation (that the amount of tracked coffee entering the chain matches the amount exiting the chain), as the coffee is not only transferred and transported, but also transformed: the parchment coffee delivered by the farmer to the cooperative are separated into green beans and waste at the dry mill, and only the beans continue along the chain. When the green beans are converted to roasted beans by the roaster, it further reduces weight due to humidity extraction, while various losses occur due to quality screenings throughout the chain. The blockchain model handles these differences in masses by creating a lost category, i.e., 140 kg of green coffee equates to roughly 115 kg of roasted coffee (and 35 kg of "lost" coffee). In triangulation with a series of assumptions regarding weight changes and transformations, taking track of mass conservation appears feasible, but requires automated checks and additional control. Due to the transformation of coffee, as well as its granularity, it is also only possible to tie the identifier to the bag, not the commodity itself. In our pilot implementation this linking of the digital identification (ID) to a physical commodity was solved via QR codes on bags.

The pilot also successfully transferred information entered on quality, sustainability practices, and certification standards of the individual farmer's coffee across the value chain, to downstream actors (including consumers). The information was linked to an individual farm, rather than to a generic product chain. The system also established a direct link between downstream consumers and supply chain participants, though

Table 3
Detailed description of the relevant steps in the pilot implementation (phase 4) in the case study supply chain and the specific data input for the blockchain model.

Actor	Process
Farmer	• Creates a profile, enters personal and farm data. • Wet mill the cherries into parchment coffee beans at a washing station at their farm. Once wet-milled, the coffee is dried on African beds or concrete patios. • Sorts the processed parchment coffee, packs it in jute bags, typically weighing 40–50 kg, and adds a QR code to the coffee bag • Takes the bags for sale to the purchasing points owned by the cooperative.
Cooperative	• Buys the coffee from the farmer. A sample is quality-controlled to determine the price. • Uploads data on price and quality and any storage-related information. • Organizes transport and sends the coffee for further processing at the dry mill, which is owned and operated by the FNC. • Uploads data on shipment and delivery details. (Transport happens on an ad-hoc basis with individual purchasing points organizing transport using both independent and FNC-owned logistics services).
Exporter	• Quality-controls coffee (defects, size, cupping) before milling to determine the price. • Mills coffee at dry mills (operated by Alma Café, a subsidiary of FNC, who handles all export of coffee in Colombia. Note: For this case, we had to use a specialty mill (also owned by FNC) rather than the conventional mills to avoid losing provenance to farm). • Tests quality and coffee characteristics, and cups the coffee before and after processing.
Importer	• Specifies the quality and characteristics desired and receives a sample for test roasting.
Exporter	• Hulls and sorts the coffee to prepare milled, green coffee. • Adds a new QR code to coffee bag and uploads data on processing conditions, quality (cupping score), relevant sustainability indicators, certifications and management systems, and lot number, and stores the coffee in a warehouse before export. • Readies the coffee for export in 70 kg jute or plastic bags or 1 ton big bags, with each container taking approximately 21 tons in total. • Seals container and ships coffee by truck to the export harbour, where customs clearing follows. (The exporting and importing ports handles shipping, while the exporter and importer handle custom documents and contracts and upload these. International logistics companies handle shipping, as specified by the importer). • Delivers contract purchasing agreement receipts, including standards, price, tracking codes.
Importer	• Organizes shipping on rail and truck for warehousing (upon arrival in Europe) • Warehouses, prepares the bags for transport, and subsequently ships to roaster • Uploads data on delivery details and inventory metrics
Roaster	• Controls quality (coffee cupping) • Roasts, blends and packages the coffee, adding a final QR-code to the coffee pack, which is then ready for retail. • Uploads data on delivery, roasting, and quality characteristics.
Consumer	• The final consumer (B2B or B2C) scan the QR-code to obtain information about the product, including data on provenance, pricing, product quality, certifications, and sustainability indicators.

the specific outcome depends on the information presented to them (by supply chain actors). As actors enter pricing information, cost transparency can be established, including information on prices paid upstream and relative share paid to individual actors (Fig. 4). Given the current setup, the various process-related costs at each step, including transport, cannot be separated out. This means that it is only possible to see price differences, not profit margins.

Moreover, the pilot implementation revealed that industry-actors along the supply chain (cooperative, mill, roaster, etc). all have specific information systems to handle transactions and commodity flows. Operationalizing a blockchain system thus requires facilitating data sharing from disparate systems to a central database. The cooperative already uses a digitized system that gathers most of the relevant information, including records on the price, quantity, characteristics, and quality (yield factor and defects) of the coffee sold by farmers. Similarly, the dry mill operates on a software that stores information on business partner/vendor, quantity, price, and quality (own manual sample analysis based on visual characteristics and cupping), while the roaster uses yet another system to manage inventory, roast profiles, and cupping scores, among other things.

5. Discussion

The real-life nature of this pilot implementation revealed real-world challenges and opportunities—as experienced by the involved supply chain actors, rather than the theoretical or potential issues—for using blockchain technology to promote agro-food supply-chain traceability and transparency. Below, we discuss how these implementation challenges and opportunities relate to specific supply-chain characteristics of agro-food supply-chains (section 5.1) and the technological and organizational capacity of supply-chain actors (section 5.2), as well as how blockchain-enabled traceability and transparency can affect governance and agency of agro-food supply chains (section 5.3). These discussions are summarized in Table 4.

5.1. Supply chain characteristics

The pilot clearly revealed that the logistics of the studied coffee supply chain do not facilitate implementation of a blockchain system for traceability, with numerous challenges due product mixing, processing, and the challenge of linking digital and physical assets. Overcoming the lack of physically segregated supply-chains would require investments in new infrastructure—i.e., micro mills for specialty coffee, which conduct the same automated sorting on a smaller scale—which would have implications on the final price. While this might be possible for niche coffee, it is unlikely to be a viable alternative for coffee (and other agro-food commodities, such as soybeans, maize or palm oil) traded in bulk. Further, this also reduces efficiency and reduces the potential for scaling up.

The fact that the digital IDs in the pilot were connected to coffee bags implies that the ID might be connected to the wrong product, e.g., when coffee in a certain bag gets replaced or enters the chain on incorrect premises. Although not tested here, the use of sensors might address these concerns, as this would enable participants to know when and where coffee bags had been opened (Antonucci et al., 2019; Tripoli and Schmidhuber, 2018). This risk only applies until the point of export, as containers are sealed at the mill to avoid tampering and reduce the risk of drugs and other illegal substances being smuggled in coffee. However, this does not eliminate the possibility of coffee entering the chain on wrong premises: For instance, one farmer explained that he would sometimes sell his neighbour's coffee under his name to let the neighbour benefit from the higher price that the cooperative offers. In such cases, the data on the blockchain would not reflect the actual product characteristics (in this case provenance, any farm-related sustainability information, and certification). The cooperative tries to mitigate this risk by allocating a maximum amount of coffee per farmer calculated based on the plot size and past production, but even with a blockchain-solution, this risk would persist. DNA-based screenings of coffee (as has been piloted to detect fraud coffee supply chains (Pruvot-Woehl et al., 2020)) could potentially alleviate this, but would further increase costs. It also entail a risk that farmers report sustainability practices not undertaken (i.e., greenwashing), though the built-in events-model of the blockchain reduce this be enabling other participants (cooperative, auditors) to report this data as fraudulent.

In regions and supply chains where informal buyers are more active, coffee from private buyers might be reintroduced into the supply chain. In the case of Heliconia and Titiribi, there are very few private buyers that mostly buy lower grade beans, for which the cooperative does not always offer a good price. The manager from Heliconia added: *"Sometimes farmers go to the private buyers, when they are in need of cash. Private*

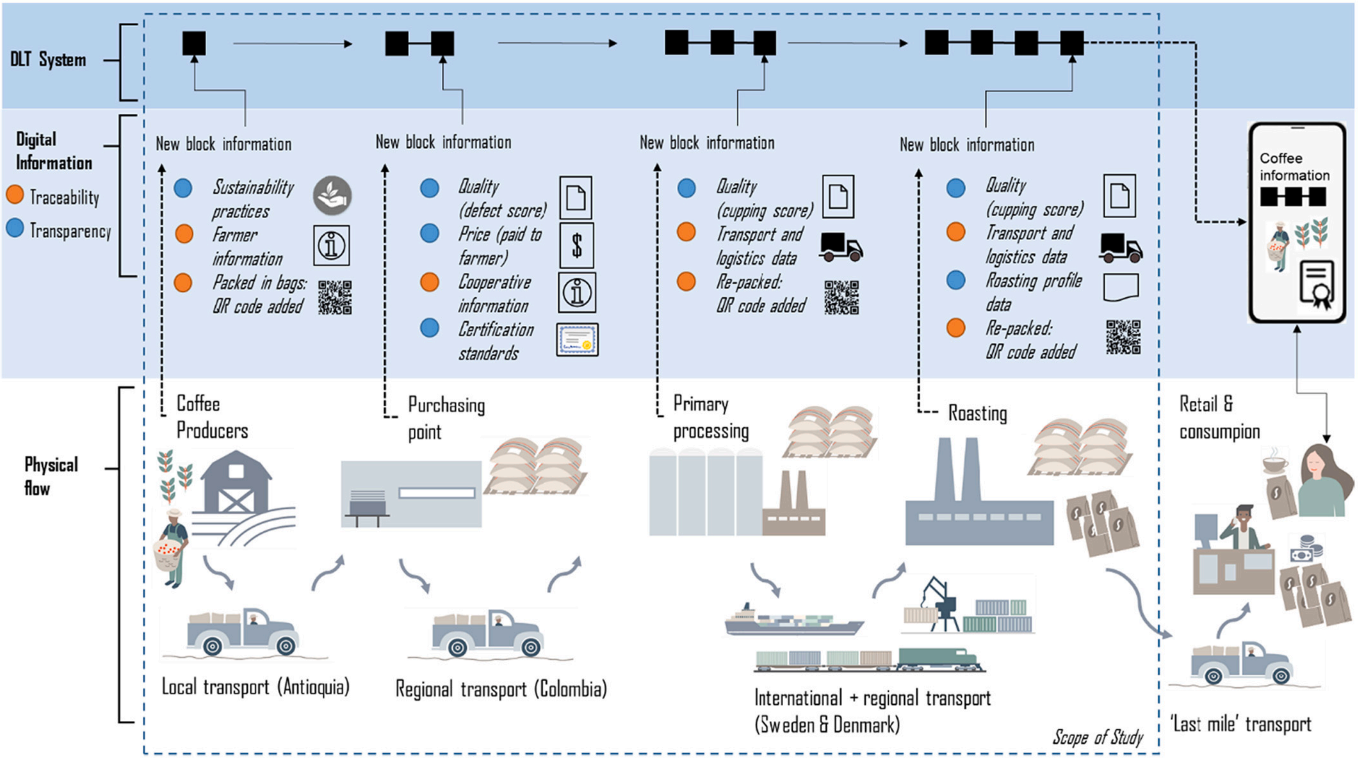


Fig. 3. Separation of the physical flow of commodities (coffee) from the digital information entered and subsequently stored on the blockchain (DLT system) as well as the link between these. Different information aspects is added in each step depending on the actors involved and the information needs required. The bullets highlight the information collected at each node. The final information sharing with consumers is not part of the scope of the study, although a QR code on the bag enabled consumers to view the information collected in previous supply chain nodes.

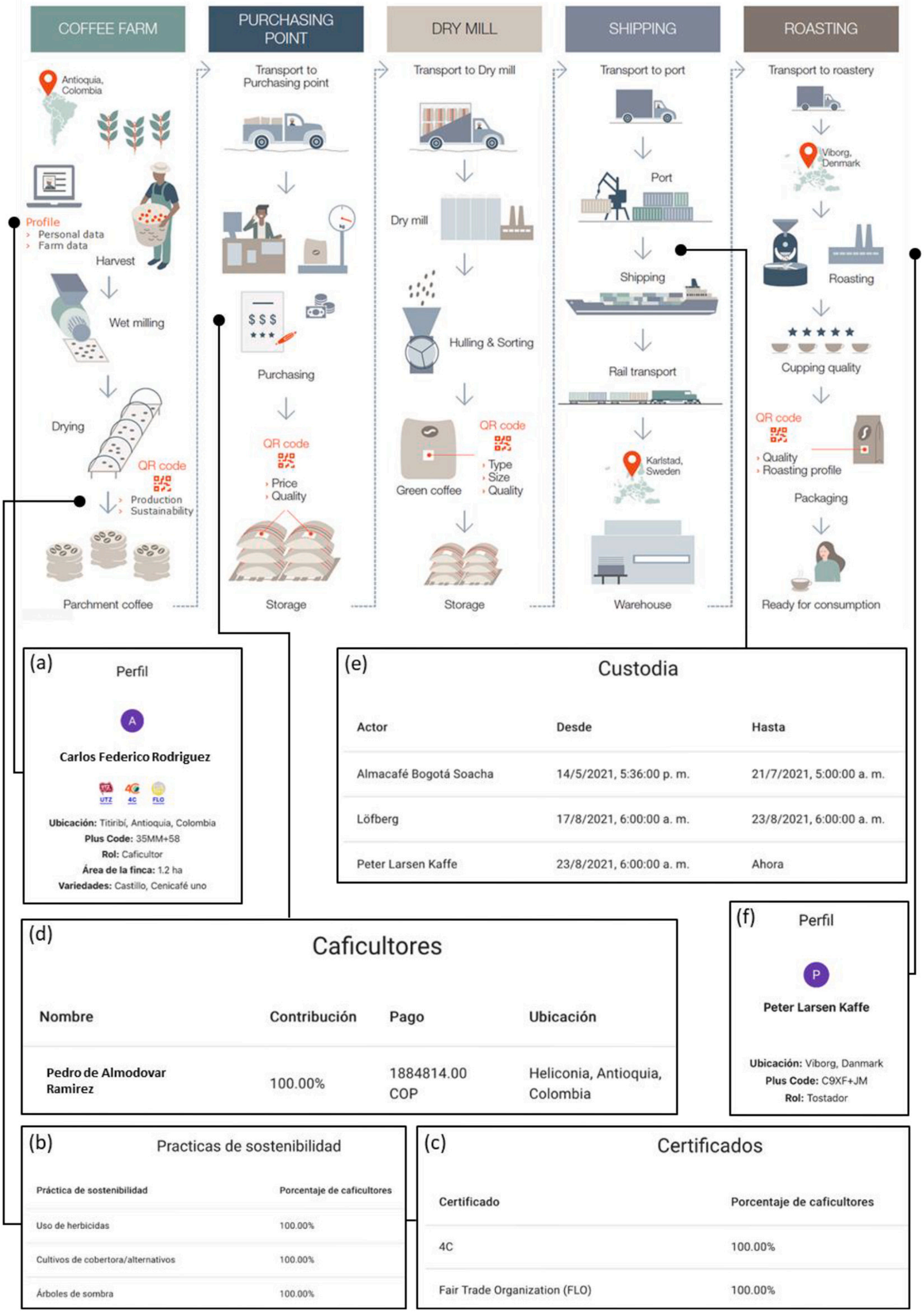
buyers can offer upfront payments and informal loans, which we are not able to provide." By using tokens or other forms of smart-contract executed payments to farmers, blockchain solutions could potentially alleviate this problem by shortening the time between sale and payment and even facilitate loans.

The challenges involved in asserting traceability of course also has implications for achieving transparency. In addition, while blockchain systems enable tamper-proof information storage, the quality and trustworthiness of the information depends on external factors (how was it collected, by whom, etc)., which the blockchain cannot directly affect (Tröster, 2020). For agro-food supply chains, it is often difficult to assure the validity and quality of the entered data, which cannot be checked at subsequent stages, which give rise to the "garbage in, garbage out" problem (Howson, 2020). As several farmers do not know various aspects related to their production, e.g., farm size and sustainability practices, the accuracy of data entered by farmers cannot always be trusted. Further, while bags can be weighed at each stage, most sustainability indicators can only be checked at farm level. It is thus difficult to turn collected information into "evidence" and, as such, blockchain does not provide absolute assurance. Automatic information using IoT could potentially alleviate this by using sensors, such as radio frequency identification (RFID)-tags, Global Positioning System (GPS) trackers, smart sensors or crypto-anchors, to automatically transmit data, but such data can still be manipulated and much of the relevant sustainability data collection cannot be automated, which leaves blockchain challenged by the gap caused by the transfer of the physical reality to the digital supply chain (Gammelgaard et al., 2019; Schmidt and Wagner, 2019; Tripoli and Schmidhuber, 2018).

5.2. *Technological & organizational capacity*

Whereas the level of digitization and technological know-how is sufficiently high downstream in the supply chain, we identified challenges with regards to lacking technological know-how, equipment and infrastructure at the farm level, where most of the sustainability-related data have to be documented. While all farmers have access to electricity and a phone network, not all farmers in the region have smartphones. Mehrabi et al. (2021) highlight how lack of basic infrastructure, e.g., 4G connection and access to technology, challenges data-driven agricultural innovations. This is an issue encountered also in this case, as our blockchain model requires a smart device with internet access. This challenge can be mitigated by having farmers enter their data at the purchasing point, where they can access Wi-Fi and computers. However, there is a lot of commotion on weekends during peak harvest and cooperative employees were afraid that data entry would result in longer waiting times for farmers if the pilot model was to be scaled up, exceeding the purchasing point's capacity and resulting in farmer dissatisfaction. An offline functionality would allow farmers to enter data, which could subsequently be synchronized when online, but this would require handling issues pertaining to verifying when specific events took place.

In addition, when using a blockchain-based system like the one we test here, coffee growers must invest time in learning a new system, which can pose a challenge to certain farmers, though the cooperative can mitigate this by offering trainings. The cooperative is already implementing a range of trainings and workshops today, and their headquarter staff showed interest and enthusiasm concerning the blockchain technology. It thus seems likely that the cooperative could facilitate the implementation of the blockchain, despite the extra administrative burden for them. However, they noted that it will be challenging to teach the farmers about new technologies. One employee from the cooperative explained: *"There are 11,000 associates, most of them are of advanced age, 60-65 years old and with low levels of formal education, which has an impact on technology adoption."* It will also be the



(a) Perfil

A

Carlos Federico Rodriguez

UTZ 4C FLO

Ubicación: Titiribí, Antioquia, Colombia
Plus Code: 35MM+58
Rol: Caficultor
Área de la finca: 1.2 ha
Variedades: Castillo, Cenicafé uno

(e) Custodia

Actor	Desde	Hasta
Almacafé Bogotá Soacha	14/5/2021, 5:36:00 p. m.	21/7/2021, 5:00:00 a. m.
Löfberg	17/8/2021, 6:00:00 a. m.	23/8/2021, 6:00:00 a. m.
Peter Larsen Kaffe	23/8/2021, 6:00:00 a. m.	Ahora

(d) Caficultores

Nombre	Contribución	Pago	Ubicación
Pedro de Almodovar Ramirez	100.00%	1884814.00 COP	Heliconia, Antioquia, Colombia

(f) Perfil

P

Peter Larsen Kaffe

Ubicación: Viborg, Danmark
Plus Code: C9XF+JM
Rol: Tostador

(b) Practicas de sostenibilidad

Práctica de sostenibilidad	Porcentaje de caficultores
Uso de herbicidas	100.00%
Cultivos de cobertora/alternativos	100.00%
Árboles de sombra	100.00%

(c) Certificados

Certificado	Porcentaje de caficultores
4C	100.00%
Fair Trade Organization (FLO)	100.00%

Fig. 4. The case study supply chain for the blockchain project implementation. The flow diagram depicts the key actors and steps along the supply chain. The boxes, which show snippets from the application, describe various features and actors enabled. A) Example of an actor profile for a farmer (Carlos) involved in the pilot. The name of the farmer has been modified to maintain personal confidentiality. B) Sustainability practices for a particular bag. The sustainability practices shown are those undertaken by the specific farmer (Pedro) included in this example. C) Certification standards for a particular bag. Data on certification standards comes from information from the cooperative, which is linked to the farmer profile. The model assumes that all coffee from a farmer pertains to the standard to which he/she is certified. D) Payment information for a particular bag. The example shows total payment made to one farmer (Pedro) for the coffee shipped under the pilot. The name has been changed to preserve personal confidentiality. E) Chain of custody for one of the green coffee bags in the system. The custody is recorded per product (here green coffee). The full chain of custody can be obtained by tracing the blocks throughout the different transformations and events. F) Roaster profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 4

Summary of challenges (C) and opportunities (O) with using blockchain technology to enable traceability and transparency (regarding product pricing, quality, and sustainability) in coffee supply-chains, as revealed by the pilot model implementation, across three different areas: supply-chain characteristics, technological and organization capacity, and supply-chain governance.

	Supply-chain characteristics	Technological & organizational capacity	Supply-chain governance
Traceability	Blockchain can establish an immutable chain of custody (O) which can increase efficiency and reduce fraud, but… …due to mixing and processing, this is likely to raise prices and might prove impossible for conventional (bulk) coffee (C).	Lacking capacity, unfit infrastructure, missing data, and the investments required to learn a new system is a barrier to adoption (C), but… …adoption may modernize supply-chains and spark interest (O). A blockchain system can facilitate integration of databases across supply-chain actors (O).	The implementation of blockchain can facilitate supply-chain integration (O). Blockchain can support farmers in branding their coffee (which may not benefit all farmers equally or risk excluding certain segments) (O/C).
Transparency	Self-reported farm-level sustainability information cannot be validated by downstream actors (C). Only pricing (not profit) information can be transferred downstream (C).	Blockchain can be integrated in supply chains to increase information availability and accuracy on various sustainability-related indicators (O), but… …the cost is prohibitively high and most supply chains are largely analogue, thus requiring significant upgrades (C)	Transparency on pricing along the supply-chain can promote fairness (O). Transaction costs and lack of price premiums might contribute to further cost squeezing for farmers (C) Providing sustainability-related information can incentivize actors to adopt sustainable practices (O)

cooperative's responsibility to organise and conduct the trainings and deal with privacy aspects, access rights, and other data-related issues, further increasing their costs. At the same time, the cooperative expressed that the next generation of coffee producers is not interested in farming, and blockchain might be a way to spark interest, as it promises modernization and the connection between farmer and consumer.

The fact that many supply-chain actors (cooperative, mill, roaster, etc). already have established IT-systems is a solid foundation for a blockchain-enabled system. However, during the pilot, we realised that the coop database is not up to date. An automated and more regularly updated system, as the blockchain presented here, would reduce such data mishaps, as farmers would have direct access to their own data. One employee of the cooperative reflected: *"I believe that blockchain could also help to secure the information of each of the actors from farmer to roaster, so that we can easily follow-up, keep databases up to date and streamline."*

Also, with participants at each supply chain stage having different data systems and data and information requirements, the blockchain-based system can integrate or replace different database systems. A more fundamental challenge is to digitize the parts of the supply chain that are still analogue (i.e., with paper-based proof of transactions such as contracts and Bills of Lading), in some cases due to legal requirements. This is currently the case for the transaction between farmer and PP, where the farmers receive a printed receipt for record-keeping. In such cases, blockchain-enabled systems could provide several advantages and could be layered on top of analogue systems to provide additional security. However, additional data requirements increase the transaction costs, leading to increased consumer costs, which will not necessarily benefit the farmer, but just cover the costs of implementing blockchain.

5.3. Governance and agency

Theoretically, blockchain systems' peer-to-peer transactions and automatic execution through smart contracts can alter governance structures by eliminating middlemen, allowing improved data access and control (Balzarova and Cohen, 2020), and ensuring timely and complete payments (Kos and Kloppenburg, 2019). Here, we do not test smart contract execution, but only data collection, access and sharing. Tripoli and Schmidhuber (2018) argue that these aspects enable greater trust, as *"actors can now do business without intermediaries brokering trust, knowing that each participant has a transparent track record and that the ledger and smart contract will execute payment only once contractual agreements are met."* However, we would argue that blockchain does not reduce the need for trust, but replace this with a reliance on technology (Deley and Dubois, 2020), while it is the process of implementing the technology that builds trust across the supply chains, as actors need to collaborate closely to implement the system (Schmidt and Wagner, 2019).

The implementation challenges encountered here support the argument that blockchain can only be implemented where existing relationships are already stable and well developed, as it requires cross-supply chain collaboration and knowledge-sharing. Köhler and Pizzol (2020) note that *"blockchain-based technologies in the supply chain requires the participation of many if not all actors along the supply chain, as well as intense coordination and collaboration among them."* As such, Leong et al. (2019) caution to consider the necessity and feasibility to implement a blockchain system in a specific supply chain, as blockchain technology is more appropriate in certain cases than others.

A representative of Peter Larsen Kaffe reflected: *"If it does not work in Colombia, where the supply chain is relatively formal and well-established, where else would it work?"* Due to lacking mobile network and access to internet, as well as limited technological know-how among farmers, the cooperative plays a key role in technology diffusion. Even today, coffee producers in Antioquia rely greatly on the cooperative for both sale and extension services (Singh et al., 2022). The increased supply chain coordination, rather than the technology itself, might be one of the key benefits of blockchain. Blockchain adoption among smallholder farmers might strengthen the coffee grower community through peer learning and attract interest among the next generation of coffee growers. In addition, it could further enhance ties to the cooperative, which is a key promoter of sustainable farming practices.

A blockchain system will likely alter power structures among participants. Generally, transparency implies a shift in power relations in supply chains (Egels-Zandén et al., 2015), and the question is whether those currently benefitting from supply chain opacity will be willing to give up their advantage? On the upstream level, benefits may not accrue to all farmers equally, as farmers can curate their own brand. This means that blockchain implementation will benefit some farmers more than others (e.g., the less technologically or business savvy). While blockchain can empower producers through increased information about downstream actions, there is a risk that the cooperative is bypassed if blockchain facilitates more direct trade (linking consumers via roasters to producers), though the infrastructural lock-in provided by the cooperative reduces this risk. With transparent pricing, the exporter and importers may lose power, as it would be made visible what these actors pay upstream actors (e.g., importer to cooperative, exporter to importer), reducing their negotiation power with downstream actors (importers and roasters, respectively).

Blockchain implementation may provide incentives for fairer pricing if all actors in the supply chain can see prices along nodes, though the knowledge about pricing might be taken out of context, as it shows only transactions, not profits. Employees from the cooperative reflected: *"If we make the information more visible, that would be fairer for everyone. We understand that every time a product undergoes a transformation, it will gain value, but I am not sure how the producer will interpret the price data. Educational spaces should be created to make the producer understand that part, that each of the actors in the chain has to cover their operating costs at a minimum."*

However, even in decentralized systems, lead actors, such as importers and roasters, still hold more power. This enables them to tailor blockchain systems to their particular supply chains, which could lead to the creation of several disparate systems at the upstream level, increasing cost and complexity for actors at that level (Lee, 2018). As such, blockchain implementation might further exacerbate the sustainability-driven supplier cost squeeze (Ponte, 2020), as time and resource investments, but also business risks are disproportionally higher for coffee producers. Further, it can also enable more power concentration for "owners" of the data, if the system is implemented on a permissioned or private blockchain. This makes it important that all actors share data and provide equal access, as already existing information asymmetries can increase if powerful actors have preferential access to the system.

A blockchain system will also affect the agro-food product characteristics. Establishing provenance allows for identification of quality back to farm. Therefore, low-quality and spoiled coffee can be easily identified and removed from chain, which increase food safety and overall quality (Leong et al., 2019), as easy tracing (both up and downstream) makes recalls easier (Pavlić Skender and Zaninović, 2020). However, this bears reputational and income risks to farmers, e.g., if the coffee quality is bad for reasons beyond the farmer's direct control such as climate change.

Blockchain also provides opportunities for identifying and realizing synergies between different actors. For example, the cooperative cups and profiles their farmers and thought that it would be beneficial if this information could be made accessible to other actors. Vice versa, the cooperative showed interest in receiving the cupping scores from Löfbergs' purchasing department. The more information the roaster has about the coffee (e.g., variety, fermentation times, etc)., the more they can experiment with roast profiles, which improves quality and provides options for tailor-made products. The chief roaster from Peter Larsen Kaffe was astonished to see the differences between the six coffees and could identify different fermentation times and processing techniques; normally, these beans would be mixed at milling, meaning these nuances get lost. Therefore, blockchain technology allows the roaster to market coffee based on quality and characteristics, and as less mixing takes place, individual coffees can be of higher quality and thus fetch increased price to both farmers and roasters.

The information could also flow the other way, as farmers could tailor production according to consumer or roaster demands (e.g. washed/natural, fermentation time, etc). which allows actors (roasters, consumers, etc). to make more informed decisions about the product according to preferences. The cooperative may benefit from better tracking and information, which allow them to provide better feedback to the farmer, which can help improve operations and overall farmer support. This leads to higher quality coffee, which again increase prices and thus farmer livelihoods. If blockchain allows farmers to better market their products and result in livelihood benefits, the coop – being a social enterprise – will profit from that as well. All these aspects provide incentives for farmers to grow better coffee. However, our pilot also showed that delays are more likely due to increased product handling and separation, which could affect the quality of the final product.

Blockchain potentially provides a first step to enable cross-supply chain sustainability. It meets several of the conditions for improved sustainability governance: traceability, transaction, activity and certification information, but not impact and effectiveness information (Gardner et al., 2019). All participants have increased information about sustainability practices at each node, which provides incentives for actors to adopt sustainability practices. Fig. 4 shows sustainability practices for selected farmers in the pilot, but indicators can be tailored to specific supply chains and actors. As coffee farmers are typically not rewarded for sustainability (i.e., price premiums are low or non-existent), there is currently weak incentives to adopt additional practices. Nonetheless, the increasing information on sustainability can potentially raise demand for sustainable production by better informing consumers about sustainability impacts and increase the awareness of the environmental and social footprint of coffee and the global inequalities that underpin the sector.

A caveat is that the selected sustainability indicators might not include the aspects that have the largest impact. Further, farmers can be recognized for their sustainability practices, which is a unique selling point and a potential price differentiator (provided that roasters or consumers are willing to pay for this, which is highly uncertain).

Blockchain systems are also likely to affect certification standards (Köhler et al., 2021). The system could facilitate data sharing and access for auditors, which could increase efficiency and provide (near real-time) access to certification reports and data for supply chain participants. Further, the provenance to farm provides increased reliability that the coffee matches the certification standards, which enhance consumer trust in certification standards. Currently, our pilot only shows which certification standards the farmer claims to adhere to; information which can be cross-checked against third-party audits and to match specific coffee batches to farmers certified under specific standards.

6. Conclusion

The aim of this study was to assess the real-world potential of blockchain technology to promote sustainability in coffee supply chains through increased traceability and transparency. While our pilot implementation clearly illustrates certain benefits of blockchain, it also suggests that blockchain is no silver bullet for coffee sustainability. Although hailed as the ultimate system for supply chain transparency and sustainability, our study suggest that the real value of blockchain and decentralized technologies for agro-food supply chains might lie in digitising the supply chain to increase efficiency and reduce costs, disputes, and fraud, while providing more insight end-to-end through product provenance and chain-of-custody information.

However, these aspects can also be achieved through centralised, less-costly digital supply chain solutions and do not necessarily require the decentralization provided by blockchain. In the case studied here, the lack of digitization, the low value of most products, and the lack of technological know-how and access among many actors implies that a blockchain is likely too costly to implement and brings too few benefits to justify the expense. These problems are likely to apply to many other coffee and agro-food supply chains, especially mass-market, non-segregated chains involving a large number of smallholder farmers. Current limitations makes high-end, specialty, direct trade or other segregated supply chains more ideal candidates for blockchain implementation, but the additional value of the blockchain is likely less in these cases, as fewer actors with higher levels of trust interact.

At the same time, our study also highlights many of the benefits that actors across the supply-chain see from increased digitization that facilitate transparency and information sharing. Studies such as this can help in designing such digital tools (be they blockchain-based or not) to consider key aspects—the incentives for actors to change their standard system; how connected the supply chain is; what the level of trust is; if there are existing technological systems implemented; where the chain is still paper-based; how available various technological options are; whether the actors are used to using technology; and how available and stable digital data transfer is—to reap these benefits and assure they are equitably shared among actors. More research is needed to assess how blockchain and other technological solutions work when implemented in real-life settings and not only as theoretical constructs. As we show here, most barriers to adoption exist within the real world, not the digital, highlighting a need to understand and minimize these before we can reap the full benefits of digitalization and decentralization.

Declaration of Competing Interest

Christina Singh is employed with Löfbergs/Peter Larsen Kaffe as of 1 November 2021. During the entire duration of the project that this paper concerns, she was employed with COWI A/S (project partner) and not otherwise affiliated with Löfbergs/Peter Larsen Kaffe. The remaining authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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