Blockchain-based traceability framework for agri-food supply chain: A proof-of-concept

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Abstract

This paper outlines the integration of blockchain technology (BCT) into agri-food supply chains (AFSC) and provides a comprehensive framework for organisations interested in adopting Blockchain (BC)-enabled traceability. Collaborating with an agri-food-based use-case organisation and a technology provider, the authors present a use case for the deployment of BCT in honey and coriander powder supply chains. The proof-of-concept (POC) for the BC-based traceability framework was developed with inputs from both the use-case organisation and the technology provider. The findings suggest that the demand for improved traceability may incentivise adoption within specific operations of the agri-food business despite existing challenges. Additionally, the pilot study introduces a cost framework, delving into the developmental and operational costs associated with the developed POC. Furthermore, the paper discusses stakeholders' perspectives by exploring challenges faced during the implementation phase and highlighting the perceived benefits of adoption. Positioned at the intersection of the agri-food sector, digitalisation, and the growing demand for information and product integrity, this research emphasises the unique potential of BCT. In practical terms, this study can serve as a valuable step-by-step guide for managers seeking to understand the process of BCT implementation in AFSC, offering insights into the operational and strategic aspects of adopting BCT.

***Keywords**:* Proof-of-concept, blockchain technology, traceability, agri-food sector, supply chain, transparency

1. Introduction

An agri-food supply chain (AFSC) is defined by various actors, like producers, suppliers, wholesalers, retailers, and customers (Vern et al., 2022). The AFSC is important from both an economic and political standpoint. AFSCs are the most regulated and protected supply chains with their implications on the environment, employment opportunities, and fulfilment of human needs (Joshi et al., 2020). AFSC needs to function smoothly and successfully in a volatile business environment as they are responsible for providing affordable, safe, and sufficient food, feed, fiber, and fuel to consumers. However, building robust and seamless AFSC operations is challenging due to various risks (Zhao et al., 2020). The AFSC differs from other supply chains in a number of ways due to its distinct characteristics, dependencies, and complexities, such as seasonality, perishability, regulatory compliance, globalisation, technological innovation, and consumer trends (Sporleder and Boland, 2011). The complexity of networks within the supply chains invites numerous risks, such as supply disruptions, fragmentation, poor product traceability, food contamination, difficult food recall, and food safety (Patidar et al., 2022). Managing and reducing associated issues is challenging due to the multiple functions and stakeholders in AFSCs (Srivastava & Dashora, 2021). Any failure or occurrence of any risk in AFSC directly threatens food safety. Therefore, traceability is required to track food, feed, and ingredients through production, processing, and distribution (Mor et al., 2021; European Commission, 2002). Including traceability and transparency in the AFSC may help reduce the risks (Reddy et al., 2022). It is essential to adopt food traceability systems (FTSs), which can identify, capture, record, and display information throughout all stages of the AFSC (Zhou & Xu, 2022). FTSs help to automate information sharing among AFSC stakeholders (Curto & Gaspar, 2021).

The evolution of FTSs started with the use of radio frequency identifications (RFIDs) and near field communications (NFCs) integrated with electronic product code information service standards (Islam et al., 2021). These systems deployed in AFSC aid visibility and traceability, reduce food waste, and enhance operational efficiency. FTS helps AFSCs move towards a digital and data-driven food system; however, numerous fundamental challenges remain unsolved. For example, lack of continuous monitoring, data fragmentation, and lack of transparency caused by discrepancies and inconsistencies (Rejeb et al., 2020). Responding faster and more accurately to food safety and quality outbreaks is challenging without comprehensive and real-time product information (Ameri et al., 2022). Furthermore, FTSs used in AFSCs are usually centralised, monopolistic, asymmetric, and opaque, which may cause trust issues among stakeholders, including consumers (Zhao et al., 2019). That is why AFSCs are slowly shifting towards automation (Shahid et al., 2020). With the advances in information and communication technologies, AFSCs are shifting towards emerging digital technologies for extended traceability and transparency (Latino et al., 2022). Blockchain technology (BCT) has recently captured significant attention in this domain (Pearson et al., 2019; Khan et al., 2023; Sharma et al., 2023). BCT is a digitally distributed ledger for capturing and storing consistent information between stakeholders in a decentralised, secure, and trusted manner.

The study has opted to focus on the agri-food supply chain to explore the applicability of BCT. This decision is based on numerous studies identifying AFSC as a promising domain for BC integration. The AFSC includes all the stages, from farming, harvesting, processing, transporting, marketing, and distribution to its final consumption. In addition to general risks such as social, political, cultural, and economic, the AFSC faces vulnerability because of perishability, seasonality, climate changes, quality, and safety standards. The AFSC operations have an impact on socio-economic factors (employment and income), the environment (climate), and food security (nutrition). The AFSCs are inherently complex and distinct compared to other manufacturing/service supply chains because of their specific complexities, making them susceptible to disruptions and challenges. Studies have highlighted promising implications of the BCT in this domain as it enforces end-to-end traceability, transparency, information symmetry, and high visibility in AFSC (Vu et al., 2022). Although much research has been conducted in this domain as innovation in BC architectures, applications, and business models are evolving rapidly, there is a need for an effective traceability framework for AFSC (Hameed et al., 2022). Its potential benefits have prompted supply chains to consider implementing the technology (Kouhizadeh et al., 2021). However, the operational applicability of the BCT in AFSC is still underexplored. Bumblauskas et al. (2020) suggested more research on specific countries and food products. Also, Duan et al. (2020) highlighted the need to conduct more real-world studies on blockchain implementation by focusing on various supply chains, i.e., agri-food.

Similarly, studies have highlighted the need to study the overall costs associated with blockchain implementation, such as developmental and operational costs (Nayal et al., 2023; Agi et al., 2022). Currently, the adoption of BCT in the agri-food supply chain is in the early stages, and only a fraction of BCT projects have reached the fully operational stage (Kramer et al., 2021; Rana et al., 2021; Difrancesco et al., 2023). Thus, it is essential to assess the operational applicability of BCT in AFSC using real-world scenarios. Therefore, the study proposes the following research objectives to address the gaps:

a) *Conceptualising and developing a proof-of-concept for a blockchain-based traceability framework for the Indian agri-food supply chain.*
b) *Identifying and discussing the different cost components of the proposed proof-of-concept.*

The study presents a proof-of-concept (POC), a fully decentralised, BC-based traceability framework for the agri-food supply chain to address the defined objectives. The POC will help to understand the feasibility of adopting Blockchain for the Indian AFSC. Subsequently, the study also discusses the stakeholders' perspective by discussing the challenges faced during the implementation phase and the perceived benefits of adoption. The aim is to provide preliminary knowledge on implementation challenges and benefits to agri-food organisations interested in adopting a BC-enabled traceability framework. The study also discussed various cost components that will help determine the feasibility of POC. The authors realised the motivation and scope for the study due to the scarcity of practical use cases of BCT adoption in the complete supply chain of any agri-food commodity in India. Wider application of BCT is constrained due to high implementation costs, the need for technological upgradation, unfamiliarity with technology, and technological infeasibility (Vern et al., 2023). Still, these and many other constraints cannot nullify the advantages of adopting BCT in AFSC. This is where the need for the study arose, which can give a real-life case scenario of BCT adoption in the Indian ecosystem as a complete framework of tamper-proof digital traceability. From a managerial lens, the study addresses several case-specific issues that could provide helpful feedback to agri-food organisations interested in transitioning to a BC-enabled traceability framework. Furthermore, organisations can use the findings to assess the deployment of BCT by weighing the expected challenges and benefits. The cost framework will help organisations decide if they have the financial and IT capabilities to adopt BCT. This research aims to assist academics and practitioners in adopting a holistic viewpoint and realising the potential of BCT in AFSC, considering the challenges, implications, and limitations.

This paper is organised as follows. Section 2 presents the literature review, whereas subsection 2.1 presents the technical fundamentals of BCT. Subsection 2.2 discusses the characteristics and benefits of BCT, and subsection 2.3 reviews the existing BCT framework. Section 3 describes the design methodology, and section 4 annotates the results, where subsection 4.1 presents the BC-based traceability framework (POC) and its features. Subsections 4.2 and 4.3 discuss cost components and various benefits and implementation challenges of POC, respectively. Sections 5 and 6 discuss the implications and conclusion of the study, followed by limitations and scope for future research.

2. Literature review

The study aims to develop a blockchain-based traceability framework for the agri-food supply chain. It was essential to understand the fundamental concepts of BCT to achieve the objective. The review strategy adopted by the study involved the following steps (Yadav et al., 2020; Bag et al., 2020): Firstly, key search terms were identified to address the search criterion. The key search terms included blockchain technology/Blockchain, agri-food supply chain, food industries, food traceability, food traceability systems, and traceability/BCT framework. Further, these terms were combined to search and extract the articles published in the domain. The major research databases utilised were IEEE Access, Science Direct, Springer, Emerald, and other reputed research databases. The time frame considered for the search was from 2019-2023. The articles were collected based on the search criterion for the literature review. Accordingly, the further sub-sections provide a foundation for BCT.

2.1 Blockchain technology

Blockchain technology is considered the next emerging disruptive technology. It can alleviate issues such as counterfeiting and traceability in traditional AFSCs involving multiple layers of stakeholders (Oguntegbe et al., 2022). BC came to light in 1991 when Stuart Haber and W. Scott Stornetta discussed "How to times-tamp a digital document" (Haber & Stornetta, 1991). Later, in 2008, Nakamoto introduced Bitcoin, Ethereum, and other cryptocurrencies as applications of BC (Nakamoto, 2008). BCT is a distributed ledger technology used to maintain and manage digital data. It can be described as a data management system that allows time-stamped "blocks" of data gathered from decentralised sources to be linked together to create a "chain of blocks" as well as to implement the system securely (Collart & Canales, 2020).

Understanding the fundamentals of the various layers of BC architecture is essential. BC architecture has five layers: hardware, data, network, consensus, and application. The hardware layer consists of the physical components required to support and sustain the operation of the BC network, including servers, nodes, cables, connectors, and any other required infrastructure. The data layer is the central component of the BC network as it provides the linked list of blocks of data that contains all the information about transactions. The network layer includes the data transmission protocol and verification system. The privacy and security of the system are also part of the network layer. A consensus layer generates and validates blocks and enforces the rules, allowing a decentralised system to establish consensus. Finally, the application layer creates the user interface, which bridges the user and the BC network.

BC is composed of blocks of data that are chained in chronological order. A block is a record with data, the previous block's hash code, and the current block's hash code. Each block is divided into a header and body, and a hash is used to identify each block. Metadata is stored in a block header, including a time-stamp, block number, hash code, difficulty, nonce, and Merkel root (Figure 1). The significance of the cryptographically linked chain of blocks explains the link between the hash codes of the current block and the previous blocks (Demestichas et al., 2020). Thus, the current block hash code is created by cryptographically transforming the previous block's hash code, the current block's hash code, and transaction data. The data on the BC is immutable due to the link of blocks through hash codes. The difficulty is the time BC users take to solve the mathematical puzzle. The genesis block is the first block in the chain of blocks. Blocks are stored in a Merkle tree schema where leaf nodes store the transaction data. The root node hash codes are created via the cryptographic conversion of hash codes from their immediate subtrees (Karamchandani et al., 2021). BC relies on a consensus mechanism for the validation of these data blocks.

The ledger is replicated at each node in the decentralised system. Participants in the system confirm the changes with one another, and transactions are validated through consensus (Feng et al., 2020). This helps in preventing data tampering within the system. The distributed consensus algorithms can take various forms to maintain the data integrity of the transactions, i.e., majority voting, priority voting, or a minimum number of votes (Hald & Kinra, 2019). There are multiple types of consensus protocols, such as Proof-of-work (PoW), Proof-of-stake (PoS), and other protocols (Demestichas et al., 2020). In PoW systems, the algorithm requires BC members to solve a cryptographic puzzle to validate transactions and create new blocks to mine bitcoins as a reward. This system requires vast processing power, which consumes energy to solve mathematical puzzles.

This system is utilised in networks with unknown BC members, and trust is developed through consensus algorithms. PoW consensus can result in substantial economic problems due to the high consumption of natural resources. Alternative solutions, such as proof-of-stake, were proposed to address such issues (Kamilaris et al., 2019). PoS systems are more energy efficient than PoW. The algorithm randomly selects the BC members and weights their votes based on their stake levels in the BC, such as assets and cryptocurrencies. PoS is more decentralised than PoW as it only allows limited BC members to mine for new blocks. PoS algorithms are less expensive compared to the equipment requirements for PoW (Andoni et al., 2019).

There are three types of BC platforms: public, private, and consortium. All BC platforms have distributed ledger technology, peer-to-peer transactions, and a consensus mechanism. These platforms are based on the level of access provided to the participants for the consensus of a block. A public BC is an open and distributed platform allowing all members to access, manage and validate transactions. A public platform is a permissionless network, making it difficult to identify users. Anyone can access the transactions, due to which privacy and security comprise publicly available sensitive information. A proof-of-work consensus mechanism/protocol is utilised in the permissionless network. The scalability of this network is low due to many nodes (Kumar et al., 2019). Only a set of participant nodes in a private BC can access and validate transactions. Security and privacy are high as authorised users view all transactions. The scalability is relatively high as there are fewer nodes (Kramer et al., 2021).

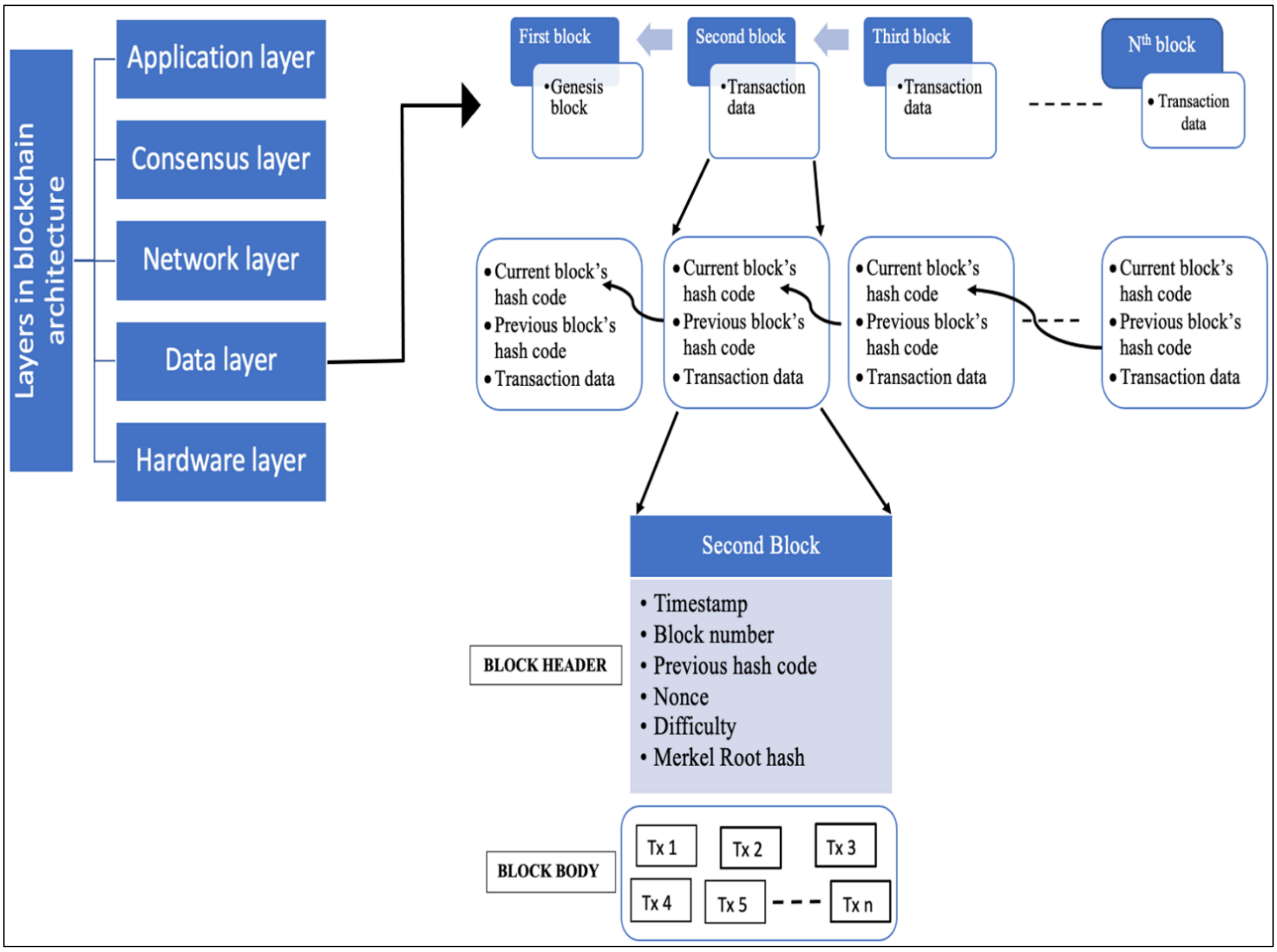

Figure 1. Architecture of Blockchain (*Source*: Authors own creation)

A consortium platform is also known as a hybrid system where the users have read-only access to the BC. The central authority grants access to only a selected group of participants to publish a new block (Santhi & Muthuswamy, 2022).

2.2 Characteristics of Blockchain

Blockchain has four fundamental characteristics that translate into its benefits: Decentralisation, immutability, consensus, and smart contracts (Kumar et al., 2019). Decentralised records replicate data across numerous computers or nodes on the BC network. It allows transactions to be processed even if a node on the BC network fails, maintaining data integrity and protecting against hacking (Yang, 2019). The data stored on the BC is immutable, making it tamper-proof (Singh & Sharma, 2023). It is difficult to tamper with the data on the block as permission from each node is required to admit it (Wu et al., 2019). Consensus mechanisms assist a distributed or decentralised network in unanimously agreeing whenever required (Seibold & Samman, 2016). The consensus mechanism helps BC nodes reach consensus on the entire network. It assures that the recent block is correctly uploaded to the BC, allowing the BC information to be stored consistently by the node. The consensus solves the problem of BC consistency and efficiency (Sankar et al., 2017). Smart contracts imply BC code that automatically executes the contract terms among the stakeholders upon fulfilling contract requirements (Kumar et al., 2019). The contract is initiated after the parties provide their agreement via their BC private keys. Its use reduces transaction costs associated with traditional contracts or the cost of contracting (Francisco & Swanson, 2018).

Furthermore, BCT exhibits additional noteworthy characteristics, including distributed ledger, disintermediation, detrusting, transparency, credibility, and anonymity (Vern et al., 2024). BC's detrustful nature eliminates the need for parties to trust one another, instead relying on cryptographic algorithms and consensus mechanisms to ensure transaction validity and security, thereby reducing the risk of fraud and manipulation (Tharatipyakul and Pongnumkul, 2021). BC enhances credibility and anonymity by offering an immutable and transparent transaction record, making it impossible to alter or tamper with existing or new data. Transactions on BC can be carried out in a trustless environment while maintaining anonymity through virtual identity codes and cryptographic keys (Torky and Hasanien, 2020). This anonymity improves the security and credibility of transactions while safeguarding the privacy of all parties involved. BC facilitates disintermediation by reducing or eliminating transaction intermediaries, simplifying operations, and reducing costs (Toufaily et al., 2021). BC removes the need for intermediaries by enabling peer-to-peer interactions and automated smart contract execution (Wünsche & Fernqvist, 2022). Its distributed ledger architecture ensures data is shared, replicated, and synchronised among network participants (Santhi et al., 2022). This ensures that no single entity controls the entire network, mitigating the risk of data manipulation and tampering (Thume et al., 2021). Finally, BC offers unparalleled transparency by allowing recorded data on the ledger to be accessed and traced by involved parties (Dutta et al., 2020). Every transaction is recorded in a sequential and immutable manner, resulting in a transparent audit of all operations. This transparency improves the trust among participants and assures accountability by making the whole transaction visible and verifiable by all stakeholders (Yang, 2019).

2.3 Blockchain-based traceability in AFSC

Blockchain technology creates a smarter and more secure agri-food supply chain by providing a clear and robust real-time audit trail of tracked products. BCT helps monitor production parameters such as the flow of raw materials, processing, production, transportation, and delivery to end consumers (Varavallo et al., 2022; Menon & Jain, 2021). Traceability information on food product origin and potential allergens or added compounds, which must be held securely and immutably, can be established and exchanged via a collaborative BC network involving farmers, producers, and distributors. It creates a flow of immutable data that all the actors of AFSC can utilise. The adoption of blockchain technology has sparked considerable interest due to its potential to address longstanding challenges in AFSC (Vern et al., 2024). For instance, BC provides a transparent and tamper-proof way to track the distribution of essential commodities in the public distribution system, thereby minimizing leaks and ensuring efficient delivery to recipients (Kumar, 2021; Thakare et al., 2021). Additionally, BC-powered smart contracts enable automated and trustless execution of agreements, eliminating the need for intermediaries and streamlining operations across various industries, including AFSC (Liu Y et al., 2021; Ronaghi, 2021). BC offers a distributed ledger system that records all supply chain transactions from farm to fork in food traceability. It also improves food safety by promptly detecting contamination sources, facilitating compliance with regulatory standards, and improving consumer trust (Salah et al., 2019; Dutta et al., 2020). Studies have also investigated how Blockchain might improve operations in precision agriculture. BC has the potential to store securely and exchange data gathered from sensors and Internet-of-things (IoT) devices, which will assist precision agriculture by empowering farmers to make data-driven decisions for better crop yields and resource allocation (Liu W et al., 2021; Torky and Hassanein, 2020).

Similarly, BC can be utilised to practice smart farming to create immutable records of agricultural operations such as planting, irrigation and harvesting (Lin W et al., 2020; Liu P et al., 2020). These records may be shared among farmers, suppliers, and consumers, promoting greater transparency and accountability in the agricultural value chain (Zhao et al., 2019). In logistics, BC's applications extend to fleet monitoring, geolocation, and real-time delivery statistics, allowing efficient supply chain management and enhancing stakeholder transparency (Rocha et al., 2021; Remondino and Zanin, 2022). BC reduces the risks associated with theft, counterfeit goods, and supply chain disruptions by securely recording the movements of goods and monitoring their provenance. Furthermore, BC has been studied for its role in the management of credit systems and land registry (Mavillia and Pisani, 2021), business process re-engineering (Johng et al., 2020), certification and auditing (Galvez et al., 2018), cybersecurity (Liu et al., 2021) and carbon footprint management (Shakhbulatov et al., 2019).

Several authors have proposed BC-based traceability solutions for specific food products (Westerlund et al., 2021; Yang et al., 2021; Thume et al., 2021). Tian (2016) proposed a framework utilising RFID (Radio-Frequency IDentification) and BCT to develop an AFSC traceability system to trace cold-chain food. The framework can guarantee food safety by collecting and sharing real-time production, processing, warehousing, and distribution data. This framework is built on the Ethereum platform, which uses a PoW consensus mechanism that requires high computational power and is, therefore, not economically viable (Lin et al., 2020). Authors have studied the role of BCT in maintaining the traceability of meat products and related food supply chains (Ali et al., 2021; Hew et al., 2020; Tan et al., 2020; Chandra et al., 2019; Chandra & Sharma, 2019). Tan et al.'s (2020) framework is based on BCT with a smart contract to improve the traceability of halal food supply chains from farm to fork. The framework solves the issue of maintaining halal compliance by assuring the transparency and traceability of the information across the supply chain. Ferdousi et al. (2020) proposed a framework based on smart contracts using a permissioned BC network for the beef supply chain. Bumblauskas et al. (2020) developed a BC-based traceability solution to track eggs.

Dey et al. (2021) developed FoodSQRBlock (Food Safety Quick Response Block), a BC-based framework to digitalise food production information and use QR (Quick Response) codes to make it easier for consumers to access, trace, and verify it. Lin et al. (2019) created a food safety traceability system based on BCT and electronic product code information services (EPCIS). The management architecture of on-chain and off-chain data will help the traceability system address the data explosion problem in BC. Similarly, Yang et al. (2021) developed a BC-based traceability system for storing and retrieving product information related to the fruit and vegetable agricultural supply chain. A dual storage structure of “database and BC” on-chain and off-chain traceable information was developed to reduce chain load and achieve effective information inquiry. Prashar et al. (2022) put forth a BC-based solution for agricultural products that uses smart contracts to track and manage all transactions and communications among all parties involved in the network. The system validates every transaction, which is recorded and kept in the central database of the interplanetary file system. An Ethereum-based BC framework for the rice supply chain is proposed by Yakubu et al. (2022), in which smart contracts are used to manage and monitor all interactions and transactions between all parties. As a result, stakeholders can access current product quality information through customer feedback, allowing them to make better decisions. Zhang et al. (2020) developed a multimode storage mechanism that integrated chain storage and offered a new system architecture for the complete grain supply chain based on BCT. The following section will discuss the design methodology adopted in the study.

3. Design Methodology

BCT claims to provide complete traceability of agri-food products to AFSC stakeholders and consumers. This study adopts a step-by-step approach to provide a guiding framework for implementing BCT in Indian AFSC to achieve traceability (Figure 2).

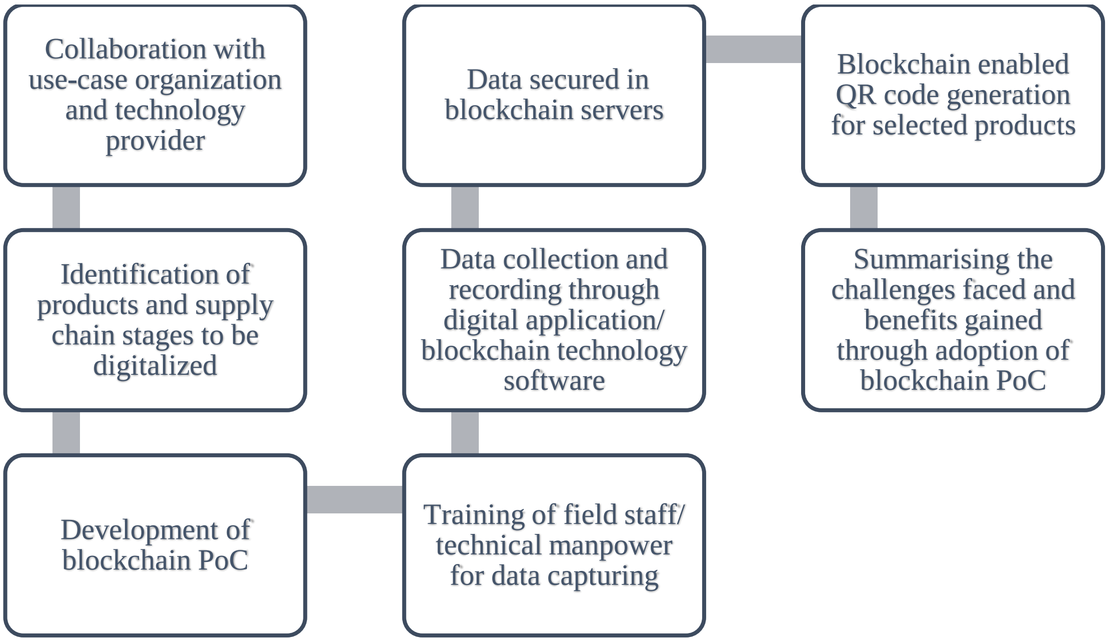

Figure 2. Design Methodology (*Source*: Authors own creation)

The case-based design methodology was commissioned and co-led by collaborating with a use-case organisation (Himmotthan Society, An associate organisation of Tata Trust, India; 'Himmothan' hereafter) and technology provider (CropIn Technologies Private Limited, India; 'CropIn' hereafter). The POC was developed for the supply chain of use-case organisation with the support of the technology provider. Initially, the requirements of use-case organisation were identified. The extensive consultations signified that the use-case organisation needs BC to provide authentic assurance of their product's origin and transparency and traceability of products along their supply chain. Accordingly, the Blockchain POC was tailored per the company's product supply chain requirements. The selection of a BC platform follows this. Cosmos was selected as the BC platform, which works on a proof-of-stake (POS) consensus mechanism. The BC POC was then finalised by identifying the points of traceability.

The data was collected at the field level through digital applications, viz. Smartfarm and Smartware were stored on BC applications based on smart contracts. A unique identifier was allocated to each processed batch, and the data tagging was done. The QR codes were finalised after receiving feedback from the stakeholders. Texts and product images were added to the QR to share the provenance story of the products. Accordingly, the QR codes were generated for each unique identifier. The system captured total and near real-time data across the supply chain so that the management could monitor processes on a single interactive dashboard. The supply chain was also configured to achieve the objective of the study. The QR code provides stakeholders with traceability information for the product.

The potential costs for introducing and managing a BC-based traceability framework were identified through literature analysis. Having identified the relevant literature, the developed questionnaire was based on Mai et al. (2010) and Chryssochoidis et al. (2009). The questionnaire was modified as per the study's requirements. The cost questionnaire was based on the developmental costs during the system planning, designing, and implementation phases and the operational costs linked to the annual costs incurred to maintain and upgrade/modify the system. Subsequently, the questions associated with the system development, operation and maintenance, education and training, data input, and manpower-related costs were developed. The response to each question was recorded from time to time per the inputs received from the technology provider (CropIn) as and when the team proceeded with the PoC development.

4. Results

This section discusses the developed framework for the blockchain-based traceability of the agri-food supply chain. The section highlights the organisational challenges during the implementation phase and the benefits gained after adopting Blockchain POC. It also provides information related to the various cost components of the developed POC.

4.1 Blockchain-based traceability Framework

The study's primary objective is to conceptualise and develop a proof-of-concept based on a use case of the Indian agri-food industry. For this purpose, the study collaborated with a use-case organisation (Himmothan) and a technology provider (CropIn). Himmothan has been working in the central Himalayan regions of Uttarakhand, India, since 2007. They are committed to collaborating with remote mountain communities by creating sustainable community-owned businesses linked to the agri-food industry and various other fields. The use case of honey and coriander powder was considered suitable for the pilot case BCT implementation. As coriander and honey are high-value agriculture crops in the region and provide farmers with greater remuneration, the supply chain of selected products was studied extensively to identify traceability points. In this case, the team worked with Farmer producer companies named Trishulii Producer Company Limited and Pahadi Utpaad Swayat Sahkarita, which are promoted by Himmothan and are engaged in the processing and marketing of Coriander powder and honey, respectively. The following sub-section will describe the steps taken in developing POC in detail.

The Proof-of-concept was built to track data about coriander powder and honey. The development of POC was carried out in three phases, i.e., data collection through mobile/digital applications (First phase), data security on BC servers (Second phase), and QR code generation (Third phase). Figure 3 illustrates a simplified view of the data flow within the system to understand the flow of data capture in the use case.

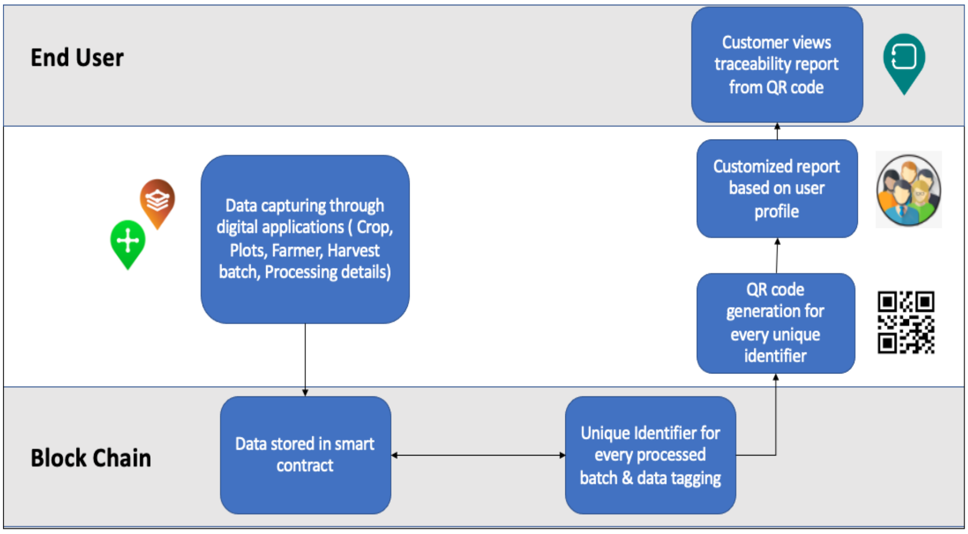

Figure 3. Flow of data (*Source*: CropIn)

a) First phase

In the first phase, the points of traceability were identified. As the land holdings of the farmers in the region were very small and there was a widespread farmer population in the area, it was decided that the collection centre would be the starting point for digitalisation. Training sessions were conducted to enable field staff to collect data at the farm level. These sessions were conducted to teach field staff how to use digital applications. The field staff collected the data through a digital application called SmartFarm. It captured total and real-time data across the supply chain, which helps view and monitor the people, processes, and performance on a single interactive dashboard. It establishes a seamless connection between farmers and the organisation, manages the standard activities, and assures compliance and certification. The platform has been utilised to create digital profiles of the collection centres/self-help groups managed and operated by Himmothan. The interface of the SmartFarm application can be viewed in Figure 4.

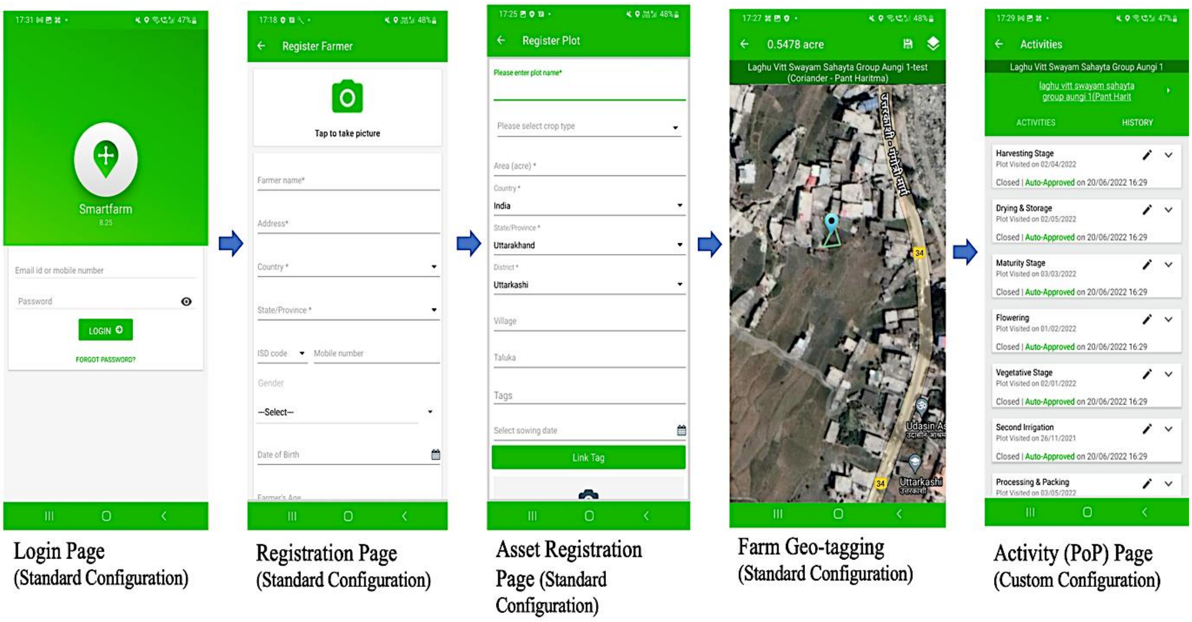

Figure 4. Snapshots of SmartFarm application used for digitisation (*Source*: CropIn)

The digital profiles have data under various categories such as personal information (socio-economic details), communication (phone numbers, emails), farm (Geo-tagged location), crop (varieties grown over time, agricultural practices followed), and production (cultivation data). This application was integrated with another application called Smartware (Figure 5). Smartware has compiled all the pertinent data from collection centres, self-help groups, plots, and planting seasons onto a single platform. The platform has been set up to accompany the user through all the collection points and provide visibility on different supply chain stages. In the case of coriander powder, the data was collected for the sowing and harvesting date, and in the case of honey, the collection, processing, and storage periods were collected.

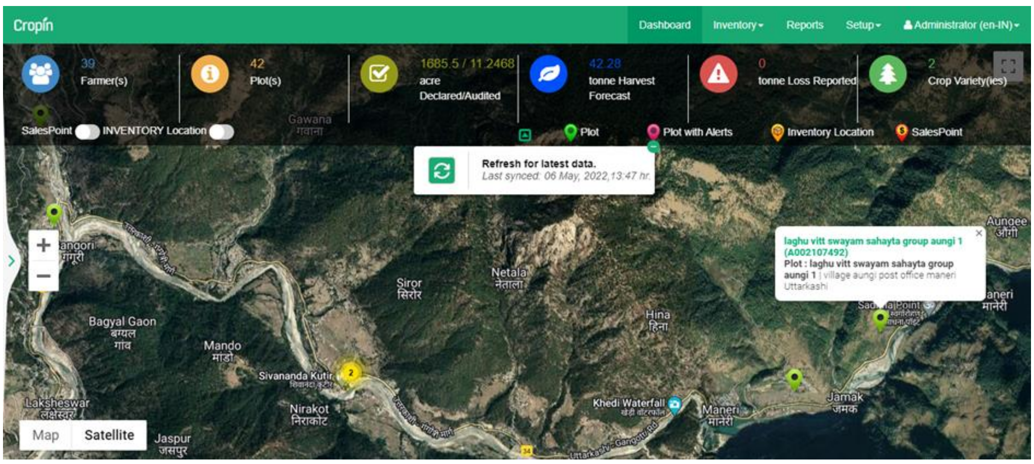

Figure 5. Snapshot of Smartware dashboard (*Source*: CropIn)

b) Second phase

In the second phase, the data captured through digital applications was securely moved to BC servers via an application programming interface (API). A crop harvest plan was added, and the batch number was tagged. Each batch number was associated with a unique identifier captured on the BC (Figures 6, 7).

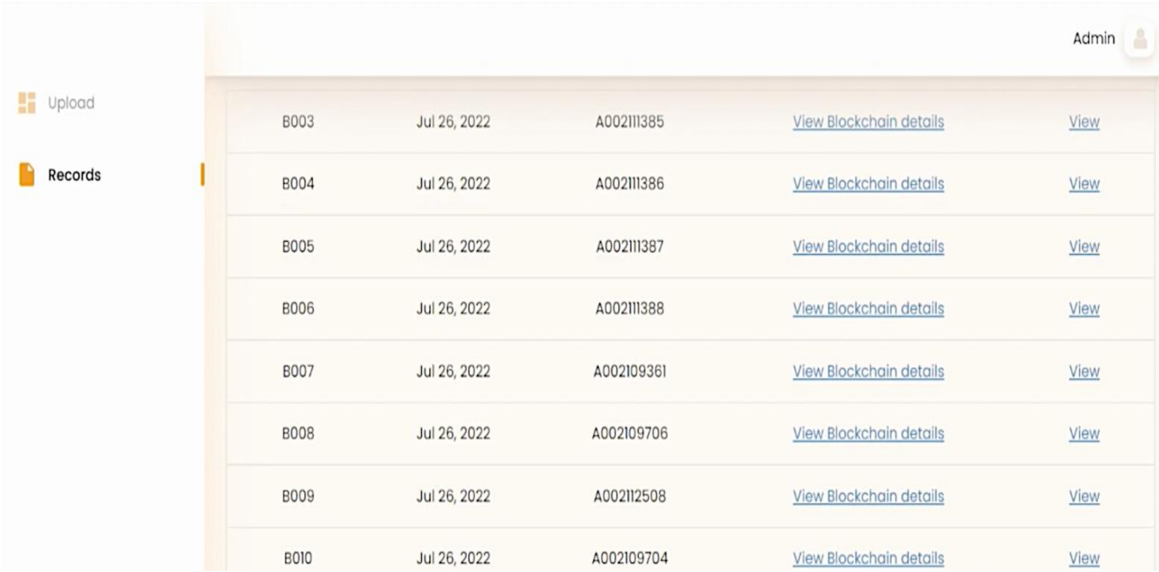

Figure 6. Data on blockchain servers (*Source*: CropIn)

All the data was recorded on the smart contract. A unique ID was created for each batch, which was tied into the BC system. Data from this ID can be retrieved at any point in time.

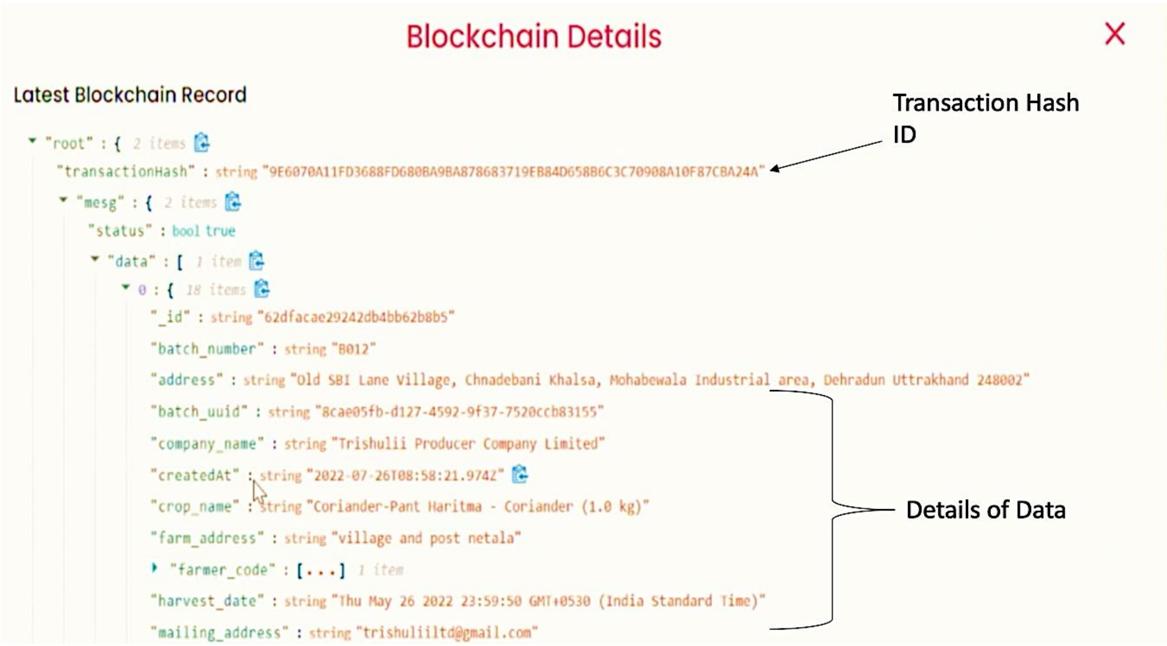

Figure 7. Data stored under the Blockchain and unique "TransactionHash" generated (*Source*: CropIn)

Only the permitted users can access the secured BC networks, strengthening security. Multiple components and technologies were required to track information and make it accessible. Fig. 8 provides a summarised depiction of the POC architecture. The POC blockchain layer was implemented using the *cosmos.network (https://cosmos.network/)* and custom smart contracts allowed relevant parties to update and access the data on the BC based on their role, access, and rights. The technology behind the cosmos is tender mint byzantine fault tolerance (BFT) consensus algorithms developed to guarantee finality, order consistency, and optional availability. A BC application called Tendermint Core offers the equivalent of a web server, database, and auxiliary libraries for BC applications written in any programming language. It is similar to a web server serving web applications.

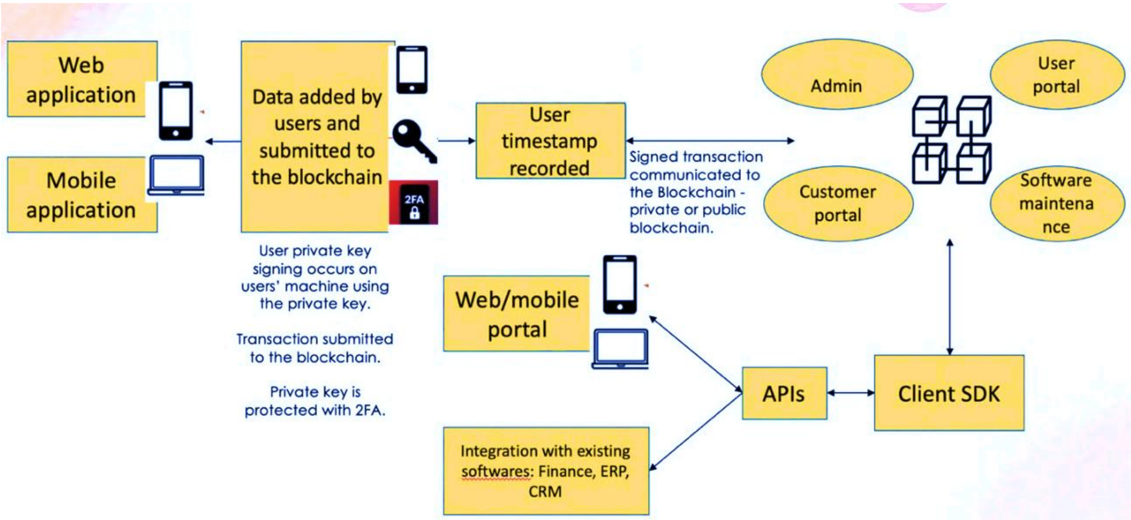

Figure 8. Proof of concept architecture (*Source*: CropIn)

Technical features

a. Consensus mechanism: The POC uses a consensus mechanism called Proof of Stake (PoS). This is crucial since BC consensus is frequently linked to poor performance and significant environmental impact, such as high power and energy usage (Bumblauskas et al., 2020). PoS significantly reduces the amount of energy required compared to proof-of-work and enables the implementation of new scaling solutions. This mechanism reduces the computational work required to verify that BC transactions are secure. All transactions are verified by validators, who then publish the block.

b. Security: Smart contracts on POC are more secure than other chains like Ethereum. Separate smart contracts were developed to accommodate different types of data. Only verified and authentic users had access to the platform. Administrators can specify which users can add/update/alter data in a particular smart contract for each new batch. Customers or end users can only view the specific publicly available data, while private data, such as prices, is encrypted on the BC. Various security measures are utilised to secure the servers. SSL was used to encrypt data and traffic between the systems. The BC servers have built-in security for data privacy, data security, and secure data sharing between the authorised parties. Secp256kq encryption is utilised to encrypt and decrypt data. Secp256kq is a standard encryption mode used in most BC platforms. SSH, or secure shell, is an encrypted protocol that provides a secure connection to servers for administration and communication. With the help of SSH keys, a private and public key pair is developed for authentication. Selected users can only utilise the private key, whereas the public key can be shared with everyone. Firewalls were configured to restrict access to everything except keeping the specific services open per the requirement. This helps reduce the server's attack surface, limiting the components that are vulnerable to exploitation.

c. Throughput: Throughput in a BC refers to the speed at which transactions are processed. In other words, it is the number of transactions per second (TPS) (Santhi et al., 2022). The POC protocol is vertically scalable to 10,000 TPS and horizontally scalable to accommodate considerably higher throughput per the requirement.

d. Interoperability: The developed POC is designed to be a highly interoperable BC with direct-on-chain ties to key BC platforms like Ethereum.

e. *Scalability*: The POC leverages two types of scalabilities: vertical and horizontal scalability. The tender mint BFT can reach thousands of transactions per second in vertical scalability. In horizontal scalability, multi-chain architectures are the foundation of POC. BCs would theoretically be infinitely scalable, with several chains operating on the same application under the control of a common validator set. POC supports the creation of sidechains and is horizontally scalable (branches of the main BC).

f. Type of blockchain platform: POC is a consortium BC platform. It is a combination of private and public BC platforms. Blockchain nodes can be hosted on public and private BCs. It can provide public and private key pairs to the stakeholders.

c) Third phase

The QR codes were generated for each unique identifier in the third phase. AFSC stakeholders can utilise the generated QR codes. Upon scanning the QR codes, stakeholders can view the complete traceability data for the products.

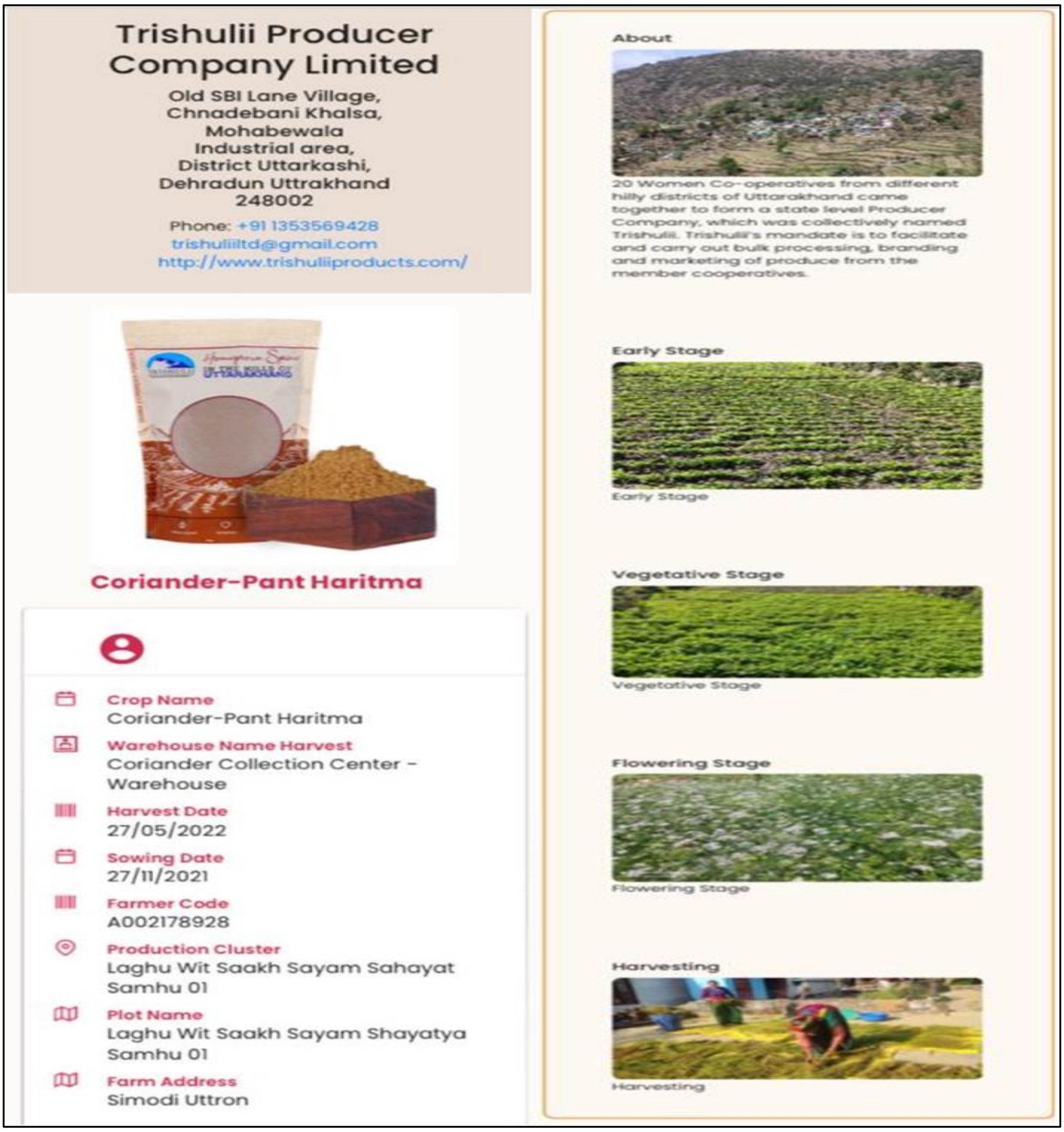

Figure 9. Traceability information of Coriander Powder (*Source*: CropIn)

Figures 9 and 10 present the traceability information stakeholders can view by scanning QR codes.

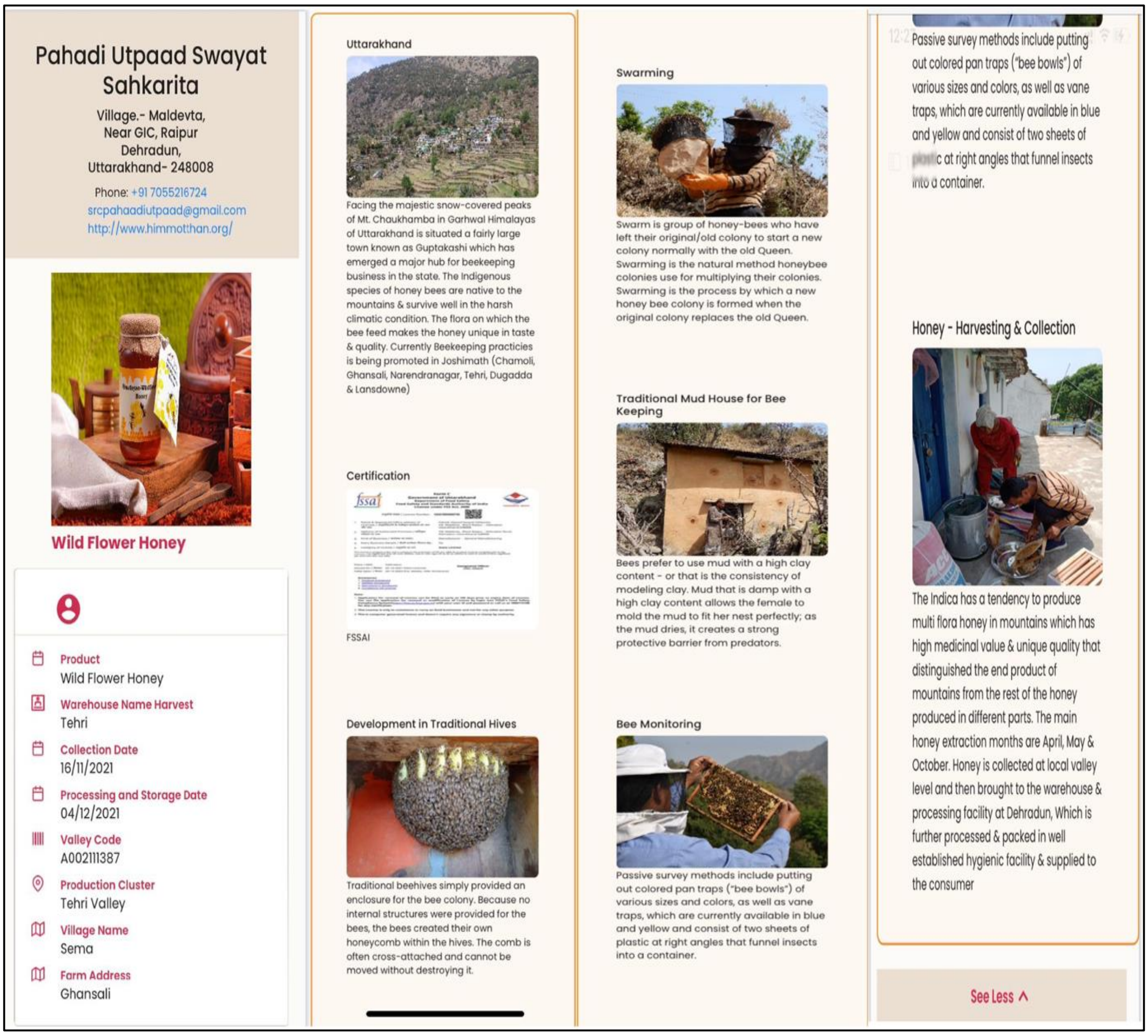

Figure 10. Traceability information of Honey (*Source*: CropIn)

4.2 Cost components of blockchain POC

This sub-section sets out the results of the questionnaire related to cost components. The findings of the two cost categories, developmental and operational costs, related to system development, operation and maintenance, education and training, data input, and manpower-related costs, are summarised in Tables 1 and 2.

Table 1. Developmental costs related to the proposed POC

Cost category	Components	Inputs/points based on the response from technology provider (Source: CropIn)

1.	Hardware	a) What will be the cost of purchasing the required IT infrastructure components (identifiers, printers, scanners, etc.)?	a) It would depend upon the scale of the specific industry. The full traceability system, i.e., from the tag printing to labelling at the farmgate to scanning of codes, storage, and end customer delivery, would need printers for tag printing, mobile devices for data recording and viewing, scanning, and allocation to production lines or storage. The phone, laptop, and printer costs would be around ₹10,000, ₹70,000, and ₹50,000, respectively.
		b) Will there be a requirement to purchase a computer system to run the BC system?	b) No Specific infrastructure is required to work on a BC-based traceability system. The system is cloud-based, and end users can access it through regular mobile/tabs and computers already in use. The cost of the computers will be around ₹ 70,000.
2.	Software	a) What will be the cost of the BC-based traceability software/ platform?	The software cost varies based on the scale of implementation and the requirements. The cost for a state-level BC implementation will depend on the number of farmers per season. This would be an annual cost based on usage and subscription.

		b) What will the cost of QR tags/stickers be? (Cost per tag/ sticker)	It depends on the QR code quality and security layers. The cost for QR tags will vary from ₹2- ₹10 per tag.
3.	Communication Devices	a) What will be the cost of the communication equipment installation (such as network adaptors, database servers, network cards, data lines, etc.)?	This is a one-time setup cost. Usually, the BC-based platform is hosted on the cloud, so the costs can be included in the license cost.
4.	Custom Software	a) Will there be a requirement for any custom software development to be designed/installed to meet the needs of the BC-traceability system?	Usually, it will not be required for the general use case. It will only be required if there are specific requirements. The cloud would have multiple backend applications to support it.
		b) If yes, what will be the cost of any in-house application development specifically designed to meet the needs of the BC-based traceability system?	The additional cost would be based on an hourly rate for the specific requirements and developments.
5.	Data input/conversion / modification/ upgradation	a) What is the cost of recording and storing new information? (Cost per transaction)	The cost per transaction would be approx. 0.20 Rupees/Kg (Per Kg of products traced through the platform) is part of the platform licensing cost.
		b) What is the cost of converting the previously used data types into new	This would be a one-time cost and depend on the data quality and modifications required. This will be part of implementation support

		ones accepted by the new system?	billed at an hourly rate. Also, there is no cost if the data is available in soft (Excel/Word) format.
		c) What will be the cost of data modification/conversion of incorrect data entered into the system?	This would be a one-time cost and depend on the data quality and modifications required. This will be part of implementation support billed at an hourly rate.
6.	System Integration	a) Is there any need for integration with the legacy systems?	Integrating existing software and ERPs is preferred for complete supply chain traceability.
		b) Will there be any need for compliance-enhancing changes within the infrastructure?	Yes, if there is any requirement for certification, the cost will depend upon the same. The data sharing and security protocols can also be integrated simultaneously.
7.	Education and Training	a) What will be the cost of education and training of company personnel? (Cost associated with the time, effort, and material required for the education and training of the project team when planning, designing, implementing, and managing the new system)	A dedicated team will be provided to support the program and end-to-end implementation process. The cost per person would depend on the scope of implementation,
		b) What will be the cost of education and training of farmers*? *Will this cost be included in the cost of	Training of farmers would be the responsibility of the industrial partner (Government representatives or associated organisations like cooperatives and non-government organisations

		training and education of company personnel? If yes, please state "Included".	(NGOs). The service provider would organise the farmer Producer Organisation's - Train the Trainer program to ensure effective training and capacity building of key resources.
8.	Manpower	a) What will a consultant cost throughout the planning, designing, implementing, and managing the BC-based traceability system?	This will depend on the scale of implementation. A Small project of 10,000 farmers can have a dedicated team of members with an average cost varying from ₹3-₹4 Lacs per month/ person as covered in 7(a).
		b) What will be the cost of field staff/support/ data collection	The program/industrial partner will decide this requirement.
		c) Will there be any "other manpower" cost incurred during the implementation period?	The manpower of the program partner implementing the BC-based traceability solution would have to be completely onboard with the dedicated team of service providers throughout the implementation phase.
9.	Business process re-engineering	d) Is there any cost of disruption to the rest of the organisation until it becomes adjusted to the new system and feels confident in operating with it?	There is no specific cost of disruption to the rest of the organisation. The transition phase can take up to six weeks for swift technical integrations.
10.	Others	a) What electricity costs will be incurred once the BC system is implemented?	This cost will be negligible.

	b) What will be the cost incurred for office space/ infrastructural space?	This would depend on the program partner.

Table 2: Operational costs related to proposed POC

Cost category		Components	Inputs/points based on the response from technology provider (Source: CropIn)
1)	Hardware Maintenance	a) What will be the cost of regular maintenance?	The service provider would maintain the servers. The client needs to maintain the maintenance of equipment, i.e., printers, laptops, mobile, etc.
		a) What will be the cost of accidental repair repairs needed for the hardware devices?	As per the applicable rates.
2)	Software maintenance	a) What will be the cost of maintaining the software platform to avoid data loss in case of sudden system crashes?	The cost of software maintenance is included in the cost of software licensing fees.
3)	Support	a) What will be the cost of internal/external support needed in case of problems or damages to the software or hardware?	Support costs will be included in the software licensing fees.
4)	Ongoing Training	a) What will be the cost of training the staff onsite/offsite when updating software?	This cost will vary per person-day. Also, online training will be enough to update if significant features are not added.

5)	Upgrades	b) What will the cost of both hardware and software upgrades be?	It would be included in the annual package. The software improvements are a part of the yearly license fees.
		c) Will upgrading the system be included in the software maintenance contract?	Yes
6)	Staff-related cost	a) What is the cost of staff involved in the traceability system's management and operation activities?	Existing staff can be used with a few headcounts besides the program. No Significant manpower, but a change in process and digital transition would be required.
		b) Will there be any cost increase due to increased staff salaries due to their skill enhancement and their gained experience in dealing with the BC-based traceability system?	Not applicable. No significant increase will be there in the costings. The client can provide incentives for their increased skill development. Also, no specific skill is required for a BC-based traceability solution; one is required to operate the tab/mobile.
7)	Consumables	a) Will there be any cost of items consumed during the system operation?	Not applicable.
8)	Licenses	a) Is there any per-year cost of the licensing?	Yes, the cost suggested above is an annual subscription cost.

4.3 Implementation challenges and perceived benefits (Stakeholders' perspective)

This section will discuss the stakeholders' perspectives by discussing the challenges faced during the implementation phase and the perceived benefits of adoption.

4.3.1 Challenges

- Identification and finalisation of traceability points with mutual understanding and agreement between the technology provider and use-case organisation were difficult because the type of dataset required by both parties was usually not in the same format.
- Due to the smaller number of farmers available per village, finalising the geo-tagging location/crop point was a major challenge.
- Deciding on information to be shared with consumers through QR codes needs consideration because this may impact the supply chain decisions.
- Difficulty in coordination between the technology provider and use-case organisation due to reasons like the engagement of staff in routine activities and lack of knowledge about the platform.
- The technology provider had a single interface for different agri-food products. This was challenging as different products have different supply chain attributes. Thus, it is crucial to have a personalised interface that can be tailored to the use-case organisation's requirements.
- Modification/ changing of the data entered in the system is difficult as data is immutable in the BC system. Thus, it is essential to properly train the AFSC stakeholders on data entry to avoid mistakes.

4.3.2 Benefits

- User login IDs would be designed so that verified and authentic users can access the platform. Only permitted users will access the secured BC networks, strengthening the security.
- BCs are specially designed to help keep data secure and prevent leaks, infiltration, and hacking. They comprise ‘nodes’ that store information. These nodes combine to form chunks of data called ‘blocks,’ this system makes up the secure BC infrastructure.
- There are separate dashboards to view all the details for crops, farmers, updates on the crops, etc. This enables the visualisation of the AFSC within the portal using geo-tagged crop/crops and key performance indicator data.
- The smart contract ensures data authenticity. Upon entering the data into the system, it automatically checks the values of various segments and records the findings on the BC.

5. Implications of the study

The findings of this study hold promise even if the possibilities for using BCT in practical applications are still being explored. The findings suggest that the demand for better traceability by agri-food organisations may drive adoption within specific parts of the agri-food business despite the various challenges to be overcome. The study also shows that in a certain environment, BCT could be implemented without the immense efforts of agri-food stakeholders. This section discusses the contribution and implications for the practice of this study.

5.1 Implications for Researchers

This study was developed to determine if blockchain technology may provide value to agri-food organisations and to support the idea that BCT can enhance AFSC traceability. This research responds to the call of Bumblauskas et al. (2020) and Duan et al. (2020) for real-life investigation of BCT adoption and its application in the AFSC. The study gathered existing research on the BC-based traceability of AFSC and then utilised it to design a practical framework for implementation with use-case organisation. In order to address the gaps in the literature, the study employs a real-life use case. Additionally, to the authors' knowledge, this is the first study to use BCT to track the supply chain of coriander powder and honey in India. The POC captures traceability and engagement data at nearly every step of the AFSC. Finally, the implementation methods highlighted in the study can be utilised to develop a framework for future research studies. The developed POC with proof of stake as a consensus mechanism guarantees finality and consistency, which contributes to developing a secure and trustworthy agri-food traceability solution using innovative techniques. This addresses the call of Karmer et al. (2021) to deploy an alternative consensus mechanism that is environmentally sustainable and reduces the energy required. The study also tries to understand the perceived costs of implementing a BC-based traceability framework for an agri-food organisation in India. This addresses the call of Nayal et al. (2023) and Agi et al. (2022) to study cost components associated with BCT adoption. The findings add to a growing body of literature on BC systems.

5.2 Implications for Managers

Blockchain technology in AFSC can potentially enhance agri-food traceability in new and existing supply chains. Operations and interaction among agri-food stakeholders have significantly improved with the adoption of BCT in AFSC. In the proposed POC, each verified stakeholder is required to manage and store the related data in the system. Other stakeholders can access the shared data through a specifically established authentication (consensus mechanism). In practice, this research can be used by managers as a step-by-step guide for understanding the process of BCT implementation. The agri-food sector is uniquely positioned to explore the potential of BCT, given the rapid increase in digitalisation and demand for information and product integrity. Although the use of BCT in the agri-food supply chain in India is still in its early stages, it can be anticipated that various organisations will make a growing number of efforts. If this is not well coordinated, agri-food organisations and society may squander resources and miss opportunities. Thus, the study will prepare practising managers to be ready and proactive for BCT adoption in the future. The study also concurs with the findings of Bumblauskas et al. (2020). The study promoted that using BCT in AFSC can only be beneficial if all the stakeholders are involved. Managers need to ensure all the stakeholders, i.e., farmers, producers, and manufacturers, are ready to participate. The integrity of agri-food products could be protected by encouraging the participation intention of every stakeholder. This helps in developing a trustworthy environment. Additionally, the proposed cost framework of the POC aims to help managers better comprehend the major cost components of the BC-based traceability framework. It can be utilised as a planning manual by managers and organisations interested in implementing BCT solutions to evaluate such deployment and comprehend innovation processes and information technology capabilities.

6. Conclusion

The literature assessment reveals a notable gap in the research concerning the application of blockchain technology (BCT) in agri-food supply chains (AFSCs). Existing studies are predominantly descriptive, lacking comprehensive solutions and practical implementations. Recognising the need for real-time evaluation of BCT benefits, this study reviewed relevant literature to identify knowledge gaps. Building upon these gaps, the study conceptualised and developed a Blockchain (BC)-based traceability framework, a proof-of-concept (POC) centred around honey and coriander powder supply chains. The study presents a use case for deploying BCT for honey and coriander powder supply chains. Collaborating with a technology provider and a use-case organisation, the study crafted a use case for the deployment of BCT in the specified supply chains. The BC-based traceability POC was crafted with inputs from both the use-case organisation and technology providers. The study aimed to demonstrate the operational applicability of BCT within an Indian AFSC context. The POC incorporated proof-of-stake (POS) as a consensus mechanism, a crucial choice considering environmental concerns and performance issues associated with traditional proof-of-work (POW) mechanisms. The system utilised digital applications, SmartFarm and Smartware, for data collection, storage and processing. Digital profiles of collection centres and self-help groups were created through SmartFarm, while Smartware facilitated data visualisation for farm field staff. Unique identifiers and QR codes ensured traceability information for each processed batch, monitored through a single interactive dashboard.

Despite its contributions, the proposed POC has limitations. The pilot study covered a limited dataset and couldn't simulate high transaction volumes, necessitating further investigation for large-scale imolementation. The use of single smart contracts was identified as insufficient for widespread application, requiring multiple contracts to maintain confidentiality at scale. Findings are limited to specific cases, geographical and infrastructural conditions, and business settings. The study dvelved into the costs associated with BCT, identifying hardware, software, manpower, and maintenance costs. However, the dynamic nature of Blockchain evolution suggests costs may vary, urging future studies to conduct in-depth analyses and validate cost benefits. Additionally, deploying QR codes in consumer markets for data and analytics collection is suggested for the next research phase, with a focus on assessing BCT efficiency in terms of sales and consumer willingness. Future research avenues may explore developing similar blockchain frameworks for other agri-food commodities.

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