Unlocking the Potential: Hybrid Blockchain and AI-enabled Traceability Model Development and Implementation in the Dairy Industry – Proof-of-concept

Abstract

Conventional traceability systems without real-time information transmission are susceptible to tampering. In contrast, blockchain and artificial intelligence (AI)-enabled traceability models offer transparency and accountability, given their decentralized nature and immutability. This research conceptualizes and develops a hybrid blockchain and AI-enabled traceability (prototype) model and implements it in the dairy industry. The study includes a collaborative research methodology, including a literature review to analyze the existing traceability solutions, identify data entry points, select model requirements, and deploy smart contracts, decentralized applications (Dapps) and Web3 technologies to develop and validate the proposed model via *Testnet*. The findings present the user interface developed as a prototype traceability model and its characteristics, such as transparency, decentralized nature, and immutability, followed by practical validation. The post-implementation data analysis highlighted the security, privacy, smart contract validation rules, and comparative insights, as well as the alignment of the theoretical model with practical applications using Web3 technologies. This research contributes to the literature on hybrid blockchain and AI-enabled traceability, highlighting the potential for exploring opportunities in the food industry.

Keywords: AI-Enabled Traceability, Web3 Technologies, Blockchain, Dairy Industry, Decentralization, Smart Contracts, Sustainability

Introduction

Traceability in the dairy industry is crucial for ensuring the safety and quality of dairy products. The existing setup lacks adequate data to assess the safety and quality of milk produced, leading to the possibility of adulteration and incorrect information recorded by middlemen (Dandage et al., 2017). Conventional centralized supply chains in India face challenges such as product irregularities, quality compromises, and data loss, highlighting the need for an upgraded decentralized supply chain model (Khanna et al., 2022). Blockchain technology can enhance product quality and improve traceability (Lu et al., 2025). The proposed blockchain-enabled supply chain platform aims to maintain the nutritional values of dairy products, identify adulteration and contamination, prevent counterfeit products, and enhance the revenue of dairy companies (Tan & Ngan, 2020). Implementing a system that can read, store, and translate complex product identity data is crucial for ensuring quality and traceability in the dairy industry. Traceability systems, including barcode and radio frequency identification technologies, play a significant role in preventing fraud and adulteration in the food industry (Malik et al., 2024). The concept of traceability has become crucial in ensuring the safety, security, quality, and transparency of goods in the modern supply chains.

Traceability refers to tracing a product or component's path to origin across different manufacturing, processing, and distribution phases (Hastig & Sodhi, 2020). This capability promotes accountability and transparency throughout the supply chain by offering a thorough product history. One of the largest milk producers in the entire globe, India, confronts challenges related to traceability (Malik et al., 2023). Given the production volume and the wide range of individuals involved in the whole supply chain, ensuring the safety and quality of dairy products is an immense challenge (Dubey et al., 2024; Yadav et al., 2020). The absence of traceability and transparency in the dairy industry has still led to an increasing number of challenges, such as the detection of contamination and adulterants in dairy products, which pose significant hazards to the well-being of consumers (Hassoun et al., 2023). Consumers anticipate milk and dairy products to comply with stringent requirements for quality, and identifying the product's origins and manufacturing processes ensures their safety and authenticity (Vp et al., 2022). When consumers understand food safety and originality, traceability becomes essential to the food industry's supply network (Casino et al., 2021).

Additionally, the significant number of milk and milk-based products sold nationwide increases the difficulty of traceability (Patelli & Mandrioli, 2020). Traceability in the dairy industry addresses consumer concerns and serves as a quality control mechanism, lowering the probability of fraudulent activity and ensuring transparency in dairy operations (Lin & Wu, 2021). Technology innovation has led to increased use of novel industry approaches to improve traceability. The dairy supply chain must maintain transparency and traceability to uphold the required nutritional and quality standards (Cabrera & Fadul-Pacheco, 2021). Blockchain and other emerging technologies have the potential to transform this convoluted supply chain altogether. Blockchain ensures the tracking of product origins from farm to fork by providing decentralization, transparency, and the capacity to create immutable transaction records. It facilitates collaboration among stakeholders, including regulators, consumers, and farmers (Dasaklis et al., 2022). Artificial intelligence (AI) and the application of blockchain technology have emerged as promising methods for enhancing food traceability. From a traceability perspective, AI can analyze data from dairy supply chain phases, including milk production, manufacturing, distribution, and sales (Bhattacharya et al., 2024; Hassoun et al., 2022). AI encourages beneficiaries to come to selections that reduce activities while decreasing waste by recognizing patterns, abnormalities, and challenges (Wang et al., 2022).

Blockchain technology, usually associated with digital assets, creates a tamper-proof ledger system. The system assures security, transparency, and immutability by interrelatedly maintaining each transaction or occurrence (Liu et al., 2020). In the context of the dairy industry, blockchain technology can create a decentralized ledger for every stakeholder in the supply chain to record from farm to table. Farmers, processors, distributors, retailers, and consumers are all involved and can gain access to this shared ledger, fostering trust and accountability (Shoaib et al., 2020). The dairy industry is not an exception to the transforming developments brought about by technological developments in other sectors. Integrating data analytics, automated processes, and technological innovations has made it possible to improve traceability throughout the dairy products' supply network. Real-time monitoring is made more accessible by technology, and it also offers helpful insights for decision-making and operation optimization (Khanna et al., 2022). A practically efficient and reliable system capable of providing complete milk traceability from farm to fork is required to deal with these issues. By providing a transparent and secure method for tracking milk throughout the supply chain, blockchain technology and the Internet of Things (IoT) have the potential to transform the dairy industry completely (Kumar & Kumar, 2020). Although traceability initiatives exist in the Indian dairy industry, their drawbacks make them insufficient. Such systems often rely on traditional, paperwork-based record-keeping, which can lead to errors and manipulation.

Additionally, the smooth transfer of data throughout the supply chain is hindered by the lack of interoperability among different traceability solutions (Vp et al., 2022). Such challenges highlight the demand for integrated and decentralized traceability systems, like those utilizing AI and blockchain, to handle the complexity of the Indian dairy industry (Malik et al., 2023). The objectives are twofold: first, to explore traditional dairy industry activities, and then to investigate the possibilities of integrating AI and Blockchain to develop a traceability system. Second, the research aims to clarify how blockchain and AI technologies might improve the dairy industry's transparency, effectiveness, and sustainability.

The research also examines current AI and blockchain applications in the dairy sector in India and internationally. It aims to highlight beneficial findings, observations, and best practices that can direct the utilization of these innovations by considering practical implementation cases. This research also examines potential roadblocks and constraints to integrating blockchain and AI regarding cost, infrastructure, technology-related knowledge, and regulatory frameworks. The organization of the paper is as follows: Section 2 discusses the literature, including the current status of traceability in dairy, the application of blockchain technology research gap, and the research questions; Section 3 presents the methodology adopted to develop the traceability system; Section 4 highlights the model development, implementation steps and functionality; Section 5 discusses the implications of the research for the dairy industry, along with challenges, and limitations; Section 6 concludes the research.

Literature Analysis

Several studies presented a detailed overview of traceability definitions, types, parts, and different aspects of the dairy industry (Malik et al., 2023; Olsen & Borit, 2013). The researchers aim to provide the most comprehensive definition of traceability by considering all aspects discussed in the existing literature. Existing research on the practical implementation of traceability based on blockchain and other digital technologies is limited; however, some authors have highlighted the concept and practices of traceability over the past decades. For example, Charlebois et al. (2014) compared the global food requirements and regulations related to traceability for 21 organizations, Dabbene et al. (2014) discussed the concept of traceability in detail and investigated how traceability influences supply chains, Aung & Chang (2014) discussed the role of traceability in ensuring consumer satisfaction and confidence by providing food safety and quality, Liu (2015) proposed a traceability system based on IoT to ensure food safety in the supply chain, Badia-Melis et al. (2015) discussed the recent developments and trends related to traceability in the food domain and discussed the key traceability dimensions, including regulations, environmental, organizational, and technical aspects.

Prashar et al. (2020) proposed a blockchain-based traceability system for Indian agricultural products to remove the middleman, optimize the existing supply chain system, and provide a decentralized system. Wigger et al. (2020) presented an integrated system using Industry 4.0 technologies and blockchain to develop a robust traceability system. Feng et al. (2020) reviewed the potential applications and possible challenges associated with the adoption of blockchain technology in food traceability methods. Tan & Ngan (2020) developed a traceability model for the dairy supply chain and validated it through a case study in the Vietnamese dairy sector. Hawashin et al. (2025) highlighted the transformative potential of blockchain and proposed a blockchain-enabled system for reducing waste in the dairy industry. Vern et al. (2025) outline the role of blockchain in enhancing agri-food supply chain performance, focusing on the enablers of blockchain in promoting sustainable development.

Vern et al. (2024) developed a blockchain-based traceability system for coriander powder and honey supply chains, highlighting the model's transparency, decentralization and immutable characteristics. Wu et al. (2023) explored the efficiency issues related to blockchain-based traceability systems and claimed to reduce the time overhead by approximately 85%. Azevedo et al. (2023) developed a blockchain-based traceability system and validated it using a case study of a meat supply chain, outlining its potential to transform existing operational processes. Biswas et al. (2023) proposed a model to demonstrate the benefits of traceability based on blockchain systems and its impact on supply chain sustainability. Kumar and Kumar (2025) developed a theoretical framework to examine the relationship between blockchain mediation and supply chain practices and performance. Patel et al. (2023) explored the role of blockchain in food safety and traceability issues in livestock products and outlined the potential benefits, emphasizing practical validation and model development. Vasanthraj et al. (2024) developed a concept that integrates blockchain technology with IoT to enhance supply chain visibility and reduce costs in the milk supply chain. Many authors discussed the existing challenges related to blockchain, IoT, and AI-based traceability solutions' adoption in dairy and other food supply chains (Caro et al., 2018; Dasaklis et al., 2022; Kayikci et al., 2022; Liu et al., 2020; Wang et al., 2022; Wang et al., 2021). Table 1 highlights some existing traceability solutions reported in the literature. Recent advancements in decentralized traceability models that address sustainability needs must be adaptable and agile.

Table 1. Recent developments in food traceability

Supply Chain/Sector	**Objective**	**Technology Used**	**Challenges Addressed**	**Limitations/ Gap**	**Reference**
Tea industry	To develop RFID-integrated and blockchain-based models for circular supply chains in the B2B tea industry	RFID, Blockchain	Circular economy practices	Not implemented practically	Paul et al. (2022)
Beef industry	To develop a blockchain-based beef cold chain model for monitoring	Blockchain, IoT	Traceability, Environmental impacts, Data management	Complete supply chain integration	Jo et al. (2022)
Dairy industry	To develop an end-to-end traceability platform for the cheese supply chain	Web-based platform	Data management, Centralized traceability	Decentralization	Regattieri et al. (2007)
Dairy industry	To develop a supply chain model for traceability in dairy	Web-based platform	Monitoring, data collection	Decentralization	Manikas & Manos (2009)

Dairy industry	To develop a traceability system based on RFID for cheese supply chain	RFID, NFC, Web-based platform	Data collection, traceability, Farm surveillance	Decentralization	Magliulo et al. (2013)
Dairy industry	To develop a prototype traceability system for raw material and milk to monitor path and temperature	RFID, GPS sensor	Monitoring, Traceability, Data acquisition	Transparency, Complete supply chain integration	De las Morenas et al. (2014)
Dairy industry	To develop an internal traceability system for different animal milk.	RFID, GPS sensor	Data acquisition, Classification, Monitoring	Covered a few aspects only	de la Vara Martínez et al. (2018)
Dairy industry	To develop a smart contract-based traceability system for dairy	Blockchain, Smart contracts, IoT, RFID	Traceability, Optimization, Monitoring	Practical implementation, Cost, Scalability, User accessibility	Casino et al. (2020)
Dairy industry	To develop a blockchain-based traceability for the Swiss dairy industry	Blockchain	Traceability, Automation, Data collection	Cost, Practical Implementation, Generalization	Niya et al. (2020)
Dairy industry	To propose a blockchain-based logistics system for the dairy industry	Blockchain, IoT	Reduce labor, Cost reduction, Automation	Generalization, Practical Implementation	Fang & Stone (2021)
Dairy industry	To develop a traceability system for low-cost, sustainable cheese production	Blockchain	Environmental impacts, Cost, and data management	Smart contracts can be utilized	Varavallo et al. (2022)
Dairy industry	To develop an integrated blockchain-based traceability for the dairy industry	Blockchain, IoT, Cloud Computing, QR Codes	Traceability, Automation, Quality assurance, Decentralization	Sustainable practical implementation	Khanna et al. (2022)
Dairy industry	To develop a hybrid blockchain and AI-enabled traceability model for the dairy industry	Blockchain, IoT, AI, ML, Big Data, Mathematical Modelling	Traceability, Data management, Sustainability, Dairy SC integration, Optimization	Development and validation conducted for milk, and it could be replicated for other products	The model proposed in this research

The proposed conceptual model aligns well with existing theories such as the TOE framework, which is well recognized for exploring technological adoptions in supply chain management. This framework presents a structured method to investigate how factors related to TOE dimensions, such as technological, organizational and environmental, impact the process of adopting and implementing such digital technologies. The conceptual framework proposed in this research integrates AI, blockchain and IoT along with Web3 frameworks, aligning with the technological components of the TOE framework. The case implementation of this research highlighted the organizational components of the TOE framework. The need for effective traceability systems and transparency, along with rising concerns related to product safety and quality, ethical and sustainable production, and environmental issues, relates this model to the environmental components of the TOE framework. Thus, the theoretical alignment supports the research in exploring how and why the proposed traceability model contributes to the existing literature, representing the identification of a proper systematic approach to implement the model and demonstrating the potential implementation benefits of the proposed model.

2.1 Research Gaps

The literature analysis reveals that existing traceability models are theoretically developed, but their practical implementation is limited. A few studies have reported practical implementations, which are currently limited to a validation scale. Blockchain-based traceability models have been developed in various supply chains, but the dairy industry remains underexplored. Although some related studies such as Casino et al. (2020) discussed a blockchain-based traceability system, but a proper case validation is still lacking. Behnke & Janssen (2020) also focused on identifying boundary conditions for blockchain-based traceability systems in food supply chains via case studies. Similarly, several authors have explored the potential, challenges, and related implementation scenarios of implementing traceability in the dairy industry. Literature analysis indicates that the dairy industry requires a traceability solution to ensure a sustainable future. Still, an integrative approach to identifying requirements and developing a hybrid traceability system, along with case implementation, is often missing or overlooked. Thus, this research aims to design a hybrid blockchain and AI-enabled traceability model for the dairy industry, which can be implemented practically to establish a permanent solution in the dairy industry. It addresses the gaps and highlights the practical implementations, offering the feasibility of such systems in real-world food supply chains. The following research objectives guide this research:

- *To propose a theoretical concept for the hybrid blockchain and AI-enabled traceability and Proof-of-concept (PoC).*
- *To develop and implement a Web3-based hybrid blockchain and AI-enabled traceability model for the dairy industry.*

3. Methods

The essential function of traceability systems is to collect related information from any use case organization. This research utilized an exploratory and step-by-step methodology to develop the proposed traceability system for the dairy industry. Unstable demands emerged due to modifications in feature prioritization and newly formed requirements from situations such as the COVID-19 epidemic. As a result, this research adopted a collaborative design method, also known as participatory design, as a practical design methodology, providing complete and immediate feedback to explore unbounded solutions for design collaboratively with all stakeholders (Hastig & Sodhi, 2020). The collaborative design method, also known as co-design methodology, allows all related stakeholders to participate in the development process as peers, and their suggestions show considerable relevance in the development process (Bai et al., 2005; Lee et al., 2025). The dairy stakeholders have been included in the proposed model. This is more acceptable than the single-stakeholder design because it gives every stakeholder an equal chance to share their thoughts and contribute suggestions. With an expanding number of users, such a user-centred, holistic strategy increases network value and utility. All stakeholders can examine the impact of the developed system with greater depth (supported by evaluation utilizing later field studies and interviews). This involvement contributed to the development of sustainable solutions for traceability in the dairy industry. The research emphasizes developing and implementing the traceability model, highlighting systems architecture, smart contracts design, AI-driven automated processes, and real-time data security protocols. This step ensures that the model meets performance standards, including traceability accuracy, transaction efficiency, and record immutability, facilitated by blockchain technology.

Phase 1: Development of Traceability Model

This phase highlights the methodology used to develop and implement the proposed model for the Indian dairy industry. The following subsections include a step-by-step process. The pre-development phase involves identifying primary requirements to develop the proposed traceability model, which encompasses all data points required from all stages of the dairy industry to collect data, as well as key stakeholders participating in the end-to-end process.

Figure 1 highlights the methodology used to develop the proposed model for the Indian dairy industry. This is more acceptable than the single-stakeholder design because it gives every stakeholder an equal chance to share their thoughts and contribute suggestions.

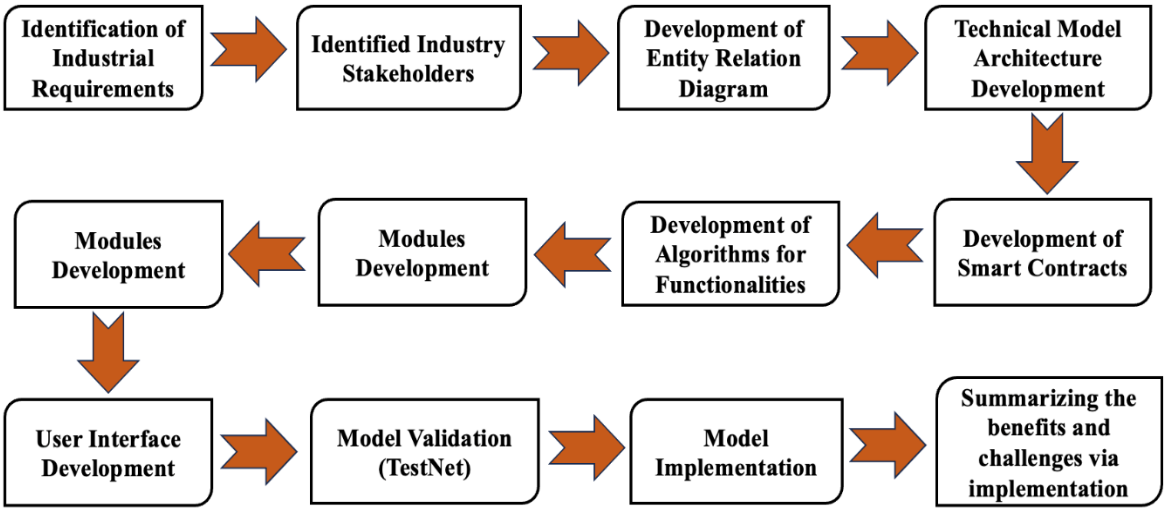


Figure 1. Development of a hybrid blockchain and AI-enabled traceability model
(Source: Authors)

3.1.1 Technical Requirements

This section outlines the materials and methods employed to develop the technical aspects of the proposed model. Firstly, a model theoretical architecture has been developed as a roadmap to technical development. The adopted technical components include Web3 technologies, such as the Solidity language for programming smart contracts, Next.js for frontend development, Python for backend development, and VS Code, as well as the *Remix IDE*. *MetaMask* integrated the wallet service with the proposed model. Following technical development, the Goerli Ethereum Testnet was used to test the functionality of the developed smart contracts. After successful validation, the developed model can be deployed to the *Mainnet*.

3.1.2 Blockchain and Traceability Layer Architecture

The proposed model integrates blockchain using *Goreli Testnet* with smart contracts to manage all data transactions. The primary objective of this layer is to generate and manage the identities of all associated stakeholders, record data, assign MetaMask wallets, verify smart contracts, and store data in transaction hashes on the blockchain. The traceability layer ensures smooth data collection related to defined parameters, such as volume, temperature, fat, and SNF, among others. Then, by detecting anomalies using AI and providing access to consumers through QR code scanning, we ensure transparency.

3.1.3 Mathematical Notations and Formulas

To simplify the smart contract coding part, the authors used mathematical notations and formulas for blockchain and traceability layers. For example, farmer ID is denoted as F_{id}, batch ID as B_{id}, quality score for i^th farmer and j^th batch as Q_{ij}, wallet address as W_a, transaction hash for data D_{ij} as $H(D_{ij})$, gas units used for each transaction as G_u, for per unit gas price P_g, transaction cost as C_{tx}, for timestamp T_s, to calculate anomaly detection θ, ϵ as threshold limit for detecting anomalies, and for validation output V_i where 1 denotes accepted and 0 denotes rejected. The mathematical formulas include digital identity generation, as follows:

$$ID_{new} = \{ID_{counter} + 1 \;\; if\; W_a \in R \; and \; A_f = 1 \qquad Rejected, \qquad otherwise\} \ldots\ldots\ldots\ldots.(1)$$

Formula 2 for immutable data hashing is given below:

$$H(D_{ij}) = encryp(F_{id} \parallel B_{id} \parallel Q_{ij} \parallel T_s) \ldots\ldots\ldots\ldots(2)$$

Formula 3 for smart contract validation is given below:

$$V_i = \{1 \;\; if \; (F_{id}, B_{id}, Q_{ij}, T_s) \in Valid\ Range \qquad 0 \qquad otherwise\} \ldots\ldots\ldots\ldots.(3)$$

Formula 4 for gas fees calculation is given below:

$$C_{tx} = G_u * P_g \ldots\ldots\ldots(4)$$

3.1.4 Model workflow and Web3 Integration

The proposed traceability model integrates digital technologies, including data collection via IoT and developed modules, an anomaly detection layer, and smart contract validation using Web3 technologies. The detailed model workflow is discussed and presented in the theoretical model, as shown in Figures 3 and 4. Further integration of Web3 technologies is presented and discussed in Section 4, along with its subsections.

3.1.5 Smart Contracts Validation

As the proposed hybrid model aligns with the TOE framework, smart contracts are developed to validate the theoretical components using validation rules. In the theoretical model, constructs such as technological factors, organizational factors, environmental factors and process activities are aligned with the validation rules. Formula 3 highlighted the acceptance or rejection of transaction execution based on the smart contract. This rule ensures that for the technological dimension, formula 2 and data collection part will execute if the set conditions are satisfied, for organizational dimension, the smart contract rules for identity generation, verification and role-based access will be executed as per defined conditions and for the environmental and regulatory dimension, the execution of the smart contract will again depend on the defined threshold limits. Regarding the requirement related to the quality parameter of the collected data, the model will adhere to the standard benchmarks provided by regulatory authorities. Therefore, the proposed theoretical model directly impacts the validation rules and execution of smart contracts; the pseudocode is in the appendix.

Phase 2: Practical Implementation

This section highlights the practical implementation methodology through a case study. A dairy farm named "Binsar Farms Pvt. Ltd, Kundli", *Binsar Farms* hereafter, operates in Haryana, India. Binsar has 10000 litres of milk, which has a daily capacity (Tushir, 2012). Binsar is a technologically advanced dairy farm. It has implemented an automatic milking system and numerous other innovative solutions to enhance its technological status. Binsar Farms has the vision to adopt cutting-edge technologies and innovation through these technologies to ensure quality and safety for its consumers, along with environmental sustainability (Tushir, 2012). With an extensive network of consumers and stakeholders, Binsar faces challenges in establishing a transparent supply chain for milk traceability, thereby ensuring the quality and safety of its products for consumers. Binsar Farm is working on sustainability by adopting digital technological solutions, traceability being one of them. To execute the developed model, Binsar Farms has been chosen as a feasible case, meeting the implementation requirements. Its on-farm production, processing, and packing make it more suitable for implementation, although it also procures some milk from registered farmers. Implementing this traceability model helped *Binsar Farms* establish transparent supply chain management and monitor its operations in real-time. Figure 2 shows a step-by-step process.

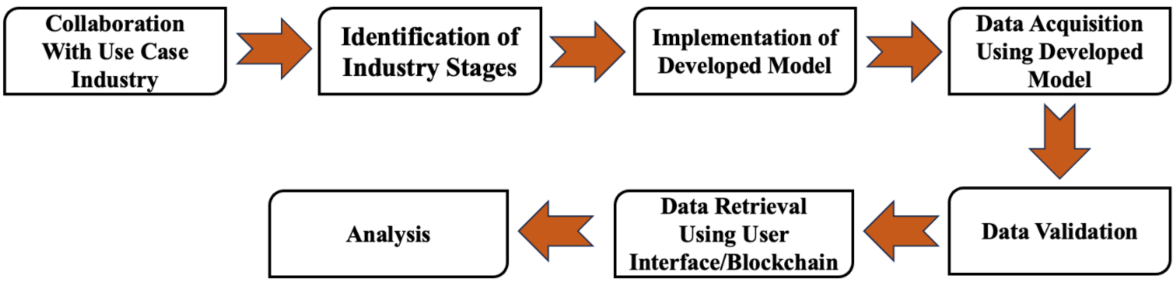


Figure 2. Validation process – as a Case *(Source: Authors)*

Post-implementation data has been collected for every module and made available to the chosen business and its registered stakeholders for their analysis and operations management.

Ethical Considerations

Before the implementation and data collection, permission was acquired from *Binsar Farm's* management and participants. The data, including names, designations, and data collected from stakeholders, has been strictly confidential. The post-analysis findings of the developed model have been shared with participants for validation and to maintain transparency and trust.

4. Model Development and Implementation

This section outlines the step-by-step process of developing and implementing the proposed traceability model, encompassing the exploration of requirements, conceptual development, proposal of the model architecture, algorithms, and module development.

4.1 Pre-model development requirements

Various stakeholders contributed to the development of a hybrid blockchain and AI-enabled traceability model for the dairy industry. To explore the industrial requirements, a pilot study and interviews have been conducted to discuss and finalize the section-wise requirements for the model from an industrial point of view. Table 2 depicts the related stakeholders, their job roles, and their contribution to model development.

Table 2. Dairy stakeholders' challenges and requirements *(Source: Authors)*

Stakeholder	**Challenge**	**Associated Issues**	**Requirement**	**Solution**
Producers/ Collectors	To authentic the origin and quality parameters of milk collection	Adulteration, Low price, Manual data management	Proof of origin, Registered stakeholder ID, Registered collection Centre ID	Traceability
Transporter	Challenges to monitor real-time temperature and route optimization	Spoilage, Carbon Emission, Loss of quality, Delays, Contamination	Registered transporter ID, Real-time monitoring, Live route tracking	
Processor	Challenges to handling the milk from various collectors, Origin and Quality tracing, Manual data handling	Adulteration, Low Quality, Improper tracing	Registered processor ID, Quality data recording, Registered product ID, Processing details recording, Packaging details recording	
Distributor	Challenges to verify origin, processing, and inventory details of products, lack of visibility	Spoilage, Demand and supply management	Registered distributor ID, Retailer ID, Recording shelf-life and inventory details	
Dairy Management	Challenges to maintain information about origin, quality, and processing activities, Manual data handling	Data management, Operations details, Lack of visibility and trust	Require registering all stakeholders, Products, and end-to-end traceability system with admin dashboard	
Consumer	No information about product origin, processing details,	Trust, health and financial issues, & Environmental concerns	End-to-end traceability system	

	storage details and product sustainability	

Smallholder farmers, intermediaries, cooperatives, transporters, processors, warehouses, distributors, and management personnel contributed to collecting data on the industrial side. *Binsar Farms* and its management team collaborated to develop initial-stage designs, which were subsequently validated through further pilot visits and expert discussions. NIFTEM-K (India) served as the academic partner providing theoretical and technical guidance, defining sustainability evaluation criteria and supporting system-level analysis. A conceptual design has been prepared using collaborative methodology and validated with all relevant stakeholders. The adopted process is like the conceptual framework developed by Groschopf et al. (2021), where stakeholders have been mapped as digital actors. The data compiled through a collaborative design methodology are related to the requirements of the dairy industry for an effective traceability model. The required data points to develop the traceability model are organized in Table 3.

Table 3. Essential traceability information sets *(Source: Authors)*

Sr. No	**Information Sets**	**Major Factors & Components**
1	Information related to products	Origin/producer details
		Collector details
		Quantity
		Lot/batch number
		Transporter details
		Processor
		Product ID
		Distributor details
2	Information related to quality factors/ parameters	Quality parameters
		Ingredients composition
		Shelf-life details
		Quality checks details
		Tests and Procedures Details
		Quality certification details
3	Information related to Process	Process details
		Timestamps
		Equipment/machines used
		Sanitation and Hygiene Reports
4	Industrial information	Automation level
		Data acquisition types/methods
		Data management
		Stakeholders list
		Registered farmers
		Registered collectors
		Registered transporters

	Registered processors
	Registered distributors
	Registered suppliers
	Compliances certifications
	Incentive programs details
	Welfare programs details

Data points from every segment of the dairy industry, including collection centres, transportation, processing centres, packaging, warehousing, distribution, and dairy management, have been considered for model development. However, the model can be generalized to the dairy sector as the data points have been considered per global traceability standards. The developed modules depend on the milk channels used by the dairy firms to establish a robust supply chain transparency and visibility system.

4.2 Conceptualization and Proof-of-concept

A theoretical conceptual model has been proposed, as shown in Figure 3. The proposed model's objectives are multifold, including integrating data related to dairy activities and stakeholders with blockchain using smart contracts and data collection for each defined module. The second step involves identifying associated stakeholders who play a crucial role in registration, data collection, and interaction with the developed model. The third step involves system requirements and entity relationship diagrams, which include the necessary data collected through a traceability model and the processes to be recorded. The relationship diagrams map the relationship between stakeholders, processes, and functionalities.

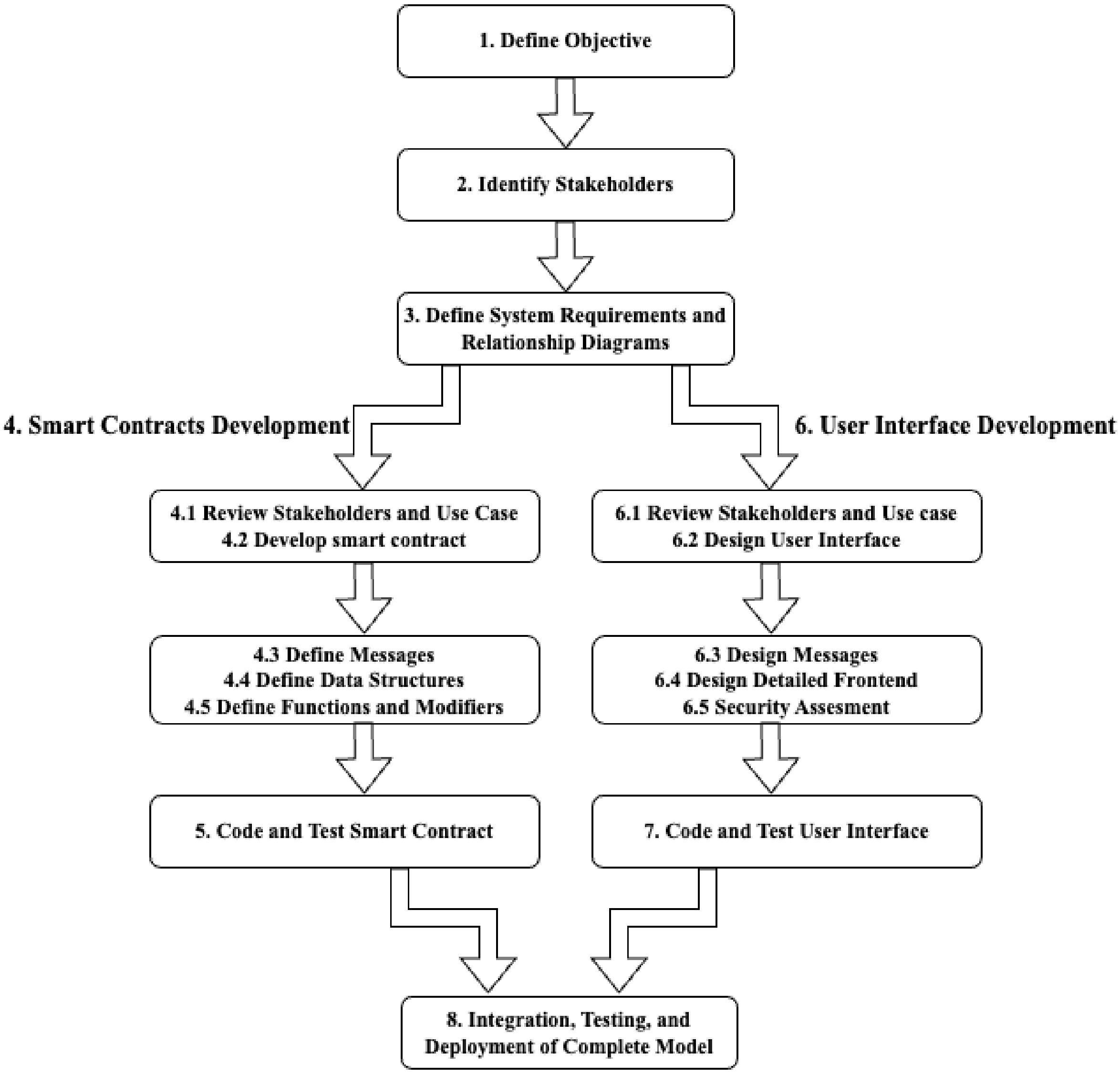


Figure 3. Theoretical model *(Source: Authors)*

After step 3, the system is divided into two parallel parts, including steps 4, 5, and 6-7, and is concluded by step 8. Step 4 is related to the backend part, specifically the development of functionality using smart contracts. Smart contracts have been developed in step 4 and tested in step 5 for their functionalities, including registration of stakeholders, products, processes, modules, and data collection. Step 6 deals with user interface development, a part of the front-end. In step 6, key users were identified to develop the required functionalities according to their role; for example, full access was provided to the user, while other stakeholders had limited access. Step 7 involves coding the user interface and validating it through testing. Finally, step 8 is the part that combines steps 4-5 and steps 6-7 to present a functional decentralized web-based application in the form of a developed model. In step 8, apart from integration, the proposed functionalities have been tested, and the model has been deployed.

This model can serve as a roadmap for developing a Web3-based hybrid blockchain and AI-enabled traceability model for the dairy industry.

The proposed model features a four-tier architecture: industry, traceability, blockchain, and user interface layers. The industry layer comprises all dairy stakeholders considered for model development, including collection, transportation, processing, packaging, warehousing, distribution, and consumer. The second layer, the traceability layer, includes traceability data from every section in the industry layer. The third layer involves executing smart contracts after collecting data from the traceability layer. The fourth layer is the user interface through which the admin monitors the complete traceability process and can access the admin panel. Figure 4 briefly represents the architecture diagram of the proposed model.

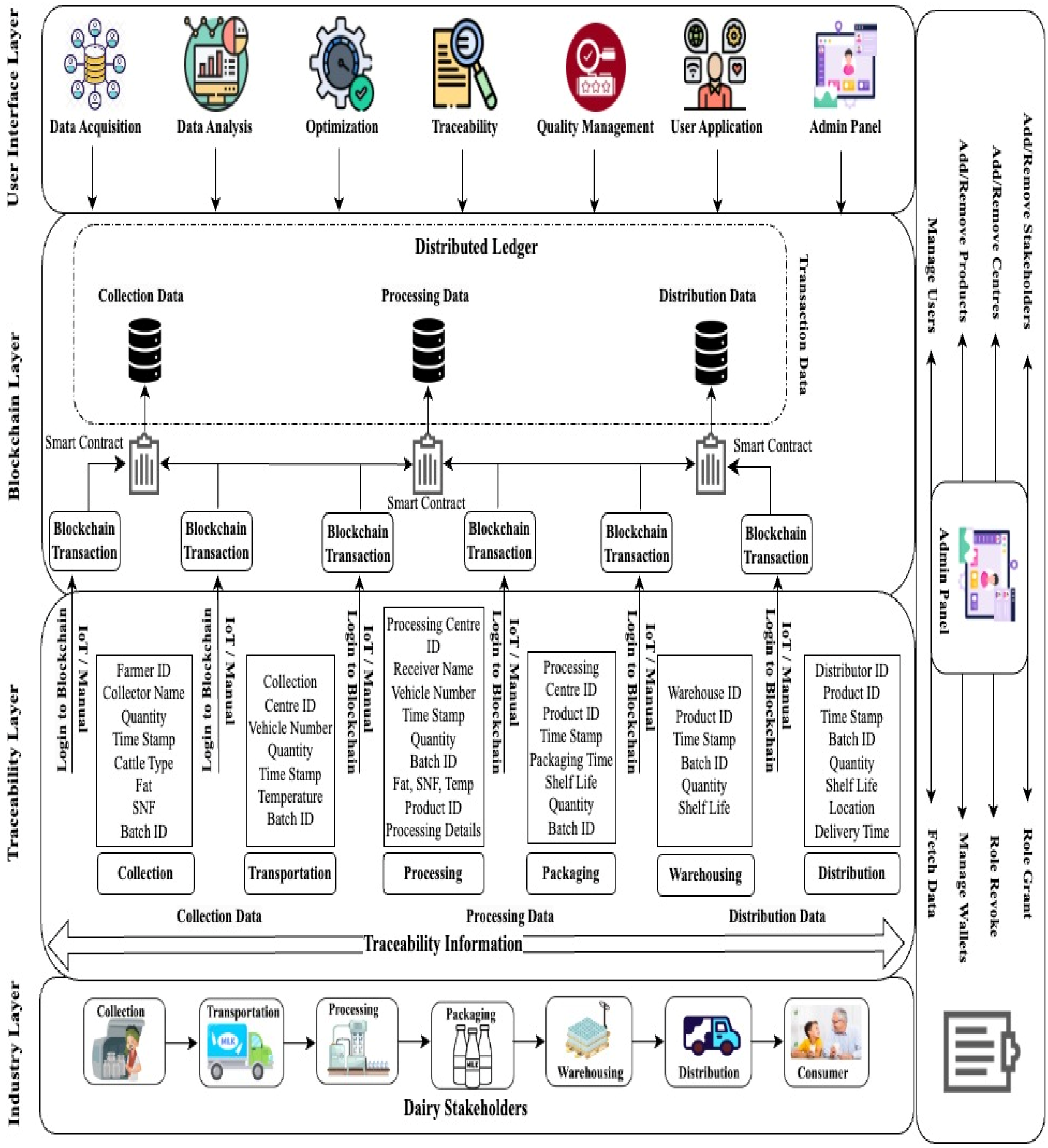


Figure 4. Proposed architecture of the traceability model *(Source: Authors)*

As shown in Figure 4, the admin can add and remove registered stakeholders, as well as any segment of dairy and product, using the admin panel. The admin manages the wallets, role granter and revokes, and data fetching, but in a decentralized manner. Figures 3 and 4 illustrate the theoretical concept of the proposed traceability model, laying the groundwork for developing the web-based model. The smart contract lifecycle encompasses data acquisition, anomaly detection, smart contract validation within the blockchain layer, secure data storage (both on-chain and off-chain), ensuring safety and security, integration with existing systems, and ultimately, consumer traceability and data verification.

4.3 Model Development and Proposed Functionality

Four modules have been developed for the traceability model, including 1) Procurement data, 2) Processing data, 3) Distribution data, and 4) Admin section. This section outlines the detailed process of developing a web-based application for the proposed model, based on the theoretical concept and proposed architecture, along with the functionality of the individual modules. The procurement module has six submodules: collection data, transportation data, farmer ID generator, and three data retrieval submodules for registered farmers' lists, collections, and transportation. The smart contract in algorithm A1 was used to generate farmer IDs; algorithm A2 was used to generate collection center IDs; algorithm A3 was used to add collection data; and algorithm A4 was used to add transportation details. Algorithms A5 and A6 retrieved the collection center and transportation details. The processing module comprises four submodules: processing and packaging data, and two data retrieval submodules for processing and packaging. The smart contract in algorithm A7 was used to process center ID, algorithm A8 was used to generate product IDs, algorithm A9 was used to add processing data, and algorithm A10 was used to add packaging data. At the same time, algorithms A11 and A12 have been used to retrieve processing and packaging data.

The distribution module has six submodules: warehouse data, retailer data, retailer ID generator, and three data retrieval submodules. The smart contract in algorithm A13 was used to generate retailer ID, algorithm A14 generated warehouse ID, algorithm A15 was used to add warehouse data, and algorithm A16 was used to add retailer data. At the same time, algorithms A17 and A18 retrieved retailer and warehouse data, respectively. The admin module comprises twelve primary submodules, including ID generators for collections, processing, packaging, warehouses, product IDs, and their respective data retrieval submodules. Figure 5 illustrates the procurement module, which encompasses data collection for the collection process, transportation, the farmers' ID generator module, and all related data retrieval modules.

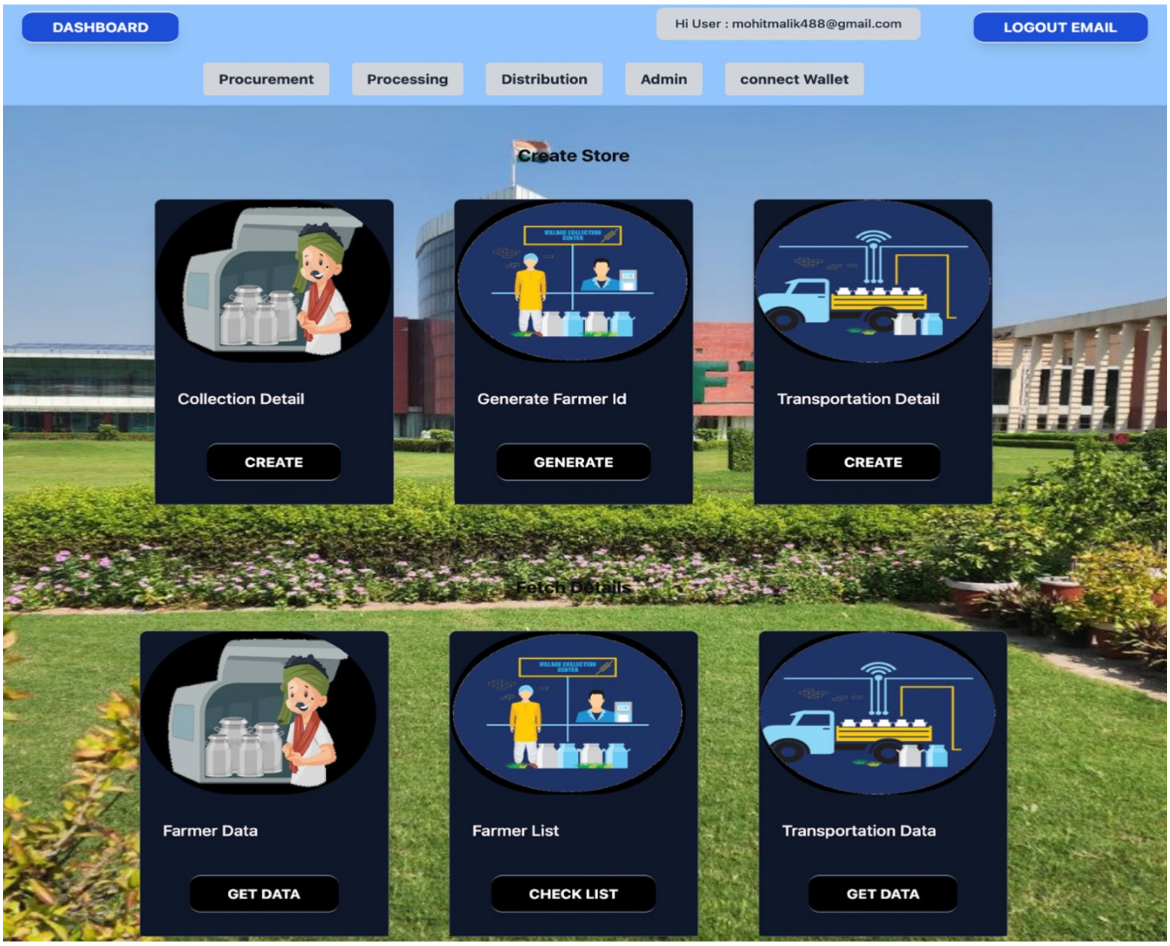
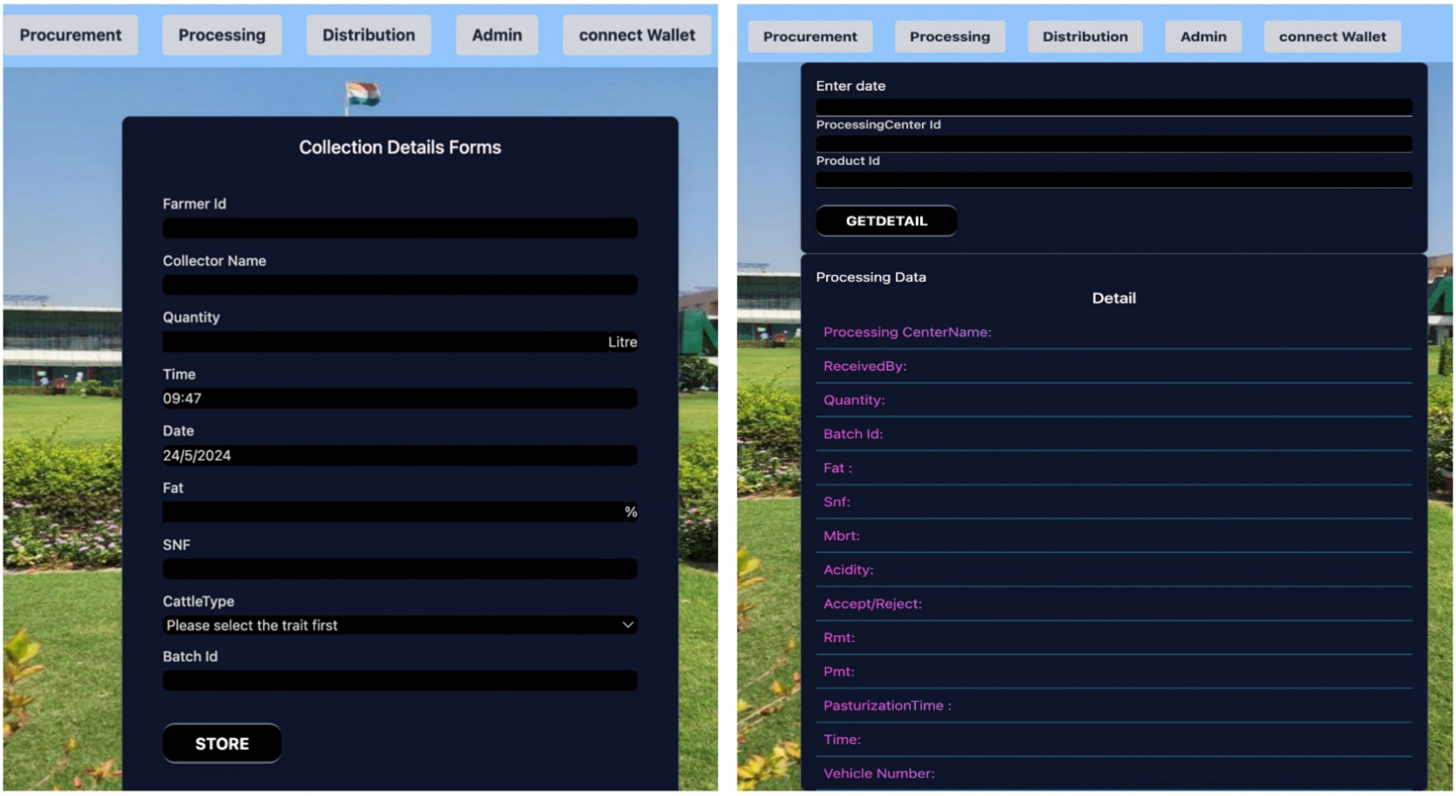


Figure 5. Procurement operations (module and sub-module interface) *(Source: Authors)*

Similarly, all modules have the same interfaces as the procurement module, as shown in Figure 5. The admin module includes two additional submodules, role grant and role revoke. Admin must assign each wallet to all modules and a main wallet for the admin panel to monitor the individual transactions for the dairy segments. These wallets can send data to the blockchain for each module. The admin must register dairy stakeholders regarding their roles in the traceability database for the dairy industry. The admin must create separate login credentials for registered stakeholders in each module, and stakeholders associated with their respective modules can collect data. Users can access their accounts through a web-based application developed for the proposed model. Then, the data was collected using each module and interacted with the blockchain using smart contracts. The admin can manage the data related to each module and registered stakeholders. The data acquisition methods depend on the industry's available infrastructure. For example, suppose any business implemented with the developed model has an IoT-supported infrastructure. In that case, the data can be collected directly via sensors and stored in the blockchain, or the operator must manually enter it. The admin provides access to users according to their role; for example, the collectors and transporters only get access to the procurement module. Similarly, all stakeholders get access according to their job roles. Admin can also fetch data and access a list of all registered stakeholders. Figure 6(A) shows the data collection module where registered stakeholders can enter data related to the collection process. Similarly, all types of data can be collected using their respective modules.



A B

Figure 6. Data collection and retrieval module *(Source: Authors)*

Figure 6(B) illustrates the data retrieval module for processing, which allows users to verify the entered data for any specific date using their registered ID. Similarly, users can check and retrieve data for each module. The next section demonstrates the practical application of the developed model through a case study.

4.4 Data Security and Privacy Mechanisms

Ensuring data security and privacy is crucial in the development and implementation of digital solutions, such as the proposed model. In current research, researchers adopted several safety measures to protect the stakeholders and industrial data. Data security and privacy mechanisms include four layers integrated in the model to enhance its security. Layer 1st includes identification and authentication for each associated stakeholder, such as farmers, collectors, drivers, processors, distributors, etc. Everyone has been assigned a unique and digital decentralized identity. Additionally, for each developed module, a separate *MetaMask* wallet is assigned for authentication, role-based access, and proof of ownership support. Layer 2nd includes smart contracts, encryption, and data integrity, which store all data related to stakeholders' digital IDs and data collected via each module. Each data entry is hashed on the blockchain, ensuring integrity and immutability. Only smart contract owners and admin with assigned roles can view and access the data. Layer 3rd includes smart contract validation based on the defined rules and ensures automatic validation of collected data before uploading it to the blockchain. These validation rules encompass registered users' IDs, data related to quality parameters, processing, and distribution, among other aspects. Entering incomplete or invalid data will reject that transaction automatically to maintain uniformity. Layer 4 encompasses secure data storage and data access in dual modes, including on-chain and off-chain storage. The on-chain data storage presented immutable identifiers and hashes, while off-chain storage's security depends on the type of system developed by the organization. The current research employed an on-chain storage mode, focusing on its immutable and transparent nature. Customers can access authentic data related to product traceability using QR codes or hash identifiers, ensuring the tamper-proof nature of the data. Thus, the security workflow includes role-based authentication, encrypted data collection, automated smart contracts validation, on-chain storage, immutable audit and customer transparency. Following such a workflow, the developed model observes for unauthorized access, transaction rejections due to invalid data entries, real-time changes in sensor data, etc. and transactional data access by authorized roles.

4.5 Pilot Implementation: Blueprint and Digital Evidence

The model has been implemented at *Binsar Farms*, encompassing its collection, transportation, processing, warehousing, and distribution. Data points have been predefined for every module integrated into the developed model, which includes quality parameters, personnel details, time stamps, and other required parameters. Figure 8 illustrates the overall implementation process, which includes user login for data validation. A wallet has been assigned to the admin to ensure the proper functioning of blockchain transactions for every module. As the developed traceability model is a prototype, a single wallet has been assigned to each module; later, it can be extended module-wise according to industry requirements. Data has been collected based on *Binsar Farm's* availability of technological infrastructure. The operator used the web-based application to collect the data module-wise. Personal visits ensured the smooth functioning of the data collection procedure. The collected data has been stored on the blockchain server and the developed model database. Due to privacy concerns, some hypothetical data, such as the stakeholders' names and vehicle details, has been used instead of actual information.

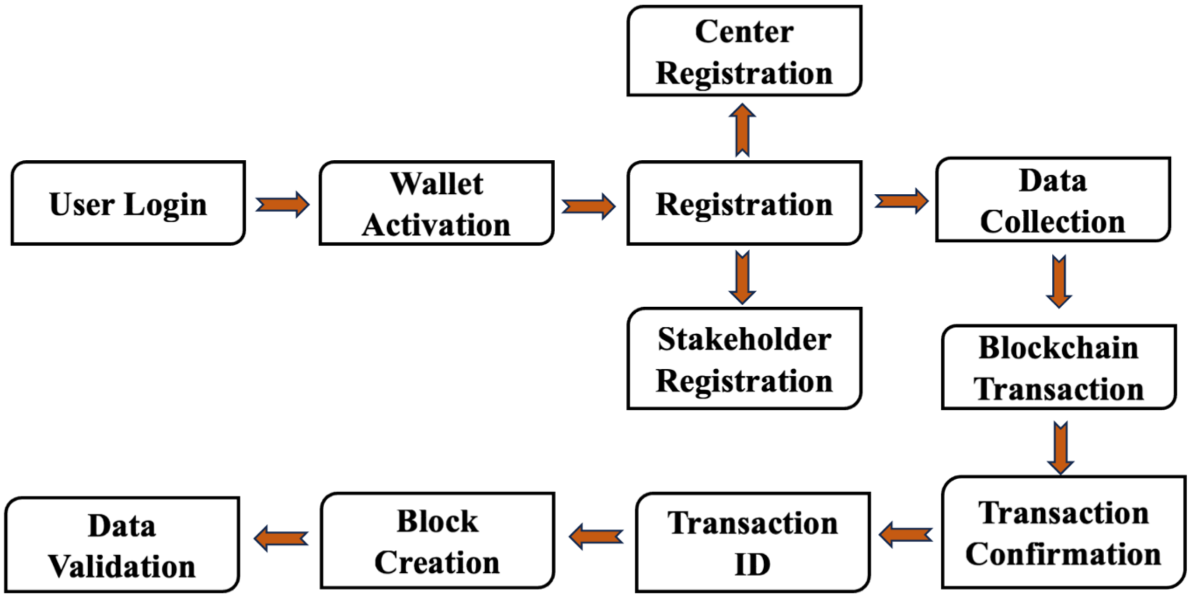


Figure 7. Model implementation process *(Source: Authors)*

As shown in Figure 7, the data collection process remained the same for every module in the developed traceability prototype during the implementation and validation process at Binsar Farms. The stakeholders associated with *Binsar Farms* have been identified to implement the model effectively, including its farmers, collection centers, transporters, processors, packing centers, warehouses, and distributors. The admin role was assigned to Binsar management to manage its registered stakeholders. A training session has been organized to provide hands-on experience with the hybrid blockchain and AI-enabled traceability model and collect data for every module. The admin registered and created digital IDs for their stakeholders. The associated farmers, collection, transporter, processing, packing, warehouse, and distribution centers were registered. Figure 8 demonstrates the confirmation of the collection centre ID generation on the blockchain network. Similarly, users can register their stakeholders on the blockchain network and assign them a digital ID.

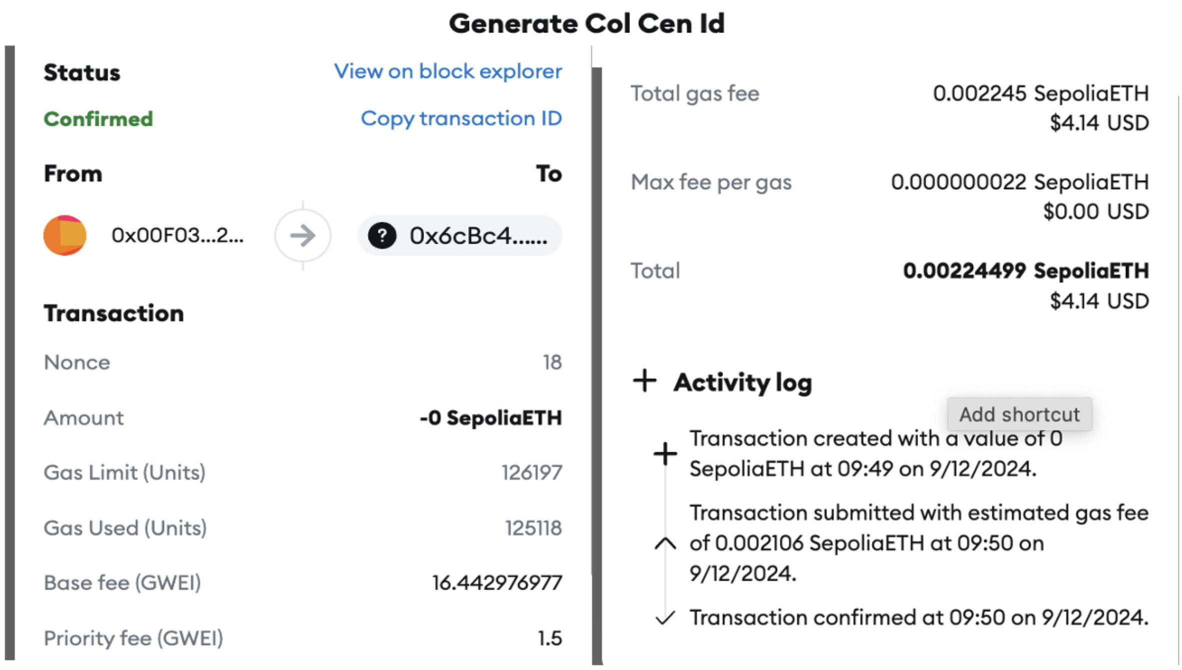


Figure 8. Confirmation of ID generation *(Source: Authors)*

The data collection process has been hybrid per the technological infrastructure available at collection centers, including automatic data collection via IoT sensors and manual data entry. Data collected from collection centers concerned milk quality, quantity, and farmer and collector details. The time stamp was made mandatory to ensure real-time monitoring. Data collected from the transport module included the real-time temperature of milk until it reached the processing center. Then, the model is integrated at the processing center, where all details related to processing activities and packaging are captured. Finally, the distribution module collected data about the warehouse and distribution, including time stamps and other information from previous modules, to ensure end-to-end traceability. The admin management can now manage the data to trace, recall, and analyze it to improve the management at the farm. Figure 9 (A & B) shows data collected via the developed model on the blockchain network; here, A shows data transaction confirmation, and B shows detailed transaction hash.

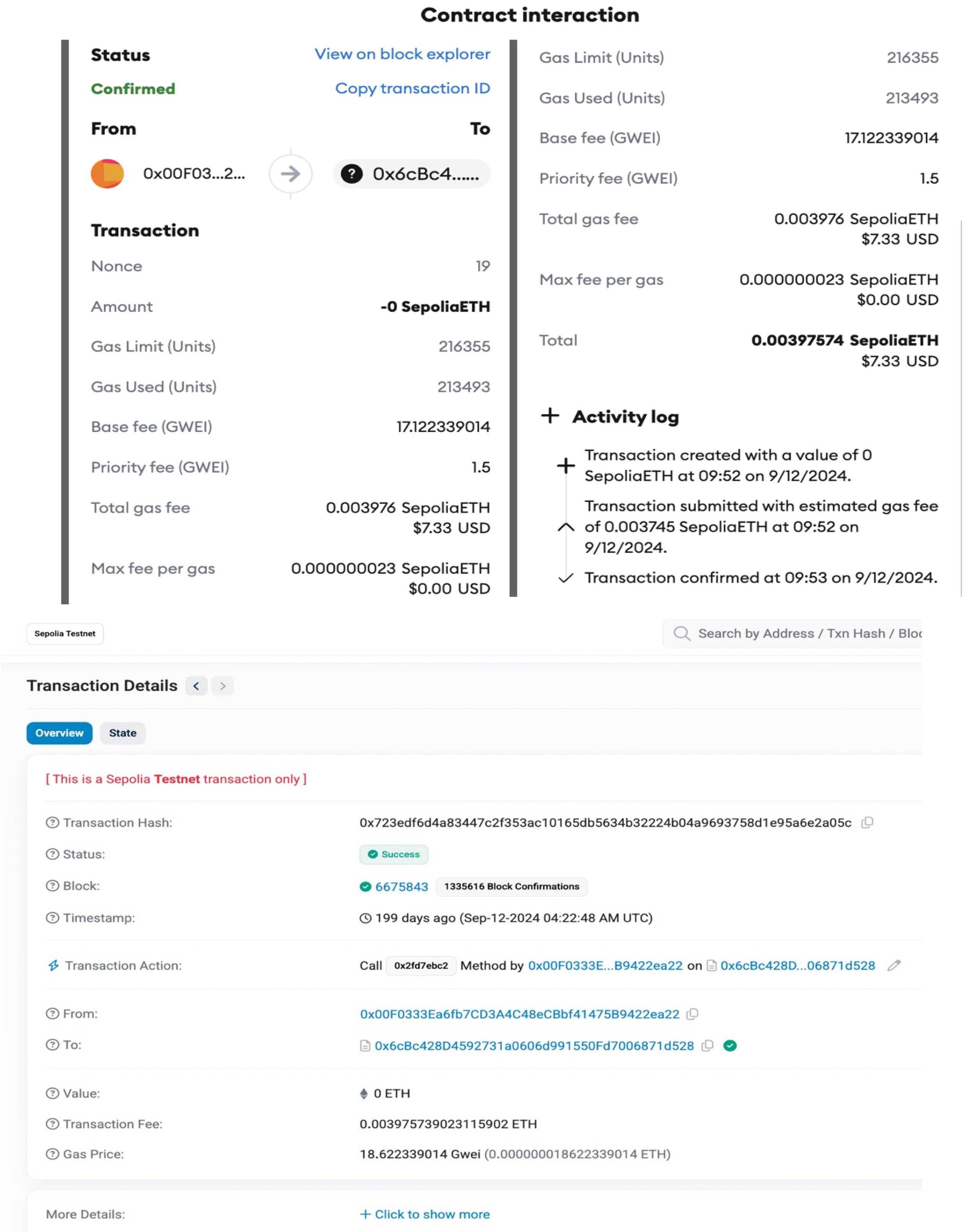


Figure 9 (A & B). Transaction hash confirmation *(Source: Authors)*

Using the *'Transaction hash'* provided in Figure 9, the user can track all the data collected via the developed model internally. For external traceability, providing this hash on products can help consumers track the required details related to product traceability. Here, the farmer ID represents the registered farmers, the collection center ID represents the registered collection center, and the rest are data points in the procurement module. Due to ethical and data respondent privacy concerns, the implementation process did not use the actual personal information (names) of stakeholders, vehicles, drivers, etc., and the numeric entries represented all required IDs, and the time stamp was fetched in real-time. The admin can access and analyze all the data related to all modules in a single place. Later, the data can also be fetched from the blockchain server.

4.6 Implementation Outcomes: Model Assessment, Comparative Analysis, and Challenges

To evaluate the model's functioning post-implementation, the data were compared with the traditional working mechanism, which includes data management related to registered stakeholders, quality parameters, and various processes such as transportation, processing, packaging, warehousing, and distribution. The findings are extracted from smart contracts executions, event logs and transactions on the blockchain. Using the formulas 1-4 given in Section 3, certain metrics were employed to compare the proposed model with the existing traceability system. The evaluation metrics include average transaction time (ATT), gas fee per transaction (C_{tx}), product recall time, data entry error rate, cost saving, successful traceable batches, traceability coverage (TC), data accuracy rate (DAR), etc. Formulas for each metric are given in Section 3. Table 4 presents a comparative analysis of the existing traceability system vs the developed hybrid traceability model based on the defined metrics. It highlighted the potential comparative insights following the post-implementation of the hybrid traceability model; the evaluation metrics are well-supported by the data generated after implementation. For example, the average transaction time for the developed model is around 1.0-4.7 seconds, as shown in Figures 8 and 9, whereas the existing traceability system takes around 20-30 seconds.

Table 4. Comparative analysis of Hybrid Traceability Model vs Traditional Mechanism
(Source: Authors)

Dimension	Metric	Traditional System	Developed Model	Key Improvements
Traceability	Average transaction time	20-30s	1.0-4.7s	The developed model is significantly faster than the existing traceability system.
	Traceability coverage	40-50%	100%	It offers complete traceability coverage as data collected via every module can be traced at any time using the generated QR or hash.
	Traceable batches	--	100%	In the existing traceability system, the analysis revealed that

				batch traceability is uncertain; however, the developed model ensures 100% batch traceability, as every batch is linked to a unique data transaction.
	Product recall rate	~2-4 hours	~25-30 min	The developed model significantly improved product recall time using end-to-end traceability.
Operational efficiency	Manual record management	Mostly paper-based and partial record-keeping	100% digital data management and storage in both on-chain and off-chain systems	The developed model achieved complete digitalization.
	Gas fee per transaction	-----	0.00398 ETH	In traditional systems, the gas fee is not applicable, as owners must pay one-time or annual fees to manage the system.
	Data accuracy	70%	96%	Data accuracy is significantly improved in the developed model as effective validation rules are defined to detect the anomalies.
	Operational cost	Standard	Lower comparatively	Operational costs in a traditional system depend on business-to-business transactions due to the fragmented nature of the ERP or traceability system; however, the developed model offers a single-stop solution for traceability, reducing costs.
System transparency	Data integrity	Can be tempered	Immutable nature	In a manual system, data is prone to tampering, but the developed model has immutable characteristics.
	Consumer transparency	Limited	Data availability via QR and hash	The existing system has limited access to customer data, but the developed model offers end-to-end traceability.
	Data sharing among stakeholders	Limited and role-based	Grants access to real-time data as per assigned module roles	The developed model enhanced 360-degree supply chain visibility
Sustainability impact	Data availability related to each operational activity	Limited and fragmented	End-to-end data collection and sharing	The developed model enables effective data analytics, leading to real-time and smart decision-making, which further reduces carbon emissions along with adverse environmental impacts

For metrics such as gas fees, transaction time, and data accuracy, Web3 receipts are shown in Figures 8-9. Additionally, the authors compared the developed model with the traditional traceability system used at Binsar Farms, and the values align with those suggested in the existing literature by Behnke & Janssen (2020) and Casino et al. (2020). In the developed model, certain metrics, such as data accuracy and data error rate, are influenced by the mode of data entry adopted by the industry. Thus, the insights indicated that the evaluation metrics performed by the developed model significantly supported its characteristics compared to traditional traceability systems. Issues such as scalability and interoperability with existing systems still require further exploration and improvement, although the developed system supports multiple collection centres associated with *Binsar Farms*, indicating the scalable nature of the model. These findings align with existing studies (Behnke & Janssen, 2020; Casino et al., 2020), which highlight the lack of trust and interoperability as common challenges. Vern et al. (2024) also outlined the implementation challenges, including cost, interoperability, scalability, etc. Biswas et al. (2023) highlighted the negative environmental effects of implementing such systems, including high energy consumption. These observations, related to implementation aspects such as scalability, compatibility with existing systems, and energy consumption, along with gas fees, are consistent with literature studies on blockchain-based traceability systems (Choi & Siqin, 2022; Li et al., 2022). Post-implementation data analysis shows that the hybrid blockchain and AI-enabled traceability model ensures end-to-end traceability for milk by tracing its journey throughout the supply chain with transparency and decentralization. The real-time data fetching and timestamp ensure the accuracy and reliability of the collected data. Overall, the developed traceability model enhances the traceability of milk as compared to traditional techniques. Automated data collection minimized human errors and manipulations in data entries. It also reduces the cost and time required for maintaining manual data records and tracking data in recall cases. Real-time monitoring, key data entries related to storage conditions, and product details ensure product quality and minimise wastage, while maintaining an efficient supply chain. To assess the model's effectiveness. The data entry also provides origin-related information, product nutritional parameters, and monitoring of storage conditions, including shelf life. The decentralized characteristics of the hybrid blockchain and traceability model ensure 360-degree supply chain visibility and data sharing among all registered stakeholders. The immutable nature ensures that the data collected through the model cannot be tampered with. The user-friendly model interface ensures smooth data collection for all developed modules, and the admin dashboard makes the complete dairy supply chain management more effective and optimized. Post-implementation, some improvements in operational efficiency, end-to-end traceability, quality and safety enhancement, and optimized data management compared to earlier traditional traceability systems have been observed.

Table 5. Stakeholders’ perspective on the developed model *(Source: Authors)*

Stakeholder	Existing Challenges	Advantages of the Developed Model
Farmers & Collection Centers and Transporters	• Infrastructure requirements for technological solutions • Resistance to adopting new technology • Lack of skills • Need for training • Manual Paperwork	• Automated data collection • Maintained records • Immutability and decentralization • Transparency and ability to track products through the supply chain
Processing and Packaging Centers	• Technical issues during the initial setup • Need for system maintenance	• Enhanced ability to monitor processing conditions and ensure batch traceability • Data Management related to processing activities • Real-time data monitoring
Warehouses and Distributors	• Managing the transition from traditional methods to blockchain-based systems • Inventory management • Traceability • Manual records	• Improved inventory management • Real-time tracking of storage conditions • Real-time monitoring • Supply chain visibility
Dairy Management	• Understanding and using QR codes to access product information	• Increased consumer trust and confidence • Quality assurance • Traceability • Effective data management

The advantages of the developed model are not limited to Table 5, as the model has been implemented on a pilot basis. Further analysis can help evaluate the full potential of the developed traceability model.

4.6.1 Challenges and Limitations of Implementation

Blockchain and AI provide a more efficient, straightforward, and trouble-free method for data recording for traceability in the dairy industry, ensuring the data remains unaltered. Like any other technology, these have certain limits. The implementation process reveals the numerous advantages of the hybrid blockchain and AI-enabled traceability model, while also highlighting some limitations and challenges that necessitate further improvements. Industrial readiness for adopting traceability systems is a crucial barrier, alongside the industry’s existing infrastructure and supply chain activities, which are also important parameters to consider before implementation. The hybrid blockchain and AI-enabled traceability model works for milk traceability only, although it can be customized for other milk-based dairy products. To enable this customization, the developer needs to modify the smart contract-based data collection fields and validation rules. By generalization, the authors suggested that the model can be replicated for other dairy products also by adding or replacing the data collection modules and updating the smart contracts execution rules. This section discusses the challenges faced during implementation and the limitations of the developed model.

- The significant challenges are the selection of data acquisition points for traceability in synchronization with the developed model, and the format of data points differs with use cases.
- Lack of technical knowledge among stakeholders affected the implementation process.
- Data-sharing decisions related to collected information appeared to be another key challenge, as they can affect managerial decisions.
- Model customization per industrial requirements, such as the industry scale, number of users, etc., has also been challenging.
- Immutable characteristics of the developed model have also been challenging because of the immutable nature of the data; hence, training the users to avoid such mistakes has become critical. Stakeholders are hesitant to adopt such systems due to concerns about maintaining compatibility with traditional systems.
- Due to recent technological advancements, more qualified individuals are needed to develop blockchain. Researchers and developers skilled in various blockchain systems (public, private, hybrid) are severely restricted in their ability to develop smart contracts, cryptocurrencies, and consensus protocols. Only some national organizations, whether private or government-run, possess the required qualifications and infrastructure to conduct practical training on blockchain technology.
- The lack of regulatory standards and guidelines on the transactions/data collection format also poses a challenge.
- Blockchains' open-source and collaborative nature adheres to specific codes and rules, which are vulnerable to security issues and breaches.
- Establishing a large-scale system for implementing the hybrid blockchain and AI-enabled traceability model requires significant initial expense.

The implementation was conducted for a limited period to validate the model and test the developed functionalities. Various challenges arose during implementation, such as integrating the model with the existing technical infrastructure, training, and hands-on operation of the model interface.

5. Implications

This research has significant implications for researchers, dairy stakeholders, technological developers, and policymakers. It contributes to the existing literature on implementing emerging solutions, such as traceability based on digital technologies, including AI, IoT, and blockchain, in supply chain management, particularly in the agri-food sector, by explaining the development and implementation aspects of these solutions. Key implications are as follows.

5.1 Theoretical Implications

This research enhances the conceptual understanding of how traceability solutions based on AI and blockchain can enhance sustainability and transparency in the dairy industry. It thoroughly analyzes the design and development aspects of a hybrid blockchain and AI-enabled traceability model, providing valuable insights into the practical uses of the developed digital solutions for the dairy industry. Researchers and technology developers in the dairy context can use findings to modify and improve theoretical frameworks and techniques for generalizing the developed concept to other application areas. This research contributes to the ongoing discussion on how emerging technologies can address sustainability issues in agri-food value chains. It also highlights how blockchain technology can enable the monitoring and authentication of dairy products throughout the supply chain, demonstrating the capacity of technological advancements to enhance transparency, mitigate milk adulteration, milk fraud, and counterfeiting, and promote ecological responsibility. Furthermore, it fosters additional multidisciplinary research on the relationship between technological advancements, sustainability, and management. Finally, the research fills the gaps highlighted by (Hassoun et al., 2023, 2024; Hastig & Sodhi, 2020) and contributes towards advancing digital traceability by integrating blockchain technology and AI.

5.2 Practical Implications

The findings have considerable implications for all dairy stakeholders, including offering a transparent 360-degree view of dairy operations. It could provide real-time insight into product flow, improve supply chain resilience, and enhance consumer trust by increasing transparency. The regulatory organizations can use the findings to develop standards and guidelines for implementing digital technologies, including blockchain technology, in food traceability processes. This research highlights the significance of collaborative endeavours, including those of industry stakeholders, technology developers, and researchers, to promote the adoption and implementation of technology-driven solutions for effective traceability. Through collaborations and knowledge-sharing activities, stakeholders can address and tackle challenges such as scalability, interoperability, and privacy concerns, thereby accelerating the widespread adoption of digital technologies in food supply chains. It has significance beyond the dairy industry, providing a pathway for using blockchain technology to enhance transparency, sustainability, and confidence in global supply chains. Overall, the implications highlighted the game-changing potential of the AI-enabled traceability model to ensure a transparent, efficient, sustainable, and greener future for the dairy industry. Further study and collaboration are needed to utilize such hybrid traceability models based on digital technologies to improve the agri-food sector.

6. Conclusion

This research explored the conceptual and practical development aspects of an AI-enabled traceability model for the dairy industry, presenting a brief overview of the development process that includes the concept, proposed architecture, proposed functionality, and smart contract development. It offers significant potential for enhancing transparency, accountability, and sustainability in dairy operations. It demonstrates a use case for implementing a hybrid blockchain and AI-enabled traceability model for the dairy industry. The developed model provides each module's secure, transparent, decentralized data collection and tracking mode. The developed model has been implemented for various modules, including collection center, transport, processing, packaging, warehousing, and distribution. The data collection process reveals significant changes compared to traditional traceability data collection processes. Post-implementation analysis highlighted several advantages, including enhanced traceability, increased transparency, improved quality assurance, technological advancements, and economic benefits. The model has been successfully validated as a case, and all modules functioned as designed, ensuring the specified characteristics were met as outlined in the smart contracts. The findings highlighted observations such as automated data collection, effective data management, real-time monitoring, and transparency in product processing-related details. The findings show the model’s immutable, decentralized, and transparent nature. The implementation process also highlighted the impact of the AI-enabled traceability model on dairy stakeholders, such as farmers/producers, who would benefit by getting fair prices, enhanced consumer trust, and effective resource management. *The Binsar Farms management and leadership team endorsed the developed model and are keen to deploy a 360-degree approach to maintain operations and collaborate more effectively* with stakeholders. It can positively impact consumers by ensuring the end-to-end traceability of dairy products, as well as their quality and safety. Despite the potential advantages, this prototype system has some limitations, such as manual data collection at some supply chain points, which can be digitalized, extending the smart contracts, and integrating Industry 4.0 technologies. The developed system needs further optimization for gas fees, transaction speed, and execution time. The developed model is currently limited to one product, specifically milk. Although the admin can register multiple products, further development is required to establish criteria related to each product.

6.1 Future Research Directions

The current research has paved the way for an advanced understanding of blockchain technology's potential applications in the dairy industry. However, additional investigation is required to optimize smart contracts for cost, scalability, and IoT integration to make the model fast, secure, and more effective. A multifaceted strategy is needed to thoroughly investigate the technical, environmental, economic, and social factors of blockchain adoption from a dairy perspective. The prototype model can incorporate aspects of farmer and animal welfare, waste management, and carbon footprint to provide a comprehensive 360-degree approach to dairy management, ensuring a greener and more sustainable future. As the dairy industry is in its initial stages of blockchain-based traceability adoption, several factors, such as technological, organizational, and environmental aspects, need further investigation. The current research can also be extended to investigate the impact assessment of the developed model through a case study by implementing it on a large scale, which would benefit from the development of an upgraded version of this prototype system. Considering the volume and time constraints of current research, the authors propose a detailed empirical investigation of potential benefits and implementation challenges from the perspective of industry stakeholders as a possible extension. The model can be customized per industrial requirements, and research related to industrial readiness to adopt such technological solutions needs to be done. Further, this model can be implemented as a permanent traceability solution to measure and analyze its impacts and challenges for future improvements. This impact assessment can inform the development of an industrial readiness index to adopt such a traceability system, facilitating the creation of a more advanced traceability system for the dairy industry. Scalable, hybrid, on-chain, and off-chain traceability models, along with supportive policies and guidelines for implementing and adopting such technological solutions, need to be developed in the future. The current research opens opportunities to develop global technological solutions for sustainable dairy, including Industry 5.0 technologies.

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Appendix

Pseudocode for **Smart Contract Validation**

Algorithm: validateTransaction

Input: payload = { stakeholderID, role, batchID, IoT_Data, Quality_Params, GPS, Timestamp }

```
Begin
   # 1. Verify stakeholder identity (A1, A2, A7, A13, A14)
   IF !isAuthorized(payload.stakeholderID, payload.role) THEN
      RETURN "Rejected: Unauthorized Wallet"

   # 2. Check for duplicate registration (A1, A2)
   IF role == "Farmer" OR role == "CollectionCenter" THEN
      IF walletExists(payload.stakeholderID) THEN
         RETURN "Rejected: ID Already Exists"
      ENDIF
   ENDIF

   # 3. Validate IoT data thresholds (A3, A4, A9, A10, A15)
   IF !isValidIoT(payload.IoT_Data) THEN
      RETURN "Rejected: IoT Sensor Anomaly"
   ENDIF

   # 4. Validate milk quality against thresholds (A9, A10)
   IF payload.Quality_Params.Fat < MIN_FAT OR payload.Quality_Params.Fat >
MAX_FAT THEN
      RETURN "Rejected: Invalid Fat %"
   ENDIF
   IF payload.Quality_Params.SNF < MIN_SNF OR payload.Quality_Params.SNF >
MAX_SNF THEN
      RETURN "Rejected: Invalid SNF %"
   ENDIF

   # 5. Verify GPS-based route authentication (A4, A16)
   IF !isValidRoute(payload.GPS) THEN
      RETURN "Rejected: GPS Mismatch"
   ENDIF

   # 6. Validate batch timestamp (A5, A6, A11, A12)
   IF payload.Timestamp < ALLOWED_START OR payload.Timestamp >
CURRENT_TIME THEN
      RETURN "Rejected: Invalid Timestamp"
   ENDIF

   # 7. Generate SHA-256 hash for traceability (A3, A5, A6, A17)
   hash = SHA256(payload.stakeholderID || payload.batchID || payload.IoT_Data ||
payload.Timestamp)
```

```
    # 8. Store off-chain assets on IPFS and get CID (A17, A18)
    cid = IPFS.store(payload.certificates, payload.labReports)

    # 9. Commit validated data to blockchain ledger (All A1-A18)
    saveOnChain(payload.batchID, hash, cid, payload.Timestamp, msg.sender)

    RETURN "Success: Transaction Recorded"
End
```
Output: transactionStatus