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THEORETICAL MODEL FOR BLOCKCHAIN INTEGRATION IN A CONSTANȚA COUNTY AGRICULTURAL COOPERATIVE

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Abstract. *Blockchain technology offers significant theoretical potential to enhance transparency and operational efficiency in agricultural cooperatives, especially in regions with strong export opportunities such as Constanța County, Romania. Despite its advantageous geographic position near Romania's major maritime port, agricultural cooperatives in this region face challenges related to limited traceability and suboptimal resource management. This paper proposes a theoretical model for blockchain integration into a local agricultural cooperative, focusing on improving transparency, supply chain traceability, and operational workflows. Using a systematic meta-analysis of recent peer-reviewed studies, the paper synthesizes evidence regarding blockchain applications in agriculture to inform the model's design. The proposed conceptual framework does not involve direct practical implementation but outlines potential processes and expected outcomes based on existing technological evidence and local logistical conditions. Blockchain's immutability and decentralized structure ensure reliable traceability of agricultural products, thereby reducing fraud risks, enhancing compliance with export standards, and optimizing resource utilization. Furthermore, leveraging blockchain technology within logistical and managerial processes can significantly benefit cooperatives by reducing operational costs and strengthening trust among cooperative members and commercial partners. The model emphasizes the strategic advantage of proximity to the maritime port for logistics and export activities, making it potentially replicable for cooperatives in similar agricultural regions. This theoretical approach highlights the pathway towards modernizing cooperative structures, enhancing product quality, and increasing competitiveness on international markets.*

Keywords*: traceability, transparency, supply-chain, export compliance, meta-analysis.*

INTRODUCTION

Blockchain technology has emerged as a powerful tool capable of addressing numerous challenges within agricultural supply chains, especially concerning transparency, traceability, and resource management. Agricultural cooperatives, in particular, have increasingly recognized blockchain as a viable solution for optimizing their operational workflows and enhancing trust among stakeholders (Kamilaris et al., 2019; Demestichas et al., 2020; Rejeb et al., 2020). Despite these potential advantages, practical blockchain implementations remain limited, especially within Eastern European agricultural contexts, characterized by fragmented land holdings and ambiguous cooperative structures (Dogaru et al., 2020; van Hilten et al, 2020).

Constanța County, strategically situated near Romania's major maritime port, offers substantial opportunities for agricultural exports. Nevertheless, local agricultural cooperatives face persistent issues related to traceability of products, inefficiencies in resource allocation, and difficulties in managing compliance with stringent international market standards (Nistoroiu et al, 2024; van Hilten et al., 2020). Given these constraints, the adoption of blockchain technology in the region represents a promising but largely unexplored theoretical solution (Torky et al, 2020).

This article proposes a theoretical model for integrating blockchain technology into an agricultural cooperative in Constanța County, based on a systematic meta-analysis of peer-reviewed literature from the past 15 years. The model aims to theoretically illustrate how blockchain integration could enhance transparency, improve traceability throughout the cooperative's supply chain, and optimize resource management practices. Moreover, the proximity to the maritime port of Constanța enhances the strategic relevance of such a theoretical blockchain application, particularly regarding compliance with export regulations and improving logistic efficiency.

Through this conceptual exploration, the article aims to contribute significantly to existing literature, offering insights into potential blockchain applications tailored explicitly to the regional agricultural context of Romania and similar settings elsewhere.

MATERIAL AND METHODS

This study employs a systematic meta-analysis approach to explore recent advancements in blockchain technology applications within the agricultural sector, specifically targeting studies published in peer-reviewed academic journals from the past 15 years (2009-2024). The primary objective of this meta-analysis is to synthesize existing evidence regarding blockchain technology's roles, benefits, and limitations, emphasizing transparency, traceability, and operational efficiency within agricultural cooperatives.

The search strategy involved querying several major academic databases, including Web of Science, Scopus, IEEE Xplore, and Google Scholar. The key search terms utilized were "blockchain in agriculture," "agricultural cooperatives blockchain," "supply chain transparency blockchain," and "traceability in agriculture blockchain." Inclusion criteria required articles to be peer-reviewed, published within the specified timeframe, and relevant to blockchain applications within agricultural or cooperative contexts. Exclusion criteria removed articles focusing exclusively on non-agricultural sectors or studies primarily centered on technical blockchain aspects without clear agricultural applications.

After the initial database search, a screening of titles and abstracts was conducted, followed by a full-text review to finalize the selection of relevant studies. Data from selected studies were systematically extracted, including publication year, geographical context, blockchain implementation type, identified benefits, encountered challenges, and the overall theoretical and practical contributions to agricultural cooperatives.

The extracted data were synthesized qualitatively to develop the proposed theoretical blockchain integration model specific to agricultural cooperatives in Constanța County. The meta-analysis findings were critically assessed to ensure methodological rigor and reliability. The resulting synthesis guided the theoretical framework, which emphasizes local logistical dynamics, export-oriented operations, and cooperative management practices.

This structured methodological approach ensures replicability and clarity, facilitating the evaluation of blockchain's potential impacts on cooperative efficiency, transparency, and supply chain traceability within similar regional agricultural contexts.

RESULTS AND DISCUSSIONS

Key Findings from Meta-analysis

The systematic meta-analysis identified consistent themes across recent literature regarding blockchain technology's potential to enhance traceability, transparency, and operational efficiency in agricultural cooperatives. These studies affirm blockchain's capability to mitigate traditional agricultural supply chain issues, such as product fraud, inefficient resource utilization, and inadequate traceability of products from production to export (Kamilaris et al., 2019; Dogaru et al, 2024). Rejeb et al., 2020 and Kamilaris et al., 2019 also stress that beyond traceability, blockchain provides a platform for the secure exchange of information across the entire agri-food value chain.

Furthermore, Nistoroiu et al., 2024 note that Romanian agricultural systems face additional challenges, such as fragmented land ownership and a lack of trust among stakeholders, making blockchain's trust-building potential especially valuable in this regional context. Studies also confirm that transparency is not only a regulatory requirement but a key factor in improving the reputation and competitiveness of agri-food systems on international markets (van Hilten et al., 2020).

Blockchain Benefits and Traceability

A major benefit highlighted across reviewed studies is the immutable nature of blockchain records, which ensures secure, transparent, and tamper-proof documentation of agricultural products throughout the supply chain. Blockchain has proven effective in providing comprehensive traceability solutions, addressing consumer demands for product authenticity and regulatory compliance for exports (Rejeb et al., 2020; Nistoroiu et al, 2024). Enhanced transparency from blockchain implementation fosters greater stakeholder trust, an essential factor for the success and cohesion of agricultural cooperatives (van Hilten et al., 2020).

Moreover, the ability of blockchain to trace agricultural inputs—such as fertilizer, pesticide use, and seed origin—was reported by Demestichas et al., 2020 to enhance food safety and quality assurance. Sendros et al, 2022 emphasize that blockchain also helps reduce recall times in the event of contamination or quality issues, which is particularly critical for export-oriented production where compliance with international phytosanitary standards is mandatory.

Theoretical Blockchain Model Proposal

The theoretical blockchain model proposed for the Constanța County agricultural cooperative is designed to provide a decentralized, permissioned blockchain infrastructure that supports a secure, transparent, and efficient agricultural supply chain. This model builds upon a layered architecture comprising four key components: (1) Data Acquisition Layer, (2) Blockchain Core Layer, (3) Smart Contract and Governance Layer, and (4) Interface and Access Layer.

(1) Data Acquisition Layer: This layer includes all field-level and post-harvest data sources, such as IoT sensors deployed in silos, transport containers, weather stations, and farm machinery. Real-time data—including geolocation, humidity, temperature, soil moisture, and fertilization and pesticide application—is gathered through these connected devices (Torky & Hassanein, 2020). These data are encrypted and transmitted to the blockchain system, enhancing granularity and reliability of traceability information (Sendros et al., 2022).

Incorporating standardized soil classification and monitoring data enhances the contextual relevance and traceability granularity in blockchain systems. For instance, Niță et al., 2020 demonstrated the spatial distribution of first-level monitoring sites for soil hydro-physical properties in Western Romania, emphasizing the importance of structured datasets for sustainable agricultural practices. Integrating such localized agro-environmental data into the blockchain model ensures a reliable foundation for input traceability, certification, and compliance verification.

(2) Blockchain Core Layer: At the heart of the model, a permissioned blockchain network ensures secure data storage and consensus among stakeholders. Each node—operated by farmer clusters, cooperative management, processors, and regulatory bodies—hosts a copy of the ledger. The consensus algorithm (e.g., Practical Byzantine Fault Tolerance or Proof-of-Authority) ensures validation of blocks without the high energy costs typical of public blockchains (De Angelis et al, 2017). Immutable logs of product movements, quality certifications, and input traceability are preserved.

(3) Smart Contract and Governance Layer: This layer automates internal and external workflows. Smart contracts are used to manage input supply chains (seed, fertilizer), quality validation at reception, payment execution upon delivery acceptance, export certification requests, and compliance tracking. For example, if a grain shipment maintains optimal storage conditions during transport (validated by sensor data), payment to the farmer and transport company is automatically triggered. Governance protocols define who can write, validate, or access specific data points (Rejeb et al., 2017; Torky & Hassanein, 2020).

(4) Interface and Access Layer: Through mobile or web-based dashboards, different stakeholders interact with the system based on their access rights. Farmers upload planting data and monitor their deliveries. Cooperative staff validate volumes and generate export documentation. Buyers can verify the origin and quality of shipments in real time, using QR codes that connect to blockchain entries (Kamilaris et al., 2019; Demestichas et al., 2020).

This detailed framework ensures that the cooperative gains end-to-end visibility across its supply chain while empowering participants with automated, fair, and transparent transactions. Additionally, the model supports modular expansion, allowing for the future integration of AI-based forecasting modules, drone surveillance data, and carbon footprint tracking for sustainability certifications.

Figure 1 illustrates the theoretical model for blockchain integration in an agricultural cooperative, structured across four functional layers that collectively support a transparent, efficient, and secure supply chain. At the base, the Infrastructure Layer provides the foundational digital and computational resources, including network connectivity and computing power. The Blockchain Network Layer ensures data integrity and synchronization via a distributed ledger and consensus mechanism, supporting the immutability and trustworthiness of transactions. The Contract/Chaincode Layer introduces smart contracts that automate key processes such as compliance verification, quality-based payments, and certification validation. At the top, the Application Layer comprises user-facing functionalities that enhance cooperative governance and market performance: supply chain transparency, fraud reduction, resource management and interfaces for cooperative members. This layered architecture not only facilitates data flow from field-level operations to final market documentation but also ensures modular adaptability to the specific needs of cooperatives operating in export-oriented regions such as Constanța County.

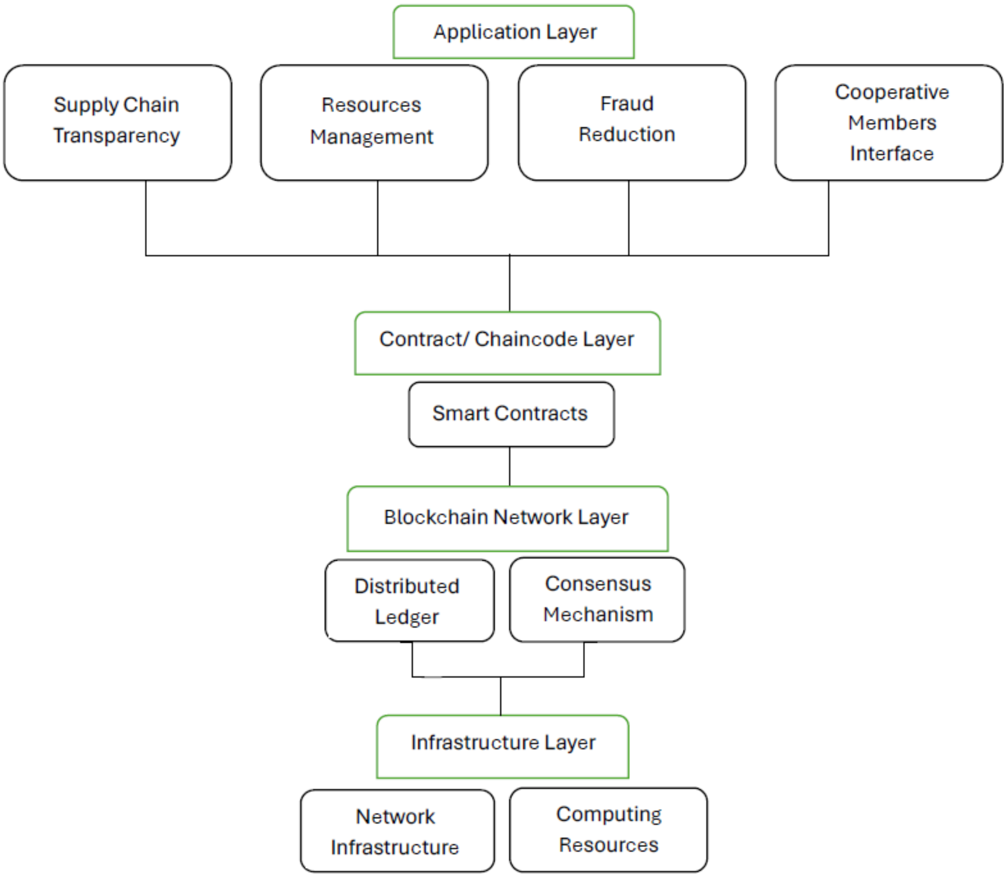

Figure 1. Theoretical model for Blockchain integration in a Constanța County Agricultural Cooperative

Strategic Logistic Advantages

Strategic implementation of blockchain technology is expected to significantly enhance logistical operations and resource allocation efficiency. Given Constanța County's proximity to the maritime port, leveraging blockchain could theoretically offer competitive advantages in managing export logistics. Enhanced transparency and efficient information sharing among stakeholders are anticipated to optimize decision-making processes, align operations more effectively with market standards, and strengthen competitiveness in international markets.

Additionally, blockchain enables a single source of truth for documentation, improving customs clearance and certification verification at borders. As Rejeb et al.,2020 highlights, this leads to reduced transit times and costs, while increasing credibility with international buyers.

Challenges and Implementation Considerations

Despite the promising outlook, several implementation barriers must be considered. Wamba & Queiroz, 2019 report that resistance to digital adoption, especially among older farmers, is a significant cultural challenge. Moreover, financial constraints for initial setup—including blockchain infrastructure, training, and devices procurement—may deter smaller cooperatives from adopting the technology.

Regulatory uncertainties, data privacy concerns, and the lack of interoperability standards across platforms are further complications noted in the literature (Torky & Hassanein, 2020; Sendros et al., 2022). Therefore, phased implementation—beginning with pilot testing, followed by targeted capacity-building and stakeholder engagement—is recommended. Additionally, national and EU-level policy frameworks may need to evolve to support blockchain adoption through financial incentives, institutional support and legal harmonization.

To ensure the effective integration of traceability and data reliability in agri-food blockchain systems, it is essential to rely on established national standards for classifying agricultural resources. For instance, the Romanian Soil Taxonomy System (SRTS-2012) provides a structured and scientifically validated framework for soil characterization, which can serve as a foundational dataset for precision agriculture and digital monitoring solutions (Țărău et al.,2012). The integration of modern cultivation technologies in some crops, as demonstrated by Panaitescu et al.,2015, highlights the importance of adapting agricultural practices to local pedoclimatic conditions. Such region-specific data, when encoded in blockchain systems, could enhance agronomic decision-making and precision input allocation.

Ultimately, while theoretical models like the one proposed can provide guidance, real-world implementation will require customization to specific cooperative structures, economic conditions, and technological readiness levels.

Practical Scenario Illustration

To enhance the applicability of the proposed theoretical model, consider a simulated use case within a Constanța County agricultural cooperative specializing in wheat and sunflower production. At the start of the agricultural cycle, farmers input seeding data into the blockchain system via a mobile application, including plot geolocation, seed variety, and fertilization schedules, and throughout the crop development, they record phytosanitary treatments applied and fertilizer dosages. IoT sensors installed in silos and transport containers continuously record environmental conditions such as temperature and humidity.

As the harvest progresses, each batch of grain is tagged with a QR code linked to its unique blockchain record. These records contain data on field origin, crop treatment history, and storage conditions. When a buyer, either local or international, receives a shipment, they can scan the QR code to verify the entire supply chain history, including compliance with phytosanitary standards.

During transport to the maritime port, smart contracts monitor sensor data in real time. If storage conditions remain within predefined parameters (e.g., humidity below 14%), the system automatically triggers payment releases to both farmers and transport companies. Regulatory authorities also have access to these immutable records, ensuring compliance with export requirements.

This scenario demonstrates the seamless integration of blockchain technology, IoT devices, and smart contracts in optimizing cooperative operations, enhancing transparency, and reinforcing trust across the supply chain.

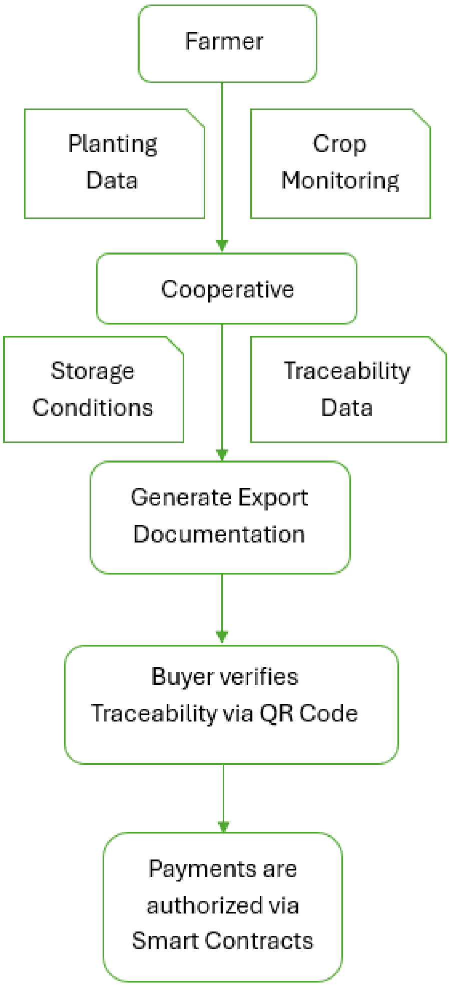

Figure 2. Data flow in blockchain-based traceability system for agricultural cooperatives

CONCLUSIONS

This paper presented a theoretical model for the integration of blockchain technology into an agricultural cooperative located in Constanța County, Romania. Based on a comprehensive meta-analysis of recent peer-reviewed literature, the model proposes a multilayered architecture designed to enhance transparency, traceability, and operational efficiency within the cooperative's supply chain. The findings suggest that blockchain—especially when combined with IoT and smart contracts—can serve as a powerful enabler of trust and accountability, offering automated data validation, secure transaction records, and improved export readiness. The strategic geographic position of Constanța, with direct access to a maritime port, further strengthens the applicability of blockchain for ensuring regulatory compliance and accelerating market access. While the proposed framework remains theoretical, its components are grounded in validated academic models and reflect current technological trajectories.

Future research should explore practical implementation pathways, pilot deployments, and the socio-economic impact of such innovations on cooperative members and rural communities. In addition, policy implications must be considered, particularly regarding the creation of regulatory frameworks that facilitate blockchain adoption, establish data interoperability standards, and offer financial or institutional incentives for digital transformation in the agricultural sector. By aligning technological innovation with public policy, Romania can strengthen the role of cooperatives in rural development and enhance their integration into global agri-food markets.

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