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REVIEW ARTICLE

Blockchain technology in agriculture: Ensuring transparency and traceability in the food supply chain

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Abstract

The study explores the transformative role of blockchain technology in enhancing transparency and traceability within the agricultural food supply chain. By leveraging blockchain's inherent characteristics of decentralization, immutability, and security, stakeholders can significantly improve information sharing and visibility from farm to consumer. The study delves into how blockchain addresses longstanding transparency and traceability issues that have plagued the agricultural sector. Real-world examples illustrate blockchain's successful application in agriculture, showcasing its capacity to boost transparency, operational efficiency, and trust among supply chain participants. These case studies demonstrate how blockchain creates tamper-proof records, enhances end-to-end visibility, and provides reliable, real time data. The technology's potential to combat fraud, promote sustainability, and ensure product authenticity is also explored. Furthermore, the research investigates blockchain's impact on food safety, particularly when integrated with Internet of Things (IoT) devices and smart contracts. These synergies enable automated, secure data collection and the execution of predefined agreements, further streamlining supply chain processes. Successful implementations across various areas of supply chain management, including logistics, inventory tracking, and quality control, are highlighted to demonstrate the practical benefits of blockchain adoption. By providing an in-depth analysis of blockchain's potential, this study underscores its pivotal role in building consumer trust regarding food safety, quality, and origin. The research concludes by discussing the challenges and opportunities for widespread blockchain adoption in agriculture, offering insights into its future trajectory and potential to revolutionize the global food supply chain.

Keywords

agricultural supply chain; blockchain; IoT; secure; smart contract; traceability; transparent

Introduction

In the agricultural sector, it is crucial to prioritize transparency and traceability in the food supply chain (1). The adoption of blockchain technology enables stakeholders to effectively document and access every stage of the process, ensuring accuracy from farm to table. Blockchain technology offers a promising solution to tackle the challenges and complexities of achieving transparency and traceability in the food supply

chain. By harnessing blockchain's decentralization, security, immutability, and innovative contract features, the agricultural industry can transform how information is documented and shared (2).

Materials and Methods

Keyword selection

This review adhered to an earlier methodology for selecting keywords for article search (3). Accordingly, as a first step, a search was performed via the Google Scholar platform using "blockchain" as a keyword “the top 100 results were then downloaded and screened”. Their titles, abstracts, and keywords were assessed to generate a new list of keywords for this review's literature search.

Based on the screening results, it was found that the most frequently used keywords in the paper’s titles, abstracts, and keyword lists are 'blockchain', 'traceability', 'agricultural supply chain', 'blockchain technology', and ‘food traceability’. These keywords were therefore collected and used to search for relevant papers across all the databases.

Journal selection and inclusion/exclusion criteria

To identify pertinent academic articles for this review, inclusion and exclusion criteria were established in accordance with previous studies (4). Consequently, an article eligible for this review must be a scholarly work, written in English, published in a peer-reviewed journal, and centred on blockchain technology. Additionally, to ensure the quality of the journals, consistent with previous systematic review papers (5), the Australian Business Dean Council (ABCD) journal quality list and the impact factor in Journal Citation Reports (JCR) were used as quality proxies. Accordingly, papers were considered for this review only if published in journals listed as A or A* by ABDC or in journals with an impact factor of one or above in JCR.

The initial search of selected databases using specified keywords yielded a total of 4,115 papers. Only business, management, & accounting articles (n=310) and agricultural and biological sciences articles (n=123) were selected. Then, inclusion and exclusion criteria were applied to the remaining 433 papers. The first criterion was to remove non-scholarly work. Non-scholarly work is publications in non-academic sources (e.g., newspapers, blogs, and trade journals). Therefore, 159 papers from non -scholarly sources were removed.

Further, as per the second criterion, only articles written in English 242 were selected. After that, only open access article was chosen, reducing the count of th98 open -source papers. After further inclusion, only 90 articles were finalized (Fig. 1).

Descriptive findings

This indicates sources (AJG 3 and above journals) that have published articles on the subject. Among these sources, the Annals of Operations Research contributed the most (13 articles), followed by Production Planning and Control (10 articles), International Journal of Production Research (9 article), and Supply Chain Management: An International Journal (8 articles). The IEEE Transactions on Engineering Management and Transportation Research Part E: Logistics and Transportation Review each produced 6 publications during the study period. The International Journal of Production Economics, International Journal of Operations and Production Management, and Journal of Business Logistics published 5 articles each. Production and Operations Management and Omega had the fewest contributions, with each journal publishing only one issue related to the topic during the research period. The distribution of articles also suggests that the application of blockchain in SCM (Supply chain management) is an attractive research topic for operations management and operations research (6) (Fig. 2).

Results and Discussion

Understanding block chain technology in agriculture

In the context of today's globalized food supply chain, the importance of transparency and traceability cannot be

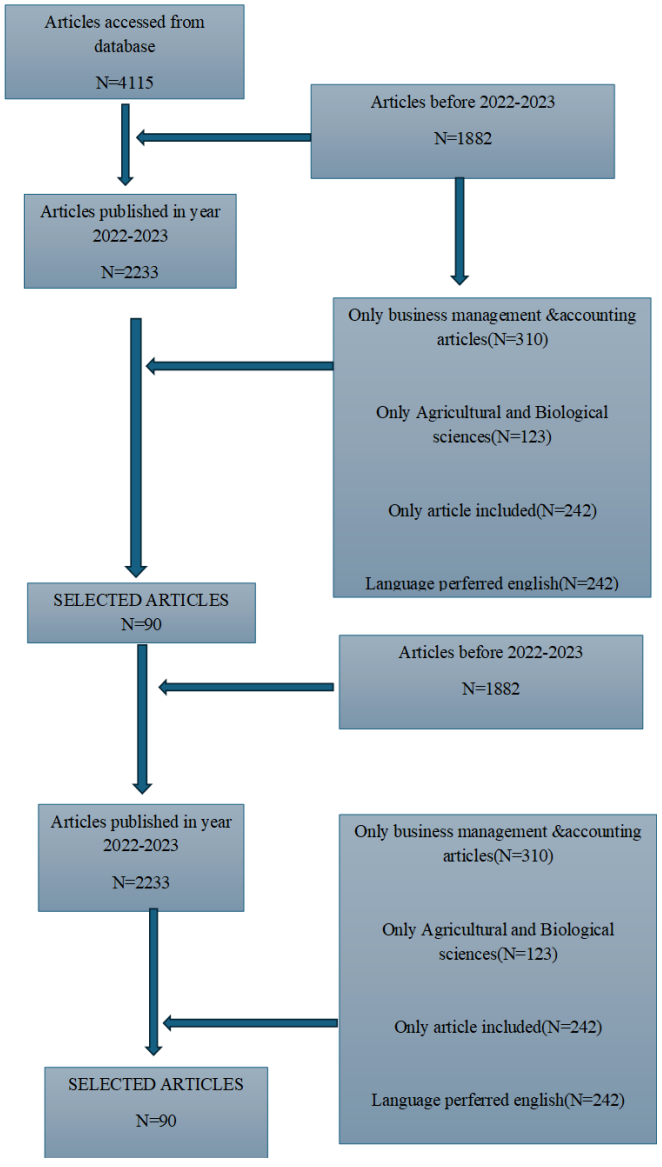

Fig. 1. Inclusion and exclusion criteria.

Fig. 2. Published articles on the subject.

overstated. This holds true for consumers, regulators, and businesses alike. By integrating blockchain technology into the agricultural sector, we can establish a system that ensures the secure and transparent tracking of food products from their origin on the farm to their consumption by the end consumer (7). The implementation of blockchain technology enables the recording of every transaction and movement of food products on a decentralized digital ledger, guaranteeing that the information remains unaltered and cannot be manipulated. (example: dairy farming).

Blockchain technology offers a promising solution to this challenge by offering a decentralized, immutable, and transparent ledger system that can effectively monitor and verify each stage of the food supply chain. From the production phase to distribution, blockchain can capture and store crucial data such as the source of ingredients, farming techniques, transportation specifics, processing methods, and storage conditions. This ensures that such information is accurately recorded, securely stored, and accessible to all relevant parties.

The transparency and traceability provided by blockchain not only foster trust between consumers and producers but also facilitate more efficient implementation of food safety measures, recall management, and quality control processes (8). Moreover, blockchain technology can effectively address issues related to fraud and counterfeit products within the agricultural sector (9). By utilizing blockchain technology, data pertaining to the food supply chain can be securely stored and accessed, creating an immutable record that cannot be tampered with. This level of data immutability and transparency plays a crucial role in verifying the authenticity and quality of agricultural products, thereby preventing fraud and safeguarding consumers, Example: TraceX streamlines organizational hierarchy, user levels, and role configurations to optimize operational efficiency and ensure seamless collaboration within the system. Strengthening milk traceability with an objective covering animal welfare and women empowerment. Additionally, the integration of blockchain technology in agriculture has the potential to revolutionize the way farmers and other stakeholders interact and conduct business.

Enhancing food supply chain transparency through blockchain: Blockchain technology offers a promising solution for enhancing food supply chain transparency through its immutability, visibility, and data integrity (10). With blockchain, the entire journey of a food item can be accurately documented and verified, starting from its origin to its destination. This level of transparency not only aids in preventing fraud and reducing counterfeiting but also empowers consumers to make informed decisions about the products they purchase (11). Furthermore, blockchain technology can bolster trust in the food supply chain by ensuring that claims regarding product quality and authenticity are backed by verified data (Fig. 3).

Additionally, by integrating blockchain with other technologies such as IoT devices, the traceability and management of agri-food products can be greatly enhanced like IoT includes radio-frequency identification (RFID), a global positioning system (GPS), a geographic information system (GIS), a wireless sensor network (WSN), and so on. IoT provides the facility of automatic recording through IoT sensors, which collect information such as temperature, voice, and humidity. Traceability plays a vital role in ensuring the management of food quality and safety (12). Traditional traceability systems in the food supply chain often fail to provide complete and transparent information to consumers. Blockchain technology has the potential to address these shortcomings by offering a decentralized and transparent system for recording and tracking food products.

Traceability in agriculture- The role of blockchain: Blockchain technology has the potential to revolutionize the traceability of food supply chains, ensuring transparency and accountability throughout the entire process (13). By utilizing blockchain technology, every step in the supply chain, from farm to fork, can be documented and verified, granting consumers access to comprehensive information regarding the origin and quality of their food. This innovative technology can enhance food safety and promote sustainable practices by enabling the monitoring of crucial sustainability metrics such as carbon footprint and water usage(14, 15). By harnessing the power of blockchain technology, the agricultural industry can effectively address concerns about food traceability and

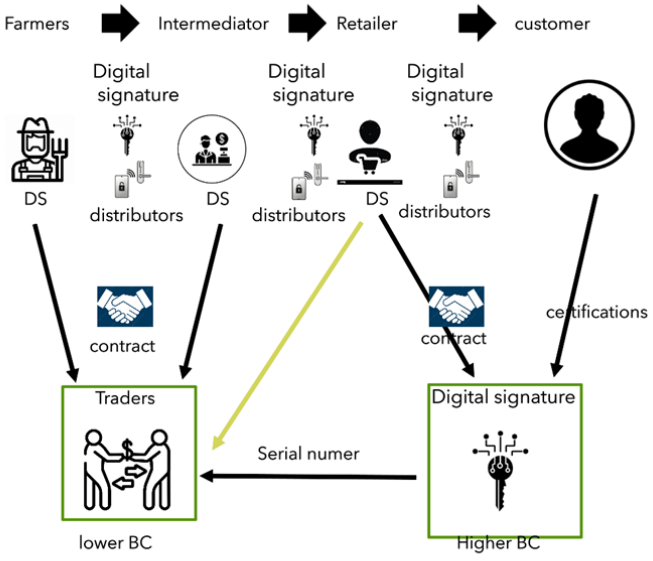

Fig. 3. Blockchain application model for food supply chain.

sustainability. This encompasses reducing food waste, enhancing supply chain efficiency, and advocating for fair trade practices (16). Through the implementation of blockchain technology in agriculture, we can establish a more sustainable and transparent food supply chain, fostering ethical practices and minimizing waste (17, 18). Furthermore, blockchain technology empowers consumers to make informed decisions about the food they purchase, enabling them to support sustainable farming practices and contribute to a greener future. Overall, the use of blockchain technology in agriculture holds immense potential to significantly impact supply chain sustainability and promote a more transparent and ethical food system (19). By leveraging blockchain technology, the agricultural industry can effectively address concerns related to food traceability and sustainability, ultimately establishing a more sustainable and transparent food supply chain (Fig. 4).

The impact of blockchain on farm-to-fork transparency

Consumers are increasingly concerned about food origins, production practices, and adherence to ethical standards. This rising interest in food transparency has created a demand for increased information and accountability across the entire supply chain. Blockchain technology emerges as a viable solution to address these concerns, providing a decentralized and immutable ledger that meticulously records every transaction and movement of food from farm to table (20). By leveraging blockchain, a transparent and traceable system is established, enabling consumers to access comprehensive information about their food's journey easily. Through blockchain technology, consumers gain access to detailed insights about the farm of origin, production methods employed, and the certifications obtained. This heightened transparency empowers consumers to make informed choices, supporting sustainable and ethical practices.

Furthermore, blockchain proves effective in preventing fraud and reducing the risk of counterfeit goods infiltrating the food supply chain. With a transparent and traceable system, the introduction of fraudulent or counterfeit products becomes considerably more challenging. This not only safeguards consumers but also ensures fair compensation for farmers and producers. Beyond enhancing transparency and accountability, blockchain technology streamlines and automates processes within the agricultural industry. Farmers can utilize blockchain to monitor their crops from planting to harvesting, ensuring compliance with quality standards and minimizing waste (21). Additionally, this technology optimizes logistics and supply chain management, boosting efficiency and reducing costs.

In summary, the incorporation of blockchain technology in the food supply chain has the potential to elevate transparency, accountability, and efficiency significantly. It empowers consumers to make informed choices, advocates for sustainable and ethical practices, and guards against fraud and counterfeit goods. The agricultural sector has already made notable strides in integrating blockchain technology, and its continued adoption promises further enhancements in the farm-to-fork supply chain (22) (Fig. 5).

Revolutionizing food safety with blockchain solutions: Blockchain technology can revolutionize the assurance of food safety by transforming the way we monitor the entire food production process. Through the integration of blockchain and IoT technologies, a dependable and effective system for tracking and monitoring food production can be established (23). This system engages all participants in the agricultural ecosystem, ensuring transparency and accountability throughout the food supply chain (24).

The utilization of IoT devices in place of manual recording and verification reduces human intervention and enhances efficiency (25, 26). Furthermore, the incorporation of smart contract technology allows for prompt identification and resolution of issues. The adoption of a traceability system based on blockchain presents several advantages, including enhanced security,

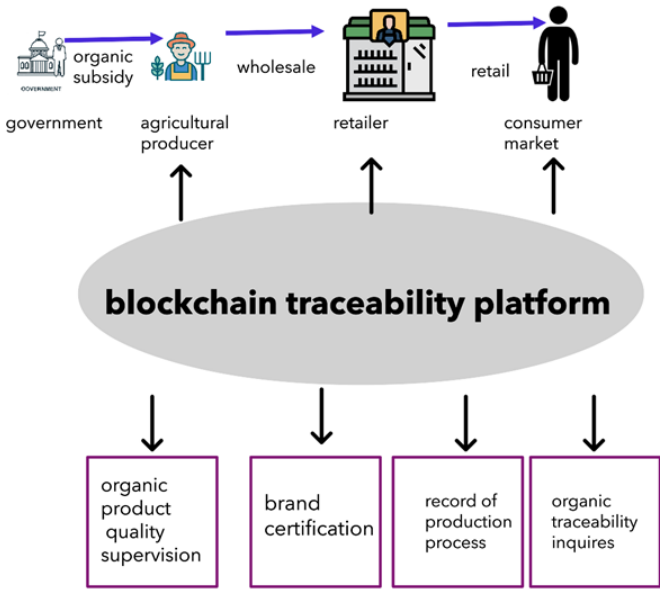

Fig. 4. Traceability of food supply chains.

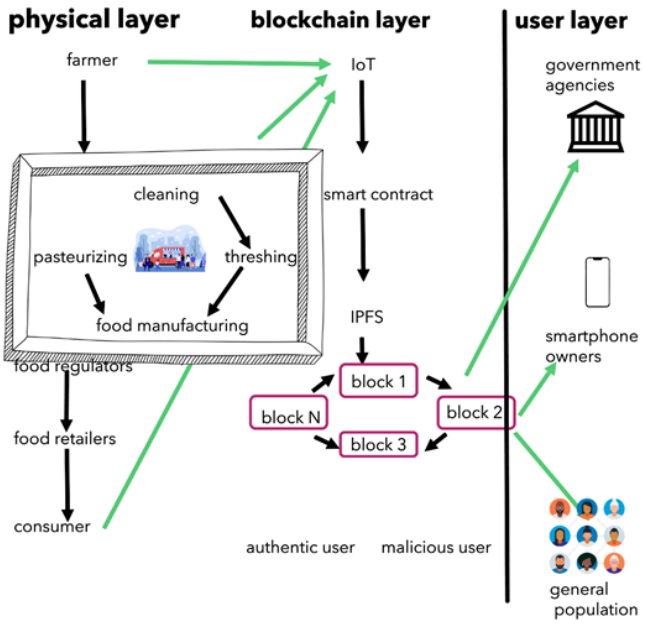

Fig. 5. Working of blockchain in food supply chain.

decentralization, immutability, and the ability to create smart contracts. These benefits address challenges linked to conventional centralized server-client systems, where consumers face difficulties accessing comprehensive transaction information and tracing product origins (27). The introduction of blockchain technology into the food supply chain facilitates sustainable food management and traceability (28).

In summary, blockchain technology offers an innovative solution to enhance food traceability and safety (29). Implementing a reliable food traceability system based on blockchain and IoT technologies has the potential to transform food safety by ensuring transparency, accountability, and efficiency throughout the entire food supply chain. The incorporation of blockchain technology into the food supply chain can establish a trusted and effective system to monitor the whole life-cycle of food production, guaranteeing transparency and traceability(30, 31). Overall, blockchain technology holds the potential to revolutionize food safety and traceability by providing a dependable and efficient system for monitoring the entire food production process.

Blockchain applications-streamlining agricultural operations: Furthermore, the paper delves into case studies and real-world examples of how blockchain technology has been successfully implemented in agricultural operations, such as supply chain management, food traceability, and quality control (32). It highlights the benefits of using blockchain in agriculture, such as increased transparency, efficiency, and trust among stakeholders. The paper also discusses the potential impact of blockchain technology on smallholder farmers and developing countries, emphasizing the importance of inclusive and sustainable agricultural practices (Fig. 6).

Overall, the paper serves as a valuable resource for researchers, policymakers, and industry professionals interested in exploring the potential of blockchain technology in agriculture (33). It includes a content-analysis-based literature review on blockchain adoption within the food supply chain. Published in the International Journal of Environmental Research and Public Health. The paper provides a comprehensive overview of the current landscape, challenges, and opportunities in this rapidly evolving field, offering insights into how blockchain can revolutionize agricultural operations and contribute to a more sustainable and transparent food system (34).

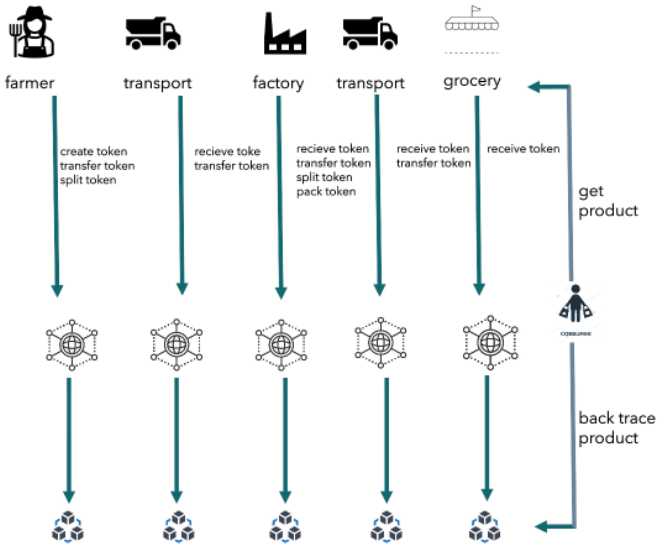

Fig. 6. Iot connected devices.

Building trust in food sources with blockchain technology

Today, consumers are increasingly focused on food safety and quality. This concern has driven demand for greater transparency and traceability across the food supply chain (35, 36). While traditional traceability systems in the IoT have offered some solutions, they often rely on centralized servers, which makes it challenging for consumers to access all the necessary information regarding the origin and journey of their food products (37). However, blockchain technology presents a promising solution to this problem. By leveraging blockchain technology, the food supply chain can be transformed into a transparent and secure system where all transactions and events are recorded in a decentralized manner. This ensures that the information remains tamper-proof and accessible to all participants. Consequently, consumers can easily track the origins of their food and verify its authenticity, thereby fostering trust in the food sources. Moreover, the utilization of blockchain technology in the food supply chain can effectively address other challenges such as food fraud and counterfeit products. By providing an immutable and transparent record of every transaction, blockchain technology significantly reduces the risk of fraudulent or counterfeit products entering the market.

Additionally, it can enhance efficiency and reduce costs in the food supply chain by eliminating the need for manual record-keeping and third-party intermediaries. Overall, blockchain technology has the potential to revolutionize the food supply chain by enhancing traceability, transparency, and trust among consumers (38). The introduction of blockchain technology brings tremendous potential to revolutionize the approach to food safety and traceability (39). Through the utilization of blockchain technology, stakeholders in the food industry can establish a decentralized and transparent system that ensures the safety and quality of food products.

The future of agriculture: Blockchain-enabled supply chains

Walmart food traceability in China: Hyperledger Fabric is a modular blockchain framework that serves as a foundation for creating blockchain-based goods, solutions, and applications utilizing plug-and-play components designed for private organizations. Walmart partnered with IBM, Tsinghua University, and food suppliers to develop a blockchain-based monitoring system utilizing Hyperledger Fabric for the traceability of pork and mangoes. This system recorded product data, including farm sources, batch numbers, processing details, expiration dates, and shipping information. The result was a significant reduction in tracing time, from days to just 2.2 seconds.

Agri digital grain supply chains: Agri Digital offers a cloud-based system where farmers input grain deliveries and quality data linked to digital wallets and contracts on a blockchain. This not only ensures transparency but also automates transactions between farmers and commercial buyers.

AgriDigital's acclaimed digital grain inventory management platform is acknowledged for its impact on the agriculture sector; yet, attaining sustainable growth and providing outstanding client experiences necessitates more than mere software. Throughout the supply chain, clients and collaborators have illustrated the integration of various technologies to improve efficiency. They emphasize the significance of cultivating robust teams and prioritizing customer satisfaction as fundamental components of success. Continuous improvement has become a vital emphasis in the current dynamic landscape. Perspectives from many sectors of the supply chain are highlighting these practices and their influence on business excellence.

Beef ledger cattle tracking: Beef ledger employs blockchain to record animal movements, health data, and slaughter details, providing a reliable monitoring system for the beef supply chain from farm to retailer. This enhances safety measures and prevents counterfeit meat trading (40).

Fishery transparency with provenance: In traditional fishery transparency, records are often kept manually, leading to potential inaccuracies, fraud, and inefficiencies. The process is prone to tampering and lacks realtime updates, making it difficult to verify the authenticity and origin of fish catches. In contrast, using blockchain technology establishes a decentralized and immutable register of fish catches, documenting details such as species, size, fishing method, date, and location. This creates an unbroken chain of custody, ensuring transparency, traceability, and trust in the supply chain. Blockchain provides realtime, verifiable information, reducing the risk of fraud and enhancing overall efficiency (41).

HerdX cattle health and location monitoring: HerdX utilizes RFID tags, biosensors, and a blockchain ledger to deliver cattle health, genealogy, location, and environmental data to partners in the beef supply chain. This contributes to the prevention of animal diseases and ensures compliance (42, 43).

Ripe.io Food Safety for Fresh Produce: Ripe.io collaborates with farms, distributors, and grocers to record sensor, testing, and handling data for fresh produce shipments on the blockchain. This provides credible safety attestations to retailers and consumers (44). The devices include sensors, RFID tags, QR code readers, measuring scales, thermostats, and GPS systems. They help automate the gathering, processing, and validation of data, ensuring realtime tracking and transparency from farm to fork.

TE-FOOD livestock registration in Vietnam: TE-FOOD has successfully registered and tracked millions of chickens and livestock on a blockchain ledger throughout Vietnam's supply chain. Unique identifiers enable continuous monitoring for quality control and food safety (45).

Overcoming challenges in agricultural traceability with blockchain

Agricultural traceability involves tracking food products from farm to consumer. Implementing blockchain technology can address challenges and improve traceability. Here are ways blockchain can help:

Transparency and accountability: Blockchain provides a transparent ledger for all supply chain transactions, fostering accountability and traceability (46).

Data integrity: Blockchain ensures data integrity through cryptographic algorithms, preventing tampering and ensuring reliable traceability information (47).

Decentralization: Blockchain provides a transparent ledger for all supply chain transactions, fostering accountability and traceability (48).

Realtime visibility: Blockchain enables Realtime updates and visibility across the supply chain, allowing swift responses to issues like contamination outbreaks.

Smart contracts: Blockchain streamlines contract processes, reducing manual errors and improving efficiency (49).

Conclusion

Blockchain technology holds immense potential for revolutionizing the agricultural sector by enhancing transparency, traceability, and efficiency. Key areas for adoption include smart farming, where IoT devices collect and record data on crop conditions; supply chain management, ensuring the authenticity and quality of products; agricultural insurance through automated and transparent claims; digital transactions, reducing intermediaries; and food safety, by maintaining immutable records of food handling. These applications pave the way for smarter, more efficient, and trustworthy agricultural practices, offering significant benefits to farmers, consumers, and all stakeholders in the food supply chain. The integration of blockchain with existing agricultural technologies and the exploration of sustainable practices further underscore its transformative impact on the industry.

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Authors' Contributions

BV carried out the Blockchain technology research, participated in the sequence alignment and drafted the manuscript. GV carried out the agricultural data collection. MP participated in the sequence alignment. KD

participated in the study design. MC conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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