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Blockchain-Enabled Supply Chain Traceability in Food Safety

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ABSTRACT

The food industry is increasingly focused on ensuring food safety and meeting consumer demands for transparency regarding food origins and production methods. Traditional centralized systems for supply chain traceability face challenges related to trust, transparency, and scalability, which are exacerbated by the complexity of global supply chains. Blockchain technology offers a promising solution by providing a decentralized, secure, and transparent system for tracking food products from farm to fork. This paper reviews the literature on blockchain technology and its application in food supply chains, highlighting key features, benefits, challenges, and case studies of successful implementations. We propose that blockchain can significantly enhance food safety by improving traceability, reducing fraud, and increasing consumer trust. However, challenges such as data privacy, security concerns, and technological limitations must be addressed. Future research directions are also discussed to further explore the potential of blockchain in ensuring food safety.

Keywords: Blockchain technology, Food safety, Supply chain traceability, Decentralized systems, Transparency.

INTRODUCTION

Today, the food industry is driven by increasing consumer interest in food safety aspects, such as organic, non-genetically modified, allergy-free, and others, and it is important for consumers to trace whether the claims meet the facts. Product traceability is gradually recognized as an effective and integral framework to monitor from farm to fork. However, the traditional centralized architecture has been criticized for its lack of trust between non-cooperative companies. If regulators cannot detect or punish food fraud or contamination, there is a possibility of moral hazard for the parties. In addition, the emerging trends of vertical integration and cross-border sales have extended small and geographically concentric supply chains to highly complex and diversified global supply chains. As a result, it is difficult to verify the steps involved, and regulations and standards for traceability have become difficult to monitor and regulate [1]. In this context, blockchain-enabled traceability shows great potential to ensure food safety and build consumer trust through transparent collaboration across the food supply chain. Specifically in this study, we summarize more than a dozen previous reviews that introduced and taught potential audience how to develop or use traceability technology in the context of its connection to food safety. In general, scholars can only provide rough descriptions and comparisons of various traceability technologies, but cannot provide potential implementation and substantive guidance in operation. And all that they summarize are uncomplained, lacking conflict and having overlap. Hence, this study has the following contributions: First, we provide a detailed and overall overview of blockchain technology. We conduct a literature review on blockchain technology, introduce a basic blockchain technology, and discuss the current state of research. Building on a consensus algorithm for classified distributed systems, we bring a brief introduction to practical Byzantine fault-tolerant (PBFT) algorithm in the context of blockchain security. Furthermore, we review the literature on supply chain traceability, focusing on food safety [2].

BACKGROUND OF FOOD SAFETY ISSUES

Multiple events of foodborne disease outbreaks have aroused public attention rapidly during recent decades and pushed regulatory authorities to improve food safety management over the food continuum. Food safety is currently facing a number of challenges, and it is critical to find the most effective solutions. For all stakeholders, including farmers, processors, distributors, and retailers, in-depth attention is important. These factors have driven innovation in reaching the concept of total quality assurance. The main problems and contributing factors of food safety issues will be discussed in the following clauses [3]. Consequently, a comprehensive perspective is about to be designed using the seven main, most significant, core food stakeholders from all phases of the process: foods as their information possess movers, unprocessed food safety purchasers, researchers, measuring equipment manufacturers, standard organizations, cooperative food safety. This comprehensive assessment is aimed at trying to reveal conclusions for the here approved most significant challenges in the current food safety system and using popular important capabilities due to the design of a comprehensive collaborative food safety administration. To provide for more effective protection monitoring, these problems and challenges will accept the treatments of advanced technologies and technological knowledge. Consequently, this article also assesses technological potential for several labeled research concerns [2].

THE ROLE OF BLOCKCHAIN TECHNOLOGY

In addressing the current state of the art on blockchain technology, most view the technology as a disruptive force. Blockchain technology has found applicability in numerous domains, providing solutions that have revolutionized how services are rendered in various sectors, from healthcare to finance, and especially in smart contracts with the introduction of the Ethereum blockchain. The use case of blockchain as the underlying technology for cryptocurrencies has forced changes in and beyond banking, significantly narrowing the scope of the cash business. One of the use cases where blockchain technology has been said to have the highest potential but has, however, also received quite an amount of criticism is the aspect of scalability. This asserts that the possibility of applying blockchain technology to the area of big data or scalable applications may be close to fictitious. Blockchain, however, is also known to currently dominate emerging technologies like the Internet of Things (IoT), which is a fusion between the physical and digital systems that support drivers in taking real-time decisions on current situations [4]. Undeniably, the concept of blockchain has revolutionized the technical landscape, making possible concepts such as the Electronic Intendant Ledger (EIL) that have led to the emergence of the trust economy. Blockchain finances are driving cryptocurrencies into the emergence of individual agricultural and food products (raising trust in donors, an agreement upon the value of products to be used in different processes or research). Is there anywhere that new technology, blockchain technologies, could be put to practice? Blockchain, in its chemistry, is a distributed ledger that makes sure mutual trust is established between the members of the chain. This is why the food value chain is 'promising' for blockchain technology application. The technology promises to bring significant changes to the domain of food safety [5].

KEY FEATURES OF BLOCKCHAIN

A blockchain is a distributed database that allows both permanent document sharing and secure distribution. The blockchain database is the origin of the data and can be shared and synced with multiple sites, institutions, and/or organizations. A blockchain refers to the technology and data in a block where the blocks contain the information of the parent blocks and the blocks are not replicated. The key features of blockchain technologies are as follows. First, blockchain is a distributed ledger, i.e., computers are connected with each other in various nodes and a network. Second, blockchain allows transactions for permanent records where it increases security and trust and enhances assets. Blockchain is also immutable, where the data in any block is verified by thousands of computers across the world where no one can actually interfere and alter the data with at-rest hash function encryption. Third, blockchain is transparent, in which everyone has access to view the transactions that are taking place. Fourth, the use of blockchain enhances traceability where the transaction data from all the old and the new blocks can be checked. At the same time, the transaction will be synced into all the computers in the bitcoin network. The final key feature of blockchain is the use of cryptographic security that enhances secure transactions. Cryptographic security uses encryption tools that encrypt and decrypt the data in order to convey secure transactions through the network [6]. Cryptocurrency flourished with the advent and advancement of blockchain technology. Blockchain technology is an open ledger and uses its decentralized nodes. These nodes are responsible for the validation of the users who request the transaction on that particular blockchain network. Blockchain technology is the combination of cryptology, distributed computing that assures reliability, trustworthiness, and collaboration among the participants through a transparent decentralized way. Therefore, blockchain as an emerging technology offers a quite amount of forecast potential for several typologies of applications. The question arises, "Is it feasible to be able to deploy and adopt in such a huge food industry made up of various transactions for the highest market value spread over the globe?" Since the data has the potential to lead to unrealistic outcomes and the usefulness in the operational functionality in the "global food system" drawing a huge amount of investment. The guess-estimates indicate machination done at the data entry points like "intermediate actors" that take care of big fat commission. The present article would enhance traceability and transparency through blockchain technology alleviates the barriers of food safety by decreasing the burden of foodborne risks by establishing a potent bridge between food safety and the supply chain [7].

BENEFITS OF IMPLEMENTING BLOCKCHAIN IN SUPPLY CHAIN TRACEABILITY

Blockchain enables the next generation of enhanced traceability in global supply chains. Distributed ledgers create value from the synergistic outcomes of transparency, accountability, and trust. Trust and traceability provide transparency, which in turn reduces information asymmetry between participants in supply chains, thus enhancing operational efficiency. This paper reviews the literature and practice of blockchain-enabled traceability in supply chains, focusing on numerous empirical case studies of industry implementations, mostly in innovative start-ups. We synthesize the literature and present a sector-agnostic framework structure that collates numerous actions, benefits, and factors which cause those benefits throughout all aspects of a supply chain. The paper provides both quantitative and qualitative research agendas, identifying a need for theory testing and industry stipulation of the operational environment for enhanced traceability [2]. Having an end-to-end overview of every segment in the supply chain forms a huge logistical advantage, often going hand-in-hand with lower production costs. Blockchain provides a secure and transparent platform – an immutable registry of transactions, recorded by a distributed network of computers, thus reducing the likelihood of transactional fraud. For end customers, these aspects create a direct link between the brand and safety and allow for a higher degree of perceived trust in the brand, thus influencing sales and market perception. Additional advantages of implementing blockchain-enabled traceability of items in the supply chain include information redundancy, accurate origin, and enhanced product authentication. Having a block of data on every web node ensures that all information can never be lost or destroyed – this has huge implications in every industry. Things 'falling off a transport boat' would be entirely prevented by the use of blockchain systems, where a centralized authority is not necessary [8].

CHALLENGES AND LIMITATIONS

The use of blockchain technology for food supply chain traceability is widely argued to have enormous potential due to the promised advantages related to secure and transparent traceability technologies. However, implementation faces various challenges and limitations. Categorizations of challenges have been attempted under various criteria including socio-economic, technological, legal, and ethical aspects. It is also pointed out that blockchain technology is not without constraints, and it is often emphasized that it is not a cure-all solution. The interest of the critics is not unlike that of the blockchain enthusiasts as supply chain management supported by the technology is popularly anticipated to be superior to conventional traceability systems. The purpose of this section, therefore, is to raise critical questions on blockchain-enabled supply chain traceability in relation to food safety. The purpose is not to completely rule out the technology for traceability but rather to frame a discussion systematically in view of potential challenges and limitations to complicate a common understanding of the technology [9]. There are broader socio-economic challenges relating to blockchain-enabled supply chain traceability. Entrepreneurial interests or those of major enterprises could possibly drive the use of traceability as a quality criterion or a marketing trick without cuidado or priority given to food safety. Blockchain is also perceived as an expensive and thus hardly accessible solution, which could exacerbate existing disparities and create gaps in the existing traceability and auditability infrastructures for MSMEs. Obstacles on the technical side include interoperability, scalability, and infrastructure gaps: the physical facilities required for simple or basic blockchain architecture may not be a default setup in some enterprises, particularly in developing countries. Ethical issues also exist, such as risks of technologization. The new form of surveillance linked to the technological solution could become a new mode of alienation, spoiling the "trust" effect and highly formalizing social relations within the supply chains beyond the issues of information asymmetry [10].

DATA PRIVACY AND SECURITY CONCERNS

Addressing data privacy and security is of paramount importance for blockchain in the context of food supply chain traceability. Various types of attacks, such as cryptographic attacks, 51% attack, DDoS attacks, fake data injection, fraud form, phishing attacks, spamming, device stealing attacks, and smudge attacks, can be performed in blockchain to damage the network. The architecture design of Ethereum was used to attack users. For example, Monero platform's user wallet was attacked, leading to a loss of 7.8 million coins. Once the data is stored in blockchain, it will produce massive entropy. The blockchains store not only truth but also fake data, and the user cannot identify and remove them. Blockchain networks provide a public, decentralized, and unchangeable approach for traceability, wherein data is visible to all users online, which exposes personal information and violates information security. Moreover, introducing a third-party intermediary, such as legislation, might be an issue to the risk of information disclosure, and the leaked food supply chain data might be trapped as evidence for the crime investigation [11]. Data privacy and security are often concerned in the application of the blockchain infrastructure. To overcome these challenges, some prior studies proposed possible approaches by combining the characteristics of blockchain with those of other data management tools. Further discussions on privacy protection using additive homomorphic property and incremental updated blockchain. Privacy-related technologies, such as cryptographic techniques, could be integrated with the blockchain system to protect personal data. The P2P protocol could be considered for data storage in a large network while preserving the immutability characteristics of the block and public verifies due to the benefits that it comes with, including scalability, security, decentralization, robustness, fairness, and incentives of storage [12].

CASE STUDIES OF SUCCESSFUL IMPLEMENTATIONS

Carrefour S.A: Carrefour, one of the world's largest hypermarket chains, began exploring the use of emerging technologies like blockchain to provide robust traceability solutions for the food it sells. The company kicked off the first of many planned blockchain solutions: chicken can be traced from the farm to the store. In their implementation, consumers can scan a code on the package with their mobile phone to better understand where the product was sourced, its production methods, nutritional details, pesticide use, and date of birth and name of farms where the animals used to produce the meat were raised. They believe that the traceability project will help them deal better with the ever-growing consumer demand for transparency. The project's ability to track and trace was validated when in July Carrefour recalled a certain batch of eggs, and using blockchain was able to locate the exact chicken farm and stop distribution within 24 hours, a process which took weeks when done manually in the past [13]. Walmart Stores Inc.: The Applications of Blockchain Technology in Business and Information Systems case reports the decision by four giants in the supermarket and food industry (Nestlé S.A., Walmart Inc., International Business Machines Corporation, and Dole Food Company Inc.) to come together to address challenges in the global food supply chain. They seek to achieve this by addressing food safety concerns by working with a wide array of partners to establish a traceability framework based on blockchain technology. Walmart has so far carried out two experiments to test the blockchain technology as a means to trace the provenance of food products, either individually or to gain an industry-level understanding. In the first trial, Walmart tested the blockchain technology to trace the distribution of Chinese pork meat in China and the production of mangoes in the United States, while in the second study, the company tested the firm's ability to use blockchain technology to trace the distribution of a variety of produce [9].

FUTURE RESEARCH DIRECTIONS AND OPPORTUNITIES

Future research directions might be aimed at exploiting other successful blockchain use cases in the agri-food industry, such as provenance and heritage traceability, possibly in combination with quality certifications. Beyond food safety, consumers in the agri-food sector are increasingly demanding guarantees about the origin and quality of their food. Food products sold with a gourmet brand and linked to their territories of origin gain value, commanding higher prices. These products often undergo quality tests to obtain certifications that classify them as organic, low environmental impact, or extra virgin. Among the most common certification schemes, organic foods dominate the certified market, with the EU being the main consumer. However, in some cases, claims made by companies have been proven to be completely unfounded. This is due to the lack of widespread systems for consumers to trust the claims of companies, dungeons, and organizations, mainly attributed to certification and traceability problems [14]. Further research is also needed to provide guidance for companies that have yet to introduce blockchain due to difficulties in accessing data. It is becoming increasingly clear that managing an innovative and complex technology like blockchain requires the skills and ability to manage the different parties involved. However, companies can benefit from equity growth, network consolidation, and technological innovation by adopting blockchain. This provides a competitive advantage. The benefits in such a systematized ecosystem arise from the cooperative nature of these processes [15].

CONCLUSION

Blockchain technology holds significant potential for revolutionizing supply chain traceability in the food industry, offering enhanced transparency, security, and trust. By addressing the inherent limitations of traditional systems, blockchain can provide robust solutions for monitoring food safety from farm to fork. Successful implementations by companies like Carrefour and Walmart demonstrate the practical benefits of blockchain-enabled traceability, including faster recall processes and increased consumer trust. However, challenges such as data privacy, security, and scalability must be carefully managed. Future research should focus on developing comprehensive frameworks for blockchain integration, addressing technical and ethical concerns, and exploring additional use cases to maximize the impact of blockchain on food safety. Through continued innovation and collaboration, blockchain can play a crucial role in ensuring a safer and more transparent food supply chain.

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