A Supply Chain Traceability System for Food Safety Based on HACCP, Blockchain & Internet of Things

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***Abstract*—In recent times food safety has drawn upsurge of academic and commercial concerns. In supply chain area, with the rapid growth of internet technologies, a lot of emerging technologies have been applied in traceability systems. However, to date, nearly all of these systems are centralized which are monopolistic, asymmetric and opaque that could result in the trust problem, such as fraud, corruption, tampering and falsifying information. Besides, centralized system is vulnerable to collapse, since a single point of breakdown will lead the whole system to be crashed. Today, a new technology called the blockchain which is a ground-breaking innovation in decentralized information technology presents a whole new approach. However, since this technology is still in its early stages, it has some inherent defects, in which scalability become a primary and urgent one when we face the mass data in the real world. In this paper we will build a food supply chain traceability system for real-time food tracing based on HACCP (Hazard Analysis and Critical Control Points), blockchain and Internet of things, which could provide an information platform for all the supply chain members with openness, transparency, neutrality, reliability and security. Furthermore, we introduce a new concept BigchainDB to fill the gap in the decentralized systems at scale. The paper concludes with a description of a use case and the challenges to adopt blockchain technology in the future food supply chain traceability systems are discussed.**

Keywords—Food supply chain; traceability systems; decentralized systems; blockchain; food safety

I. INTRODUCTION

Food touches everyone and everywhere. During the last couple of decades, customer confidence in the food industry was heavily destroyed after lots of food safety risk incidents and scandals, such as mad cow disease, genetically modified food (Aung & Chang, 2014)[1], toxic milk power, and trench oil (Xiao et al., 2012)[2]. As a consequence, further increasing consumer concerns over the safety and quality of food have drawn more and more attentions from academic and industrial areas. In response to growing food safety issues, many internet of things technologies, such as RFID and wireless sensor network-based architectures and hardware, are applied to supply chain traceability and visibility. However, there is a very important issue has not been touched is that whether the information shared by food supply chain members in the traceability systems can be trusted. This kind of centralized organization could become so powerful by possession of this data that could result in information asymmetry between the organizations and the individuals. It can become a vulnerable target for bribery, and if, for example, the administrator can be bribed, valuable information can be tampered with, and then the whole system can not be trusted anymore. This is exactly what is happening in China's food markets (see Sanlu toxic milk powder scandal). Another potential risk is that it has a single point of failure which leaves the whole system vulnerable to failure (e.g. hacking and corruption)[3]. The novel technology that could be the key to these issues is the blockchain, which can remove the reliance on a central entity. Instead of storing data in an opaque network system, with the blockchain, all the information of the food products can be stored in a shared and transparent system for all the members along the supply chain. As an emerging technology, blockchain also has its inherent shortcomings, and with the increasing application, scalability has become a primary and urgent concern. In this paper, we will try to find a solution from the perspective of the blockchain and distributed database. We hope that our system could make food traceability from "farm to fork" become a reality, and rebuild public confidence in the food supply chain.

The paper is organized as followed. Section 2 presents the existing literature on the application of HACCP, RFID and blockchain technology in the food supply chains. Then a typical flow diagram for the food supply is presented, and relevant critical points are identified with HACCP in section 3. Section 4 introduces the details of the blockchain-based system, proposes a solution for blockchain scalability issues, and demonstrates the architecture and functions of it. Through a use case, section 5 illustrates how the monitoring and corrective actions identified in section 3 can be supported by our system. Finally, we make a brief conclusion for this paper in section 6.

II. LITERATURE REVIEW

The HACCP which focused on risk management and prevention was considered to be synonymous with food safety. It can be easily linked to operational management and food chain safety assurance. In order to obtain high quality milk, Vilar et al. (2012)[4] implemented HACCP method on dairy supply chain, and they focus on the milk equipment and cooling tanks which could influence the milk quality by the hazards such as microbiological and chemical residues. They proved that implementation of HACCP can be a feasible strategy for dairy supply chain safety. Based on a Pareto analysis, Fotopoulos et al. (2011)[5] examined the literature on the food safety assurance systems and recorded the vital critical factors which affect the implementation of HACCP. In their research, they analyzed 31 studies and identified totally 32 factors that could affect HACCP implementation. By using a case study, Herath & Henson (2010)[6] pointed out four barriers to HACCP implementation, including perceptions which HAPPC is of "questionable appropriateness" to the company, the scale of change required to achieve implementation, low priority given to enhancement of food safety controls, and financial constraints.

With the rapid growth of internet of things, many researchers consider the application of relevant technologies for traceability systems in food supply chains. Folinas et al. (2006)[7] pointed out that the efficiency of a traceability system depends on the ability to track and trace each individual product and logistics units, in a way that enables continuous monitoring from primary production until final disposal by the consumer. Shanahan et al. (2009)[8] suggested a RFID based framework for beef traceability from farm to slaughter. By using RFID for the identification of individual cattle, this system proposed as a solution to the inaccessibility of traceability records and the fraudulent activities. In order to build an automated system which integrates online traceability data and chill chain condition monitoring information, Abad et al. (2010)[9] tried to validate an RFID smart tag developed for real-time traceability and cold-chain monitoring of food under the case study of an intercontinental fresh fish logistics chain. Mattoli et al. (2010)[10] developed a Flexible Tag Data-logger (FTD) which is attached to the bottles for collecting environmental data, (like light, humidity, and temperature) in order to trace the wine bottles to a supermarket. The history data stored in the FTD can be read by smart phone or Personal Digital Assistant (PDA) with integrated infrared port to evaluate the safety status of wine bottles.

All the researches mentioned above are the idea of using a centralized system which was, until recently, the only conceivable way to achieve information transparency along supply chains. Today, a new technology called blockchain has presented a whole new approach and drawn much attention from researchers in many different domains. Abeyratne & Monfared (2016)[11] discussed the potential benefit of blockchain technology in manufacturing supply chain. They proposed that the inherited characteristics of the blockchain enhance trust through transparency and traceability within any transaction of data, goods, and financial resources. And it could offer an innovative platform for new decentralized and transparent transaction mechanism in industries and business. In addition, they also use an example to demonstrate how blockchain technology can be used in a global supply chain networks. As the lack of trust is a barrier for integration of business process across organizations, Weber et al. (2016)[12] insisted that blockchain could be an emerging technology for decentralized and transactional data sharing across a network of untrusted participants. They developed a technique to integrate blockchain into the choreography of processes in such a way that no central authority is needed, but trust maintained. Among these researches, some other researchers tried to solve the shortcomings, especially scalability, of blockchain. McConaghy et al. (2016)[3] described BigchainDB, which combine the distributed database (DB) with blockchain characteristics. Therefore, it has characteristics of distributed databases: linear scaling in throughput and capacity, efficient querying, and permissioning; and blockchain characteristics: decentralized, immutability, creation & movement of digital assets. Croman et al. (2016)[13] analyzed the bottlenecks of the blockchain for supporting substantially higher throughputs and lower latencies. Their results suggested that block size and intervals should be viewed only as a first increment toward achieving the next generation. In order to realize scalability, they discussed the techniques of blockchains from five planes, ordered in a hierarchy of dependency from bottom to top, Network, Consensus, Storage, View, and Side Planes.

According to the discussion above, internet of things has been widely used for supply chain traceability systems. However, most of them are centralized systems, and there are no decentralized systems have been used in food supply chains for food safety. In this paper, a decentralized information system is developed based on HACCP, blockchain and internet of things for food supply chain monitoring and traceability. Compare to the centralized systems, this new system could become a disruptive innovation which provides an information platform for all the supply chain members with openness, transparency, neutrality, reliability and security. Moreover, we also discussed the scalability of the blockchain technology when processing massive data within a business environment. We believe that our system could be a new perspective and idea for supply chain monitoring and traceability, and significantly enhance food safety in food supply chains.

III. FOOD SUPPLY CHAIN MODEL WITH HACCP

A typical flow diagram for the food supply chain is presented in Fig. 1, and associated with HACCP in different links are identified in Table. 1. As shown in Fig. 1, the whole food supply chain is divided into 5 links: A-Production; B-Processing; C-Warehousing; D-Distribution; E-Retail.

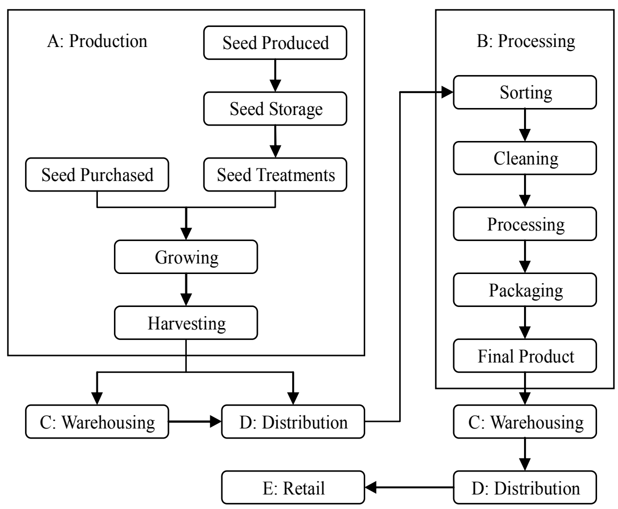

Fig. 1. Flow diagram for the food supply chain

Take crop plant production as an example. In the production link, first of all, background environment of planting should be assessed, including the quality of the soil, water, air, etc. Then all reasonable measures should be taken to ensure the safety of the growing and relevant monitoring data should be requested[14]. In the processing link, processing is likely to take place at a different site. Consequently processing environment and equipment assessment will be required. All subsequent processing activities should be carried out according to good working practices. Besides, using additives and materials should be suitable for their intended purposes. In the Warehousing link, cold-chain equipment should be properly maintained. Moreover, all warehouse management practices (like recording environment of the cold storage, quality and storage time of products) should be according to good working practices. In the distribution link, all refrigerated equipment, like truck, should be properly maintained as well. Finally, in the retail link, all retail management practices (e.g., using the refrigeration; checking the freshness lifetime; replacing expired products) should be according to good working practices and recorded as a routine document.

TABLE I. TYPICAL HAZARD CONTROLS FOR THE FOOD SUPPLY CHAIN

Control	Hazard	Control Measures	Monitoring	Corrective Actions
A1	Safety risk from background environment	Site assessment as part of assured scheme (e.g., quality of the soil, water, air, sunlight)	Regulator approval; routine reassessment	Review site classification; Reassess site designation; document action taken
A2	Safety risk from field practices (growing)	All field practices according to good working practices and recording growing information (e.g., variety, item No, producing area, growth conditions, planting time, plucking time, staff)	Site documentation	Review procedures; review workforce training; document actions taken
A3	Excess residues of applied fertilizers and pesticides	All applied fertilizers and pesticides purchased from reputable suppliers; recording the applied situation.	Regulator approval; supplier documentation; site documentation	Review supplier status; review producer; review workforce training; document actions taken
B1	Safety risk associated with processing environment	Site assessment as part of assured scheme (e.g., temperature controlling, disinfecting, equipment)	Regulator approval; routine reassessment; site documentation	Review site classification; Reassess site designation; document action taken
B2	Safety risk associated with processing step	All processing practices according to good working practices, and process additives used for suitable for their intended purpose	Site documentation; supplier documentation	Review procedures; review workforce training; document actions taken; review supplier status; document actions taken
C1	Safety risk from site equipment	Ensure all equipment properly maintained (cold storage, temperature and humidity controlling systems)	Maintenance records	Review maintenance procedures; review workforce training; document actions taken
C2	Safety risk from warehouse management	All warehouse management practices according to good working practices (e.g., recording environment of the cold storage, quality and storage time of products)	Site documentation	Review procedures; review workforce training; document actions taken
D	Safety risk from site equipment	Ensure all equipment properly maintained (e.g., refrigerated truck)	Maintenance records	Review maintenance procedures; review workforce training; document actions taken
E	Safety risk associated with retail management	All retail management practices according to good working practices (e.g., using the refrigeration; checking the lifetime; replacing expired products)	Site documentation	Review procedures; review workforce training; document actions taken

IV. THE TRACEABILITY SYSTEM BASED ON BLOCKCHAIN & INTERNET OF THINGS

A. Blockchain and smart contracts

Blockchain can be seen as a distributed database: a chronological chain of blocks and each block stores all information of network activity since the block is added to the chain[15]. All the data in the blockchain is public, and any user can add data to it by the form of transaction which is identifiable data package in the system, any user can check and copy this data at any time, but no one can change it. Therefore, blockchain is an immutable history of network, which can be shared among all nodes in the system. Blockchain-based system removes the need for any centralized trust authority. Instead, trust is achieved through a "mining process" which guarantees the security and validity of the information added to the chain among the nodes within the system.

In mining process, new transactions are vilified by the nodes in the whole system known as "miners" before being added to blockchain. Miners add new blocks on the chain or new transactions on the block by a consensus algorithm, which must be confirmed by majority or all the nodes in the system, like a voting operation, as the valid data. Blockchain-based systems rely on miners to aggregate transactions into blocks and append them to the blockchain. Once the transaction is confirmed by a sufficient number of nodes, it becomes a valid and permanent part of the database[11]. In order to constantly validate and maintain the consistency data, the system rewards the miner for adding valid blocks to the chain by some form of digital credit like "gas" which is used to discourage over-consumption resources. Moreover, no single miner can change or add invalid data without being detected by other miners as a potential threat. Therefore, this method significantly enhances the transparency, trust, and traceability in a system.

A smart contract is a kind of computer program that runs on the blockchain, i.e., executed by all consensus nodes. It consists of program code, a storage file. Any user can create a contract by posting a transaction to the blockchain. The program code of a contract is fixed when the contract is created, and can not be changed[16]. As shown in Fig. 2, the storage file of the smart contract is stored on the blockchain. Its program logic is executed by miners who reach a consensus on the outcome of the execution and update the blockchain accordingly. The code of the contract can be executed when it receives a message. The smart contract can read from or write to its storage file, while executing its code. Actually, the entire state of a smart contract is open to all the users in the system.

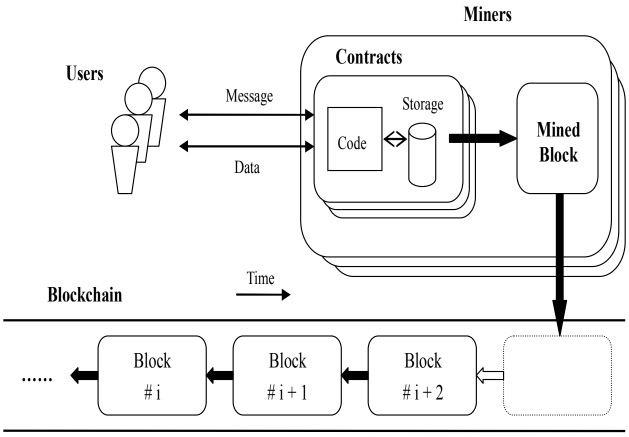

Fig. 2. Conceptual framework of a blockchain-based system

B. Scalability of the blockchain

As discussed above, the features of the blockchain-based system can improve the security and transparency of decentralized systems. However, blockchain technology has scalability issues in terms of throughput, latency, and capacity when faces mass data in a real business environment.

1. Throughput: until now the throughput of the blockchain is restricted to 7 transactions per second due to the restricted size of block, while VISA can handle up to 47000 transactions per second[17]. This throughput is unacceptable low when considered to be used in a business environment. 2. Latency: each block on the blockchain needs 10 minutes to confirm a transaction. In contrast, it takes only seconds to confirm a transaction on the VISA system. 3. Capacity: the whole Bitcoin blockchain is about 50GB in 2015. If its throughput increased to VISA's level, the blockchain database will grow 3.9GB/day[18]. Compared with normal distributed DBs which can store more than 1,000,000GB data, the data size of Bitcoin blockchain is really quite small. However, professional members still worry that it is growing too big.

According to the discussion above, advantages and disadvantages of distributed DBs and blockchains are highly complementary to each other. Therefore, we can try to solve blockchain scalability issues by giving it some distributed DBs characteristics. McConaghy et al. (2016)[3] proposed a concept of BigchainDB, which combines the key benefits of distributed DBs and blockchains.

TABLE II. KEY CHARACTERISTICS OF BLOCKCHAINS, DISTRIBUTED DBS, AND BIGCHAINDB

	Blockchains	Distributed DBs	BigchainDB
High throughput	-	√	√
Low latency	-	√	√
High capacity	-	√	√
Decentralized control	√	-	√
Immutability	√	-	√
Creation & movement of digital assets	√	-	√

As shown in Table. 2, BigchainDB keeps three key characteristics of the blockchain. The decentralized control can be achieved through the nodes in the system with voting processing, which is known as a super-peer P2P network[19]. Immutability can be achieved by a chronological blocks in which each block holds an ordered sequence of transactions, and that is a block chain. Furthermore, any user can issue an asset with the asset-issuance permission; any user can transfer an asset with the asset-transfer permission or the key of the asset. Therefore, it eliminates the risk of data tampering and single point of failure from hackers and powerful admins.

In addition, BigchainDB also emphasize on three key benefits of distributed DBs. The throughput of it can be increased with the number of nodes increased, and the scaling is a positive linear correlation: 10 × more nodes = 10c × more throughput, where $0 < c \leq 1$[20]. In BigchainDB, each node stores data through the partial replication method, which means a node only stores a subset of all data, and each bit of data is replicated on several nodes. This method enables a positive linear correlation between the number of nodes and storage capacity, just like most modern distributed DBs. By comparison, capacity of blockchain-based systems won't change as the number of nodes increases.

C. Structure of the traceability system based on Blockchain and Internet of things

1) Overview of the traceability system

As shown in Fig. 3, the proposed system is a typical decentralized distributed system, which uses Internet of things (like RFID, WSN, GPS) to collect and transfer, relies on BigchainDB to store and manage relevant data of products in food supply chains. There are many members among the supply chain, including suppliers, producers, manufacturers, distributors, retailers, consumers and certifiers. Each of these members can add, update and check the information about the product on the BigchainDB as long as they register as a user in the system. Each product is attached with a tag (RFID), which is a unique digital cryptographic identifier that connects the physical items to their virtual identity in the system. This virtual identity can be seen as the product information profile. Users in the system also have their digital profile, which contains the information about their introduction, location, certifications, and association with products.

All data in the system is stored in the BigchainDB and is opened to any user. The system is governed by a set of rules which are written in code and stored in the BigchainDB also. These rules define how users are to interact with the system, and how the data is shared among the users. Moreover, once the rules are stored in the BigchainDB, they can not be altered without broadcasting to all nodes and verified by most of them.

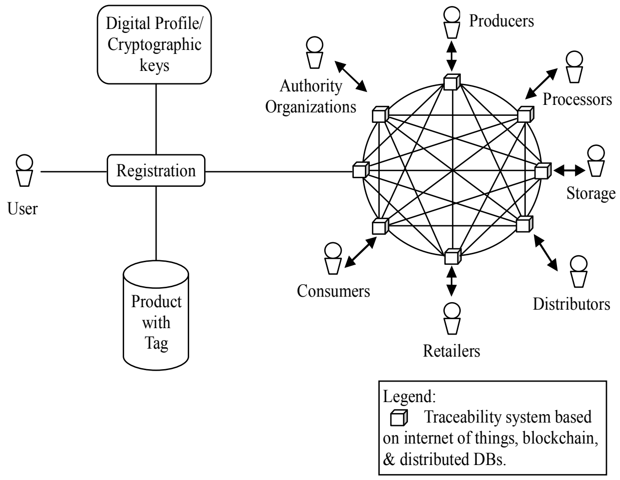

Fig. 3. Conceptual framework of the proposed traceability system

2) Registration and data updating & adding

Supply chain members can register themselves in the system as a user through the registrar, which can provide credentials and a unique identity to the members. After registration, a public and private cryptographic key pair will be generated for each user. The public key can be used to identify the identity of the user within the system and the private key can be used to authenticate the user when interacting with the system. This enables each product can be digitally addressed by the users when being updated, added, or exchanged to the next user in the downstream position of the supply chain.

In food supply chains, when a user who is in a particular link receives a product, only this user can add new data into the profile of the product with its private key. In addition, when user transfers this product to the next user, both of them have to sign a digital contract to authenticate the exchange. Therefore, the details of the transaction will be added to the BigchainDB and the system will process and update the data in the product's profile automatically, which allows users in the system sharing the status of the products at anytime.

3) Anonymity and sensitive information protection

Our system enables users on the supply chain to transfer and prove the defining attributes and status of their products to any user further along the supply chain. However, some users may want to keep some of their private information secret. Technologically, it is possible for our system to protect identities, while still transferring other important information. For example, producers in the supply chain can pass a digital contract with users from downstream while keeping their identity private. For consumers, maybe they only care about some important status of purchased products without necessarily knowing the full complication information of the whole supply chain that created them.

4) Role of the authority organizations

In our system there are still some certifications, audits, and third-party authorities, but the difference is that they also have their digital profiles, and, they will take on a new guise implemented in the system. They will check and verify user's identity and behavior, and records the result in the BigchainDB, available for all to inspect. For instance, certifiers and third-party authorities will visit the factories or facilities to check and inspect whether relevant rules and regulations for standard programs are being met. Once verified by the authorities, the user's profile and its products can be digitally updated and signed by the authority organizations. All the verification data must be published in the system, which extremely enhance the transparency of the food supply chain.

V. APPLICATION SCENARIO

In this section, an example application scenario is given to show how actions in HACCP can be supported by the proposed traceability system. All food supply chain members mentioned in this scenario, have already registered themselves in the system, and have matched their unique identities and digital profiles in the system.

A. Production link

Harvested crop plants are packaged and labeled with RFID Tag, and are entered to the system as new products. Key information of these products can be stored in their profiles. This key information includes: 1. background environment such as quality of soil, water, air, sunlight. 2. plant growing including: quality of the seed, working practices, variety, item number, production area, growth condition, planting time, plucking time, and responsible enterprise even staff etc. 3. information recording and application situation of fertilizers and pesticides. After that, a new trade is initiated between the production enterprise and the processing enterprise, where the products are exchanged after signing a digital contract that stored on the BigchainDB through handheld tag reader or wireless network.

B. Processing link

After receiving products, processing enterprise could read and enter new data into the product's profile by scanning their tags through their wireless network connected scanners. This information includes: 1. processing environment, such as temperature controlling, disinfecting, and processing equipment. 2. situation of using additives for suitable. 3. basic information of processing enterprise and relevant staff. During the processing, tags of the raw products may be destroyed, but their digital profiles are updated. After processing operation, new tags can be attached to the packages of finished products.

C. Warehousing management link

By setting up relevant Internet of things equipment in warehousing center, the information of received products can be automatically obtained. Meanwhile, with wireless sensors and monitoring equipment, the real-time storage information of the product, including quantity, category, temperature, humidity, and storage time, can be checked and updated in both product's profile and Tag. Since inventory information can be directly queried in the system or by the RFID reader, this system can also fulfill the enterprise's requirement for dynamic storage management. For example, in order to avoid loss and spoilage, based on the relevant information, managers can make decisions for which products should be given priority to move out of the storage immediately.

D. Cold chain distribution link

In distribution process, 3T principle (Time, Temperature and Tolerance) is the key factor in ensuring the safety and quality of food products. Therefore, a vehicle-mounted safety monitoring system can be established by setting temperature and humidity sensors in different temperature areas in refrigerator container with vehicle-mounted wireless network and computer. Rely on this monitor system real-time environmental data of products, such as temperature and humidity, can be added to their digital profiles and Tags at regular time intervals. Meanwhile, when the temperature or humidity exceeds the security standard it will raise the alarm immediately. Last but not least, by using GPS, distribution center could implement vehicle positioning for each refrigerated truck and make optimal distribution route to shorten distribution time, which could guarantee the freshness of the food products.

E. Retailer link

First of all, when retailers receive the products, they nearly obtain full information of the supply chain that created products. Therefore, consumers can use the RFID reader to obtain the basic information of products when they are shopping. Moreover, thanks to blockchain technology, all the information along the food supply chain is fully audit-able, which means customers could also obtain details information about the final products in a real-time manner by inspecting the traceability system. Secondly, due to the short freshness lifetime of some food product, our system can be applied to monitor the freshness lifetime of products. Therefore, retailers could replace these food products which are close to their expired time. Finally, thanks to our traceability system, once food safety accident happens, the defective products can be located immediately. Furthermore, happening reasons, location and responsible staff can be traced by our system as well, which could extremely reduce the losses and hazards.

F. Authority organizations

In different links of food supply chain, authority organizations, such as certifications, audits, third-party authorities, and government departments, will random visit the working field to check whether the rules and regulations are matched, and more important, whether the relevant data has been tampered with before being updated by the participant. After that, inspecting results will be recorded in digital profiles of both parties.

VI. CONCLUSION

In this article, we proposed a new decentralized traceability system based on internet of things and blockchain technology, and explored the challenges in scaling blockchains in general. Moreover, an example scenario was given to demonstrate how it works in the food supply chain with HACCP. This system will deliver real-time information to all supply chain members on the safety status of food products, extremely reduce the risk of centralized information systems, and bring more secure, distributed, transparent, and collaborative. Our system can significantly improve efficiency and transparency of the food supply chain, which will obviously enhance the food safety and rebuild the consumer's confidence in the food industry.

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