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Food cold chain management improvement: A conjoint analysis on COVID-19 and food cold chain systems

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ABSTRACT

Cold chains are effective in maintaining food quality and reducing food losses, especially for long-distance international food commerce. Several recent reports have demonstrated that frozen foods are serving as carriers of SARS-CoV-2 and transmitting the virus from one place to another without any human-to-human contact. This finding highlights significant difficulties facing efforts to control the spread of COVID-19 and reveal a transmission mechanism that may have substantially worsened the global pandemic. Traditional food cold chain management practices do not include specific procedures related to SARS-CoV-2-related environmental control and information warnings; therefore, such procedures are urgently needed to allow food to be safely transported without transmitting SARS-CoV-2. In this study, a conjoint analysis of COVID-19 and food cold chain systems was performed, and the results of this analysis were used to develop an improved food cold chain management system utilizing internet of things (IoT) and blockchain technology. First, 45 COVID-19-related food cold chain incidents in China, primarily involving frozen meat and frozen aquatic products, were summarized. Critical food cold chain control points related to COVID-19 were analyzed, including temperature and cold chain requirements. A conceptual system structure to improve food cold chain management, including information sensing, chain linking and credible tracing, was proposed. Finally, a prototype system, which consisted of cold chain environment monitoring equipment, a cold chain blockchain platform, and a food chain management system, was developed. The system includes: 1) a defining characteristic of the newly developed food cold chain system presented here is the use of IoT technology to enhance real-time environmental information sensing capacity; 2) a hybrid data storage mechanism consisting of off-chain and on-chain systems was applied to enhance data security, and smart contracts were used to establish warning levels for food cold chain incidents; and 3) a hypothetical food cold chain failure scenario demonstration in which information collection, intelligent decision making, and cold chain tracing were integrated and automatically generated for decision-making. By integrating existing technologies and approaches, our study provides a novel solution to improve traditional food cold chain management and thus meet the challenges associated with the COVID-19 pandemic. Although our system has been shown to be effective, subsequent studies are still required to develop precise risk evaluation models for SARS-CoV-2 in food cold chains and more precisely control the entire process. By ensuring food safety and reliable traceability, our system could also contribute to the formulation of appropriate mechanisms for international cooperation and minimize the effect of the COVID-19 pandemic on international food commerce.

1. Introduction

Food cold chains are refrigerated supply chains that are used to keep perishable products at low temperatures during production, storage and distribution, with the goal of maintaining quality while reducing losses

(Hu et al., 2019; Qian, Ruiz-Garcia, et al., 2020). The importance of food cold chains was highlighted by a study of food loss from 2009, which found that improper refrigeration was the primary factor in 20% of global food loss (International Institute of Refrigeration, 2009). In the last decade, increased demand for refrigerated and frozen merchandise,

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governmental support, and innovation in cold chain infrastructure have led to considerable growth in the global cold chain industry (Ndraha et al., 2018). A recent report suggested that the value of the global cold chain may reach USD 293.27 billion by 2023 (Markets & Markets, 2018).

The importance of food cold chains was demonstrated by the global COVID-19 pandemic, which was caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The primary goal of food cold chains is the maintenance of low temperatures (Badia-Melis et al., 2016). Unfortunately, the survival of SARS-CoV-2 is favored by the low temperatures at which refrigerated and frozen foods are kept during the majority of the “farm-to-table” journey (Han, Zhang, He, & Jia, 2021; Mercier et al., 2017; Shi et al., 2020). Unforeseen changes in temperature and improper management of food cold chains can have detrimental effects on food quality, leading to increased levels of food risk and reduced consumer confidence (Ndraha et al., 2018; Rizou et al., 2020). The concepts of the unbroken “chain” of cold temperatures and product history are the most basic core characteristics of food cold chain systems, and an unlinked chain with missing documentation can negatively affect food cold chain tracing and potentially slow the implementation of product recalls during food safety incidents (Qian, Dai, et al., 2020). A recent report suggested that cold chain traceability systems can play an important role in rapidly identifying the sources of contamination responsible for SARS-CoV-2-related food safety incidents (KristinGuðmundur, 2019).

Recently, studies of COVID-19 impact mechanisms, optimization models, and management strategies for the supply chain and food industry were performed by pioneering authors (Paul, Chowdhury, et al., 2021, Chowdhury et al., 2020; Paul, Moktadir, Ahsan, et al., 2021, Chowdhury et al., 2020; Shahed et al., 2021). The findings of these studies show that the short-term impacts of this pandemic on the food and beverage industry, including product expiry, shortages of working capital, and limited operations of distributors, are severe, while the medium-to-long-term impacts are expected to be complex and remain uncertain (Chowdhury et al., 2020). Furthermore, the study of key supply chain strategies for the post-COVID-19 era revealed that supply chain resilience and sustainability practices could play dominant roles in the post-COVID-19 era (Paul, Moktadir, Sallm, et al., 2021, Chowdhury et al., 2020). These research achievements provide good theory and practice references that can be used to optimize the food cold chain during and after the COVID-19 pandemic. However, the food cold chain has features that differ from those of the general supply chain. Environmental characteristics, particularly the ambient temperature, have important influences on the food cold chain and frozen food. Several recent incidents have highlighted the potential for cold chain foods to serve as carriers of SARS-CoV-2.

Novel information technologies can be used to achieve fundamental improvements in food cold chain management practices. Utilization of the internet of things (IoT) in food safety is a relatively new approach. Major applications of the IoT include food supply chains, where they can be used to trace food products and monitor food safety and quality (Bouzembrak et al., 2019). For example, wireless sensors and RFID tags can be used for real-time monitoring of cold chain environments via deployment in cold warehouses and trucks (Corradini, 2018; Wang et al., 2017). Effective risk management and shelf life prediction are for time- and temperature-sensitive products. AI-based models for predicting freshness and shelf life have been used to ensure food quality and safety (Tamplin, 2018; Shi et al., 2019). Lau et al. (2021) proposed a federated learning-enabled multi-criteria decision-making methodology to achieve risk quantification in cold chain management. Enhanced traceability implemented via blockchain-based technology has the potential to significantly improve the transparency and accountability of food supply chains (Kshetri., 2018; Lin et al., 2020) and prevent fraud (Qian, Wu, et al., 2020) via the application of authentication and additional cybersecurity policies (Banerjee et al., 2017). Blockchain adoption in the supply chain is country-specific (Queiroz, Telles, &

Bonilla, 2019) and food-specific (Behnke & Janssen, 2020; Garaus & Treiblmaier, 2021), so the context of applications must be considered. Although the idea of applying blockchain technology in cold chain management to formulate intelligent mechanisms has been proposed (Lau et al., 2021), a corresponding technical framework remains absent. The combination of blockchain and IoT technology can play an important role in achieving effective and efficient traceability (Creydt & Fisher, 2019). By focusing on integrated consensus mechanisms, a framework for applying a blockchain-driven IoT in food traceability was recently proposed (Tsang et al., 2019). However, the myriad potential applications of blockchain and IoT technologies in food cold chain management have not yet been comprehensively analyzed with a specific focus on COVID-19.

The food cold chain plays a dual role in the COVID-19 pandemic; it can ensure food safety and reduce food loss, but it also increases the risk of COVID-19 transmission because of the low temperature environment. Previous studies of supply chain operation management provide basic methods of improving food cold chains during COVID-19 outbreaks. However, a new view was proposed in this study, involving the use of novel information technologies to implement cold chain management and whole-chain traceability with the goal of promoting cold chain effectiveness and reducing the risk of transporting COVID-19. Two areas of improvement in cold chain management practices in the context of the global COVID-19 pandemic were identified: (1) prediction of the risk of SARS-CoV-2 transmission by analysis of food cold chain requirements and temperature ranges; and (2) documentation of critical control point information throughout the entire cold chain to implement credible traceability. Therefore, in this study, a system based on IoT and blockchain technology was developed to improve food cold chain management. Risk evaluation and prediction are achieved by recording temperature and logistical information through IoT equipment to estimate the health risk posed by cold chain products based on the established relationship between time spent at a given temperature and viral viability. Credible traceability is implemented by combining a hybrid data storage mechanism and smart contracts in the blockchain framework at critical control points in the food cold chain. In Section 2, COVID-19-related incidents involving food cold chains are reviewed. In Section 3, critical temperature control points and requirements of food cold chains are analyzed in the context of COVID-19. Section 4 describes a framework for improving food cold chain management practices. Finally, in Section 5, a prototype food cold chain management system is presented and evaluated in a hypothetical contamination incident.

2. COVID-19 incidents related to food cold chains

Several recent incidents have highlighted the potential for cold chain foods to serve as carriers for long-distance transportation of SARS-CoV-2. The earliest known incident of the transportation of infectious SARS-CoV-2 by a cold chain product occurred on the 12th of June 2020, in the Xinfadi agricultural produce wholesale market in Beijing, China, where a cutting board used to process imported salmon was found to be contaminated with SARS-CoV-2 (Pang et al., 2020). Moreover, a recent report assessing New Zealand, Vietnam and China found that contaminated food and food packaging imported from areas with active SARS-CoV-2 outbreaks were potential sources for COVID-19 outbreaks in areas where no cases had been reported for periods of several months, as well as sources of clusters of infections within existing outbreaks (Fisher et al., 2020).

In Fig. 1, 45 incidents of contamination of cold chain products by SARS-CoV-2 (through January 25th, 2021) in China are summarized. During the period from June 2020 to January 2021, December 2020 was the month with the greatest number of COVID-19-related incidents, followed by November 2020, during which 2 fewer incidents were recorded. In November and December of 2020, 24 COVID-19-related incidents were reported, which accounted for more than half of the total number of incidents that occurred from June 12th, 2020 through

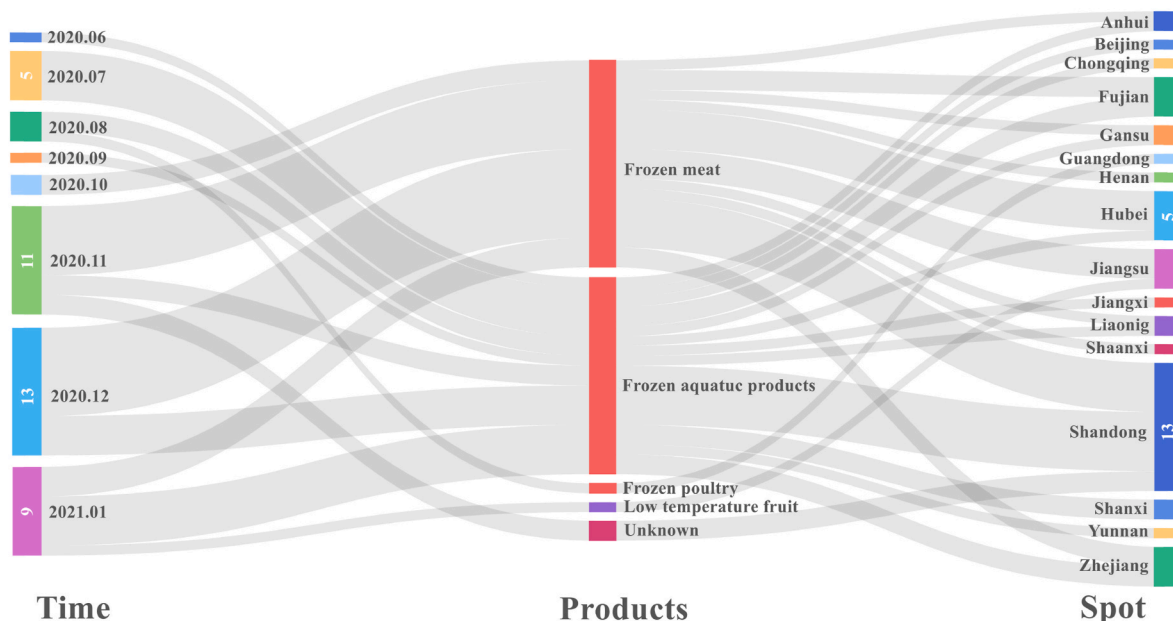


Fig. 1. COVID-19-related incidents in the food cold chain in China from June 12th, 2020 through January 25th, 2021.

January 25th, 2021. Most COVID-19-related incidents involved frozen meat or frozen aquatic products. No relationship was found to exist between the time at which each incident occurred and the type of contaminated product. The region with the most COVID-19-related incidents during the investigation period was Shandong province (13 incidents), and incidents were recorded in 15 other Chinese provinces.

More COVID-19-positive samples from refrigerated facilities and imported cold-chain foods and packaging have been detected in different places in China. The potential risk of spreading SARS-CoV-2 through contaminated refrigerated or frozen foods remains a significant concern (Sun et al., 2021).

3. Critical food cold chain control points related to COVID-19

3.1. Temperature control

The relationship between temperature and COVID-19 transmission remains unclear. However, a recent study of 62 cities in China found that the COVID-19 epidemic was not mitigated by warmer temperatures (Yao et al., 2020). In addition, a study of daily COVID-19 infections in 8 countries revealed that COVID-19 transmission was not significantly affected by meteorological factors (Pan et al., 2021). However, several groups have reported that meteorological factors affect COVID-19 transmission (Malki et al., 2020; Shi et al., 2020). Indeed, a study exploring the relationship between daily infections and meteorological conditions for 166 countries (excluding China) revealed that an increase of only 1 °C in the daily temperature was associated with reductions in daily new cases (by 3.08%) and daily deaths (by 1.19%) (Wu et al., 2020).

Temperature is the core concept that is central to the primary function of food cold chains: maintenance of food quality. Although a consensus has not been reached regarding the relationship between SARS-CoV-2 transmission and meteorological factors, the effects of temperature on SARS-CoV-2 transmission via the surfaces of cold chain foods and goods have been explored (Rizou et al., 2020). A recent study found that SARS-CoV-2 is capable of surviving for more than 21 days during cold chain transportation at temperatures as low as −18 °C (Liu et al., 2020). A study assessing SARS-CoV-2 transmission via skin, currency, and clothing showed that the virus was able to maintain viability on skin for at least 8 h at 37 °C, for at least 4 days at 22 °C, and for 14

days at 4 °C (Harbout et al., 2020).

Fig. 2 summarizes the results of studies assessing the survival time of SARS-CoV-2 on the surfaces of cold chain food products at different temperatures. According to the technical requirements for temperature-controlled transportation of perishable food in China (GB/T 22,918–2008) (Standardization, 2008), the required temperatures vary based on the product type. Frozen fish, fish products, mollusks and crustaceans must be kept at −18 °C. Frozen meat products such as pork, beef, mutton, and chicken must also be kept at −18 °C. The temperatures required for the storage of vegetables and fruits vary according to their characteristics. Leafy vegetables, beans, and berries must be kept at 0–3 °C, 2–7 °C, and 0–3 °C, respectively. The food cold chain temperatures required for a wide range of perishable products are standardized among 49 countries by the *Agreement Concerning the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage (ATP)* (UNECE, 2020).

The findings described above suggest that the risk of infection posed by cold chain products varies. For example, live SARS-CoV-2 is more likely to be transported through the food cold chain on the surface of frozen fish products in comparison with fruits and vegetables. Therefore, management practices based on appropriate risk classification are important methods of efficiently and effectively reducing the risk of SARS-CoV-2 transmission.

3.2. Main control points for cold chains

Cold chains generally begin at harvest for fresh fruits and vegetables, whereas they begin from the time of processing for meat, dairy products, and processed fruits and vegetables. Precooling is an important preliminary step, in which vegetables and fruits are brought to an appropriate storage temperature, which varies by product type. The cold chain is maintained through a series of steps, including storage, distribution, shipment, and retail, and it ends when a consumer places the product in a refrigerator or freezer prior to consumption. The duration of a cold chain can vary from a few hours for refrigerated goods to as long as several years for frozen products, depending on the specific product and target market (Gogou, Katsaros, Derensb, Alvarezb, & Taoukis, 2015). Fig. 3 shows key control points in food cold chains, which were determined according to the major stages of the entire cold chain, as well as the *Technical Guide for Prevention and Control of New Coronavirus in Cold*

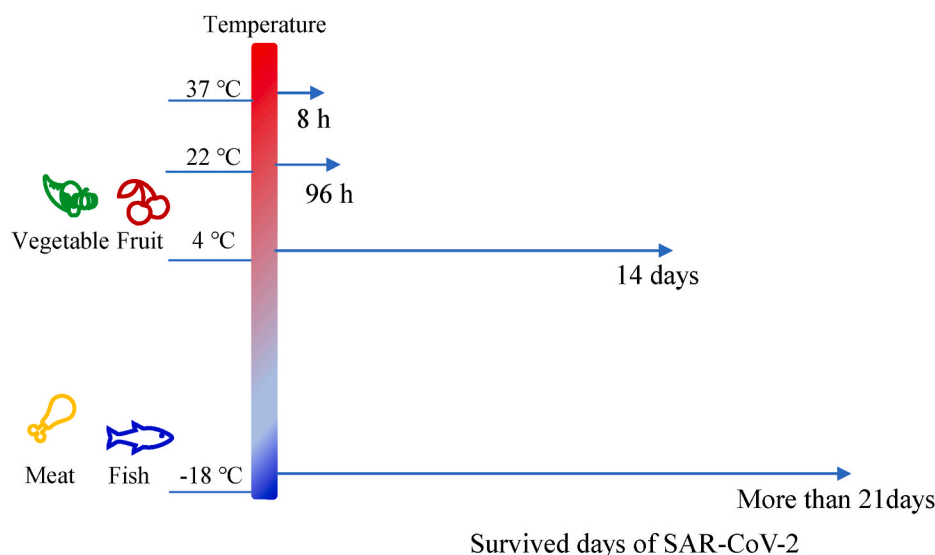


Fig. 2. Survival time of SARS-CoV-2 at the cold chain temperatures required for different types of food.



Fig. 3. Main control points for food cold chains.

Chain Food Production and Management (PRC, 2020).

As shown in Fig. 3, required health management actions for food cold chains include the maintenance of a health register for on-duty workers, daily health monitoring, management of visitors, sanitary requirements for workers, procedures for reporting abnormal events, strict procedures for returning to work after abnormal events, and communication of appropriate protection knowledge. The health register for on-duty workers must include information regarding any travel routes taken

by workers within the past 14 days, as well as the results of nucleic acid testing for the presence of SARS-CoV-2. Sanitary requirements for workers include the use of appropriate personal protection such as masks, as well as personal sanitary procedures such as hand washing. Operating measures are applied in three main stages in the cold chain: (1) processing and packaging, (2) transportation, and (3) storage, sales and catering. At each of these stages, workers should ensure that they are maintaining a safe distance from each other, using appropriate

personal protective equipment, carefully inspecting incoming goods, and applying effective cleaning and disinfection procedures. Proper application of the operating standards outlined above at major control points in food cold chains is necessary to slow the spread of SARS-CoV-2 and ensure that food products do not pose a health risk to consumers.

4. Framework of food cold chain management improvement

4.1. Importance of IoT and blockchain technology

The major stages in food cold chains include precooling, processing, packaging, transportation, storage, sales, and catering. According to the critical control points for food cold chains related to COVID-19 contamination outlined above, temperature control and whole-chain traceability are crucial considerations. Precision temperature control can reduce the risk of viral transmission and improve food safety because temperature affects the shelf life of food products and plays a major role in determining the survival time of SARS-CoV-2 on product surfaces. Critical control points exist at every stage of a food cold chain, and information collected at each of these control points can be used to trace food sources and destinations when food-related incidents occur. The importance of this information for public health merits the establishment of strict procedures to ensure the authenticity of data used to make critical decisions regarding the health risks of cold chain products. Fig. 4 shows a conceptual system structure for improving food cold chain management based on these considerations.

In the framework shown above, the three aspects of information

sensing, chain linking, and credible tracing are defined in the main stages of a food cold chain. Information sensing is crucial to the framework for cold chain management improvement. Using IoT technology, information such as temperature, humidity, and production labels can be collected and integrated to establish the chain linking layer. In the chain linking layer, the functions of information management, information exchange, data upload to the blockchain, logistics support, environmental warnings and risk evaluation are performed by artificial intelligence (AI). In the top layer of the framework, credible tracing is implemented using blockchain technology based on the information that is collected and linked in the other layers.

4.2. Information sensing

Based on the characteristics of COVID-19 and the features of food cold chains, two main types of information are collected in the cold chain improvement framework described above: environmental information and cold chain operation information. Environmental information may be collected using IoT sensors for temperature, humidity, gas concentrations, and logistic position. For cold chain operating information, production labels, worker IDs, operating steps and virus testing information may be collected with cold chain information recording applications (APPs) in real-time.

In the proposed food cold chain improvement framework, a hybrid data storage method utilizing on-chain and off-chain storage, as well as the InterPlanetary File System (IPFS), is adopted in order to achieve appropriate levels of data capacity and privacy (Lin et al., 2020). The



Fig. 4. Framework for food cold chain management improvement.

IPFS provides the capability for the system to store a wide variety of types of information, including text, images, audio, and video, which may be indexed in blocks via hashing to allow incorporation into a blockchain. This type of hash indexing meets the requirements for information confidentiality and is suitable for the limited storage capacity of each block in the blockchain. The combined hybrid data storage system provides a reliable, easy-to-supervise, and tamper-proof solution to the problem of product information traceability and effectively protects the business secrets of commercial enterprises involved in food cold chains.

4.3. Chain linking

In order to track information collected during different stages of a food cold chain, a cold chain linking mechanism utilizing blockchain technology was designed. When a food product enters the cold chain, a block with a hash index containing information is created on the chain. A block header and a block body comprise each block. The block header contains the timestamp, version number, Merkle root, and previous block hash, whereas the block body contains public information that may be used by consumers to trace products. The hash index is added to the higher-layer blockchain when each block is generated. Therefore, information management, information exchange and data upload to the blockchain are important considerations.

In addition, the risk of COVID-19 transmission can be increased at each stage of a food cold chain because of the presence of unsuitable temperatures or viruliferous methods of cold chain operation. Therefore, environmental warnings and risk evaluation should be used to reduce the health risk posed to consumers by cold chain products. Environmental warnings consist of warning information that is conveyed when a given threshold for an environmental indicator, such as temperature or humidity, is reached, indicating a significant difference between the current environmental conditions and optimal environmental conditions in a given food cold chain. In contrast, risk evaluation is achieved by analyzing temperature and logistical information to estimate the health risk posed by cold chain products based on the established relationship between time spent at a given temperature and viral viability (Fig. 2).

4.4. Credible tracing

In the proposed cold chain improvement framework outlined here, tracing query smart contracts may be executed using different types and scopes of tracing information according to the particular requirements of customers and other individuals involved in food cold chains at different levels. For example, customers can query basic product information, whereas supply chain stakeholders have access to additional information, including information about upstream and downstream stakeholders in a given food cold chain. Food safety departments and health/hygiene departments have the highest level of authority in the system and may access information regarding the entire cold chain. Using the tracing system described here, a quick and reliable recall can be implemented when a COVID-19 contamination incident occurs.

To establish credible traceability, agents may acquire traceability information and block numbers by scanning a product code. Once the code is scanned, a hash is calculated using the traceability information obtained from the product code. Next, the hash is compared with the public hash value stored on the blockchain to identify any differences. Any difference between the hash values indicates that the product information has been altered at some point during the cold chain. Furthermore, if a COVID-19 contamination incident occurs, the entire supply chain may be traced by executing a smart contract, allowing agents to determine responsibility for the accident and implement a quick recall.

5. Evaluation of a prototype blockchain traceability system via a hypothetical situation

5.1. System implementation

A prototype system was developed independently to improve food cold chain management and reduce the risk of SARS-CoV-2 transmission via cold chain products. The prototype system consisted of cold chain environment monitoring equipment, a cold chain blockchain platform, and a food chain management system.

5.1.1. Multi-parameter cold chain environment monitoring equipment

(1) Equipment

Multi-parameter cold chain environment monitoring equipment, including a power supply module, sensor module and communication module, was used to monitor environmental parameters, including air temperature, humidity, illumination, ethylene gas concentration, and position. Low-power long range radio (LoRa) wireless modulation technology was used to send information from the environmental sensors to the communication gateway, after which it was sent to the cold chain blockchain platform. Fig. 5 shows the structure of cold chain environment monitoring equipment.

(2) Module design

The power supply module was composed of a charging control circuit, voltage monitoring circuit, digital power supply circuit and precise voltage reference (to implement battery charging control and circuit power distribution). The battery charging control circuit adopted an efficient lithium battery special charging chip with the constant current/constant voltage (CC/CV) charging mode. The maximum charging current was 400 mA. Protection mechanisms against excessive current, pressure, and temperature were built into the battery. A voltage monitoring circuit was used to monitor the battery to ensure battery safety.

The microcontroller was linked with the sensors for temperature & humidity, gas, position and illumination through the Inter-Integrated Circuit (I2C) bus interface. Ethylene, an important gas in the food cold chain, was monitored using an electro-chemical sensor. The sensor output a nA signal via a constant voltage circuit, which was amplified via the amplifier circuit and input into an analog-to-digital (A/D) converter in the microcontroller to convert it into an ethylene concentration.

An SX1278 chip supporting LoRa was adopted as the radio frequency (RF) modem in the communication module. The RF signal was transmitted and received through direct sequence frequency expansion. A universal asynchronous receiver/transmitter (USB-UART) converter was used to communicate via USB with the microcontroller and transfer the USB protocol to the UART.

5.1.2. Cold chain blockchain platform

(1) Data storage design

Data collected during the cold chain transportation stage were used to demonstrate the hybrid storage mechanism of the prototype system described here. The block body was used to store information pertaining to food safety and virus risk, including batch ID, transporter, start time, main position, temperature, and end time, whereas other types of information, including product pictures, loading videos, transportation details, GPS locations, and additional information related to the product's environment and transportation history, were stored in the IPFS. Fig. 6 shows the hybrid storage design that combined blockchain and IPFS.

In order to link the block body and the data in the IPFS, the batch ID

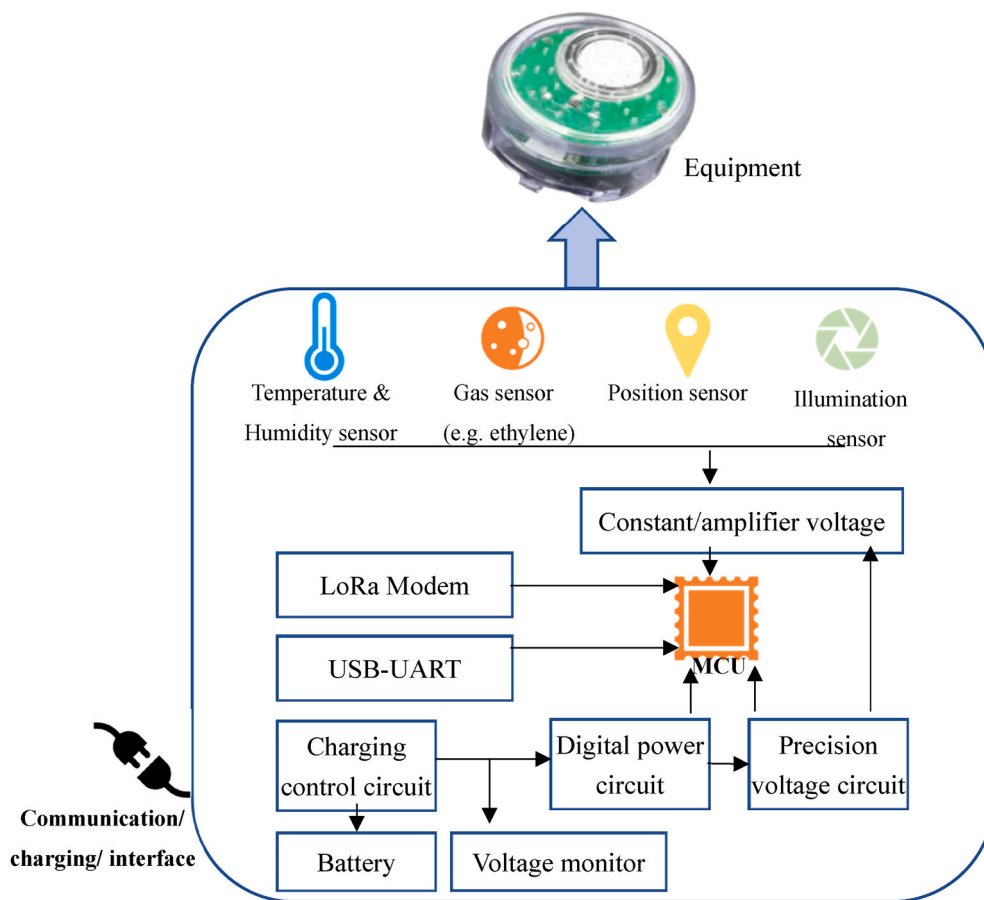


Fig. 5. Structure of cold chain environment monitoring equipment.

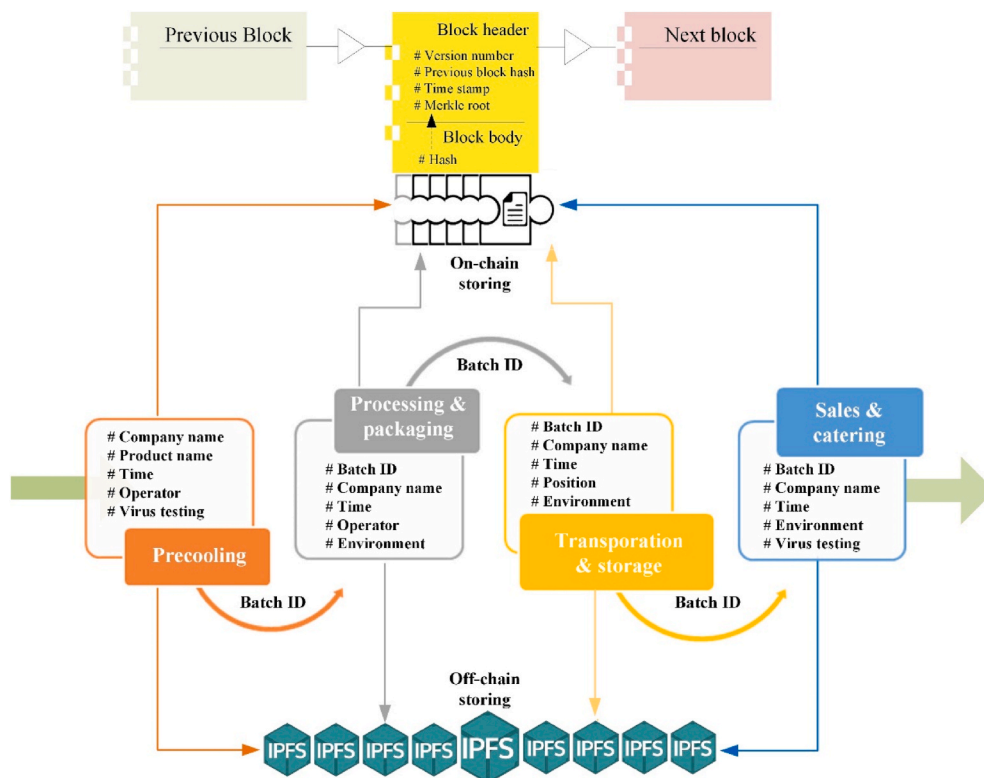


Fig. 6. Hybrid storing design combined blockchain and IPFS.

(as an association ID) was generated for storage in the blocks at the block addition step. The properties of the blocks thus become **block** = {*index, timestamp, data (associated batch ID), hash, previous_hash, Rand*}, and SHA-256 was used to encrypt the blocks. Specifically, a batch of food is processed by a food factory and enters into the cold chain logistics stage. A batch ID can be assigned to the food to create the genesis block. Along the cold chain, the environmental conditions and operating activity can be recorded in the blockchain and IPFS. When the data is sensed by IoT devices or recorded by cold chain stakeholders, a strict access authorization is performed. Large files, such as pictures and videos, can be stored in the IPFS, while their hash IDs are stored in the blockchain. Data is distributed via the blockchain. When a network node is damaged, other nodes can still support data access.

(2) Smart contracts

In addition to data storage, smart contracts are a crucial part of the proposed blockchain traceability platform. The main types of smart contracts, including information upload, environmental warnings, risk evaluation, and tracing queries are deployed in the blockchain and executed when all of the parties involved in the contract agree on its terms. Algorithm 1 shows the processing algorithm for an example smart contract for risk evaluation. The food type, virus test result, main control point, temperature, and time are used as input parameters. In the processing procedure, four steps are executed according to simple *if-then* rules to assign one of five risk levels to the food product under examination. If the virus test is positive, then a very high risk level is assigned to the product. If the virus test is negative and the parameters of the main control point did not meet the requirements for the particular type of food under examination, then a high risk level is assigned. Finally, if the virus test is negative, the main control point parameters were suitable for the type of food under examination, the temperature was maintained within the required range, and the time at the required temperature exceeded the established virus survival time at that temperature, then a very low risk level was assigned to the product. A product may also be assigned low and medium levels of risk based on evaluation of cold chain information using Algorithm 1.

Algorithm 1. Risk evaluation

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Input (food, virus check, main control point, temperature, time)
1  If virus test passed (negative result) then
2      If main control point fit the requirement for this food then
3          If temperature was in the range for the cold chain requirements of this food then
4              If time exceeded the virus survival time at this temperature then
5                  Assign very low risk
6              Else
7                  Assign low risk
8              End
9          Else
10             Assign medium risk
11         End
12     Else
13         Assign high risk
14     End
15 Else
16     Assign very high risk
17 End

```

In the processing step, the smart contract can be packaged and deployed to a blockchain network. Multiple smart contracts can be defined within the same package, and all smart contracts within it are made available to the application once the package is deployed. The smart contract is a distributed programmable application initialized on each peer. The node is employed with a consensus protocol to ensure the consistency of every copy of the ledger. This node exists independently of the peer processes and transactions on a first-come-first-serve basis across the network.

5.1.3. Food cold chain management system

(1) System architecture

As shown in Fig. 7, the system architecture consisted of an equipment layer, a communication layer, a data analysis layer, a blockchain layer and an application layer. The equipment layer primarily consists of environmental sensing equipment and virus testing equipment. Cameras are deployed at key links in the cold chain to monitor situations. In addition, RIFD and barcode equipment are important for cold chain traceability. The communication layer links the equipment and the blockchain via technologies such as Zigbee, WiFi, Ultra Wide Band (UWB), or 5G. This layer standardizes heterogeneous channels and guarantees data transmission stability. In the data analysis layer, data cleansing aims to detect and delete noisy data that are incomplete, inaccurate and redundant. Format conversion is necessary because cold chain stakeholders use a variety of applications and encode data in different ways. Classification and aggregation into different specific groups is performed to establish a prediction model from a temporal and spatial perspective. The processed data are used to form a series of blocks in the blockchain network layer. The blocks are connected in chronological order, forming blocks and finally blockchain networks. In the forming process, a consensus mechanism is required to guarantee data consistency and the fault-tolerance among distributed ledgers, while an incentive mechanism is designed to motivate stakeholders to record data. In the top layer, various functions of position tracking, environmental monitoring, abnormality warning, and cold chain tracing are implemented by creating a blockchain network using processed data collected from IoT equipment. Computers, smartphones, and tablet PCs can be accessed by the system to obtain applications and services.

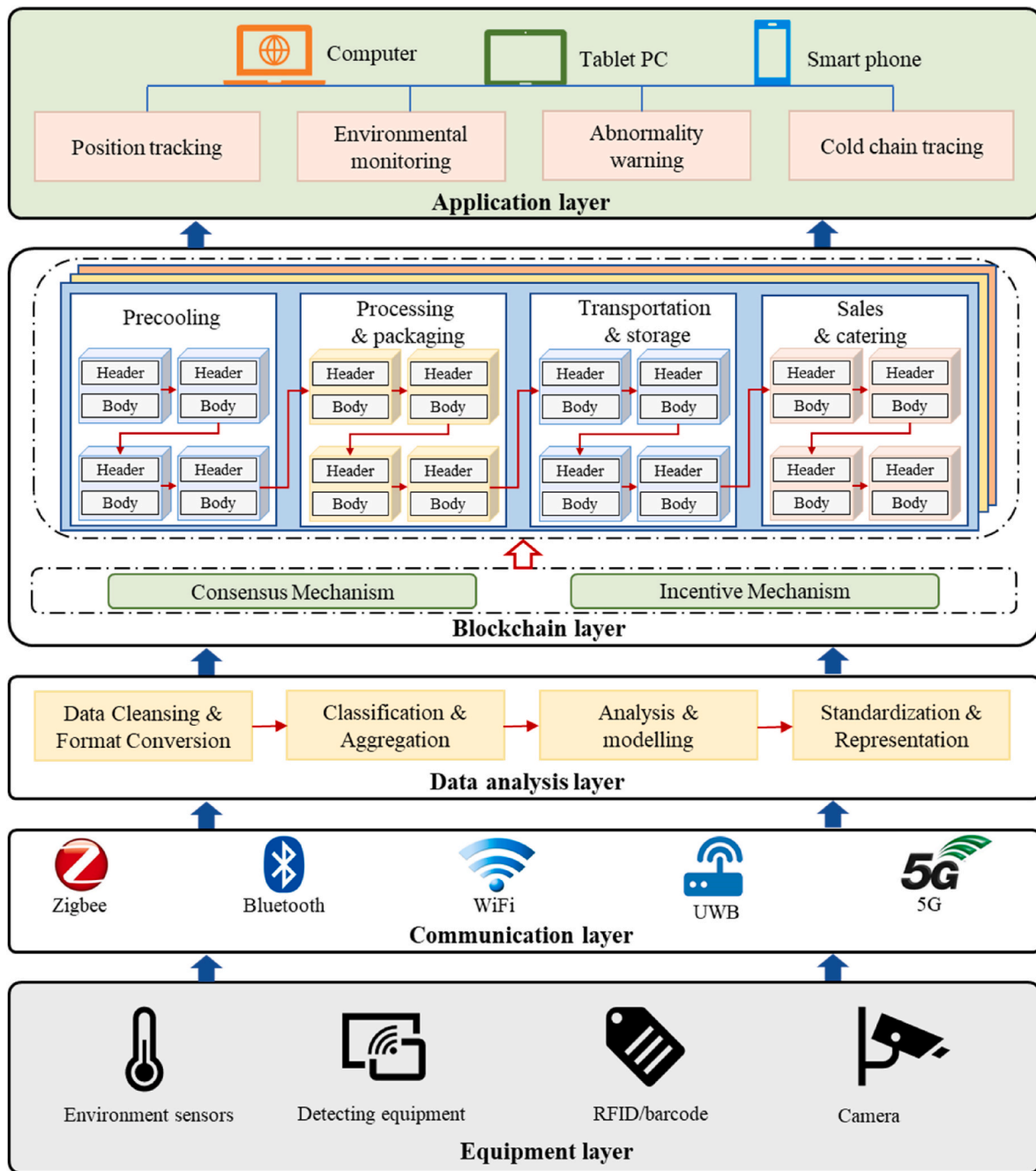


Fig. 7. Food cold chain management system architecture.

(2) System functions

By integrating static resource data, including supplier, cold chain vehicle, and cold storage information, as well as dynamic sensing data, including temperature, humidity, location, illumination, and ethylene gas concentration, a food cold chain management system was developed. The newly developed system is an open cloud platform that provides the services of position tracking, environmental monitoring, abnormality warning, and cold chain tracing. The main functions of the blockchain traceability system are described below.

Position tracking: Position information is received from multi-parameter cold chain environment monitoring equipment and used to draw a dynamic electronic route map. Cold chain warehouse and vehicle locations are tracked through real-time position information.

Environmental monitoring: Based on the collected environmental data,

real-time environmental information can be displayed, and information can be viewed for a given period of time. In particular, illumination information can be monitored to determine whether a cold chain cabinet has been opened.

Abnormality warning: Cold chain abnormalities may include environmental abnormalities and operating abnormalities. Warning rules for environmental abnormalities are set in smart contracts. When the trigger condition for a particular environmental parameter is met, then a related smart contract is invoked and a warning is conveyed to the appropriate authority, stakeholder, or consumer.

Cold chain tracing: Credible, tamper-proof tracing can be achieved using the blockchain platform. Cold chain environment information and operating information are both tracked in the blockchain traceability system.

5.2. Typical scenario and evaluation

5.2.1. Scenario description

The newly proposed blockchain traceability system described above was evaluated using a hypothetical scenario. In this imaginary scenario, a batch of frozen shrimp was imported from country A. This batch of frozen shrimp was randomly inspected by the appropriate customs office in China, including COVID-19-related nucleic acid testing. The batch of frozen shrimp passed the customs inspection and was transported to a cold storage facility in a different city, after which it was sold at local markets. During this stage, the original batch of frozen shrimp was divided into many sub-batches.

Several days after the original inspection, a sample in one sub-batch of frozen shrimp from a supermarket in city B is selected for inspection, and this sample is found to be contaminated with SARS-CoV-2, which triggers a warning mechanism. Using the blockchain traceability system, the circulation route of the contaminated sub-batch is mapped and, according to the rule of batch association, all other sub-batches from the original batch are found and checked. These additional tests show that the other sub-batches of frozen shrimp are safe and do not need to be recalled. By utilizing the information contained in the blockchain, the cold chain environment and operating measures are determined to have met the appropriate operating requirements. Finally, nucleic acid testing reveals that the contaminated sub-batch of frozen shrimp was exposed to a surface at the supermarket in city B that was contaminated by SARS-CoV-2. As a result of the application of blockchain information tracing, the source of the contamination was rapidly identified, and a product recall is rapidly instituted at the appropriate scale.

5.2.2. Improvement results analysis

Using the blockchain traceability system, information collection, intelligent decision making, and cold chain tracing were improved, as shown in Table 1. Information collection was improved via the application of real-time sensing various information, especially for COVID-19 testing and control point information. In addition, information security was maintained at a high level due to the implementation of hashing. Intelligent decision making was improved by utilizing the established relationship between COVID-19 viability and the cold chain environment to implement environmental warnings, and risk evaluation was achieved using smart contracts. The traceability of information from the entire cold chain was improved by the utilization of blockchain technology in a hybrid storage system with on-line and off-line storage, which improved data continuity, ensured authenticity, increased recall capacity, and enhanced reliability.

Furthermore, the efficiency of the proposed system was examined via analysis of block transaction time and transaction throughput. The tests were conducted in the Windows 10 environment with an Intel Core i7 CPU and 64 GB RAM, which was capable of completing the data for 80 key nodes as transaction content and linking them to the blockchain in 2 s, and it was capable of processing more than 1400 transactions in 1 min.

Table 1
Advantages of the blockchain traceability system for food cold chains.

| Aspect | Item | With the system | Without the system |
|------------------------|------------------------|---|---|
| Information collection | Richness | Food information, environmental information, operating information, COVID-19 testing information, and control point information | Food information, environmental information, operating information |
| | Timeliness | Real-time information sensing with IoT devices | Information recorded on paper or in electronic spreadsheets |
| | Security | Difficult to manipulate as a block | Easy to manipulate |
| Intelligent decision | Environmental warnings | Automatic warnings based on required cold chain environmental conditions for different foods | No warning function |
| | Risk evaluation | Evaluation based on smart contracts | No evaluation function |
| Cold chain tracing | Continuity | Whole cold chain tracing through linked blocks | Unreliable continuity based on communication between cold chain facilities and transporters |
| | Authenticity | Tamper-proof reliability based on the blockchain platform | Low reliability |
| | Recall capacity | Optimal recall may be performed in an isolated product range | Whole batch recall |

Therefore, the system had the features of low latency and high throughput.

5.2.3. Discussion of system availability

Due to the difficulty of acquiring actual COVID-19-related food cold chain incidents, an imaginary scenario was analyzed. Although it was an imaginary scenario, the scenario was representative based on our analysis of food cold chain processing and the core features of COVID-19 accidents. However, the imaginary scenario was not a perfect model of an actual food cold chain.

- 1) Data docking: In order to work more effectively, external systems such as food checking systems and customs management systems must be linked with the proposed system. Therefore, data exchange mechanisms and interfaces must be developed.
- 2) Fast responses: COVID-19 accidents spread quickly. Therefore, rapid and effective tracing is a fundamental requirement for the proposed system. Blockchain processing efficiency and system concurrency need be considered for actual applications.

In this paper, a prototype system was proposed based on conjoint analysis of COVID-19 and food cold chain systems. Actual applications and data validation with a focus on data docking and fast responses will be the subjects of subsequent work.

5.3. Implications

The current global COVID-19 not only has impacts on people's health but significantly on businesses and the global economy. Food cold chain plays an important role in the context of COVID-19 pandemic. It can provide an efficient way to satisfy the human food requirement through ensuring food quality and reducing loss. On the other hand, the development of food industry is inseparable from cold chain logistics. An increasing demand in society for greater information about the food cold chain reflects the need for more transparency and a lack of trust in current practices. The blockchain is a technological solution through which the food cold chain could be improved. However, the transition from a traditional food cold chain to a blockchain-based food cold chain may be difficult. Some global implications can be provided based on the study. This study contributed a novel food cold chain management system framework combining blockchain and IoT technologies, which can achieve improvements in the global food cold chain, including better prediction of the risk of SARS-CoV-2 transmission by analysis of food cold chain requirements and temperature ranges, as well as documentation of critical control point information throughout the entire cold chain to implement credible traceability. In the context of the global COVID-19 pandemic, application of the proposed system will play an important role in reducing the risk of contaminated products by achieving rapid responses to incidents and ensuring food safety. In addition, the proposed system and its structure will provide a reference

for the establishment of similar food supply chain management systems.

When the system described here is applied continuously and the proposed framework is extended to similar situations, some technical implications need to be considered.

- 1) In the context of combining the blockchain and IoT, data security is a serious problem. IoT technology has the advantage of real-time information sensing in the food cold chain. Although some encryption-based mechanisms, such as Ellipse Curve Cryptography (ECC), can be adopted to protect the confidentiality of information, disclosure of sensitive information is difficult to prevent completely (Grecuccio et al., 2020). Such disclosures have brought about significant losses, such as the Parity Wallet bug, which allowed the theft of around 280 million USD (Paganini, 2017). Further data security measures should be applied, including secure protocols such as Telehash and Whisper.
- 2) Considering the requirements of food quality and safety, smart contracts based on novel food analysis and forecasting models must be improved. There is a constant pressure to improve food cold chain management and performance in order to ensure food safety and quality by complying with different stakeholder requirements. Failure mode and effect analysis (FMEA) can be used as a preventative measure to eliminate potential failure modes, assess the causes and effects of failures, and improve food reliability (Wu & Hsiao, 2021). Based on FMEA, important smart contracts for risk evaluation and key point control should be applied to ensure food quality and safety.
- 3) In view of the complexity of the food supply chain, the systems required for collaboration may not be readily available to all food cold chain stakeholders. It is necessary to consider cooperation and interoperability between different stakeholders in order to improve the capacity of sustainable applications (Zheng & Lu, 2021). Consensus mechanisms based on collaboration should be designed in accordance with the profit concerns of all involved parties and must be continuously updated according to newly released food rules. In addition, interoperability and standardization between this system and other systems must be considered.

6. Conclusions and future work

Improving standards for food cold chain management is an extremely urgent concern, because proper operation of food cold chains ensures food safety and prevents the spread of SARS-CoV-2 through contaminated products. In this study, a new framework based on blockchain traceability was designed to improve food cold chain management. Based on an analysis of 45 COVID-19-related incidents involving food cold chains and critical cold chain control points related to COVID-19 in the context of temperature and storage time, a conceptual system including information sensing, chain linking and credible tracing was developed. Furthermore, a prototype cold chain traceability system consisting of environmental monitoring equipment, a cold chain blockchain platform, and a food chain management system was developed, and a typical scenario was used to evaluate this system. The results of the evaluation showed that information collection, intelligent decision making, and cold chain tracing were improved by implementing the blockchain traceability system described here.

Although some blockchain-based food supply chain systems and COVID-19-related incidents involving food chains have been studied, most existed studies do not include dynamic analysis and credible traceability because of mismatches between available technologies and cold chain incidents. This study contributed a novel food cold chain management system framework that combined blockchain and IoT technologies. With the proposed system, improvements in cold chain management can be achieved, including better prediction of the risk of SARS-CoV-2 transmission by analysis of food cold chain requirements and temperature ranges, as well as documentation of critical control point information throughout the entire cold chain to implement credible traceability. In the context of the global COVID-19 pandemic,

application of the proposed system will play an important role in reducing the risk of contaminated products by achieving rapid responses to incidents, ensuring food safety. In addition, the proposed system and its structure will provide a reference for the establishment of similar food supply chain management systems.

This study has some limitations. The risk evaluation and prediction model was relatively weak, and the application was restricted to an imaginary scenario. Certain challenges regarding food cold chain management systems have arisen that should be addressed in future studies. For example, a precise risk evaluation model is an important tool that could be used to provide earlier and more accurate warnings regarding potential outbreaks of COVID-19 and future pandemics. The combination of rapid viral testing technology and AI could allow for the development of a multi-parameter smart evaluation model that could provide timely warnings of potential health risks. Finally, food cold chains and COVID-19 transmission are international concerns, and enhancing the international exchange of information concerning food cold chains and COVID-19 is necessary to ensure the safety of cold chain products and prevent future outbreaks.

CRedit authorship contribution statement

Jianping Qian: Paper conception, System design, Draft preparation. **Qiangyi Yu:** Blockchain part implementation. **Li Jiang:** COVID-19 and food chain analysis. **Han Yang:** System testing. **Wenbin Wu:** System framework propose.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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