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INVITED REVIEW

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A review of epidemic investigation on cold-chain food-mediated SARS-CoV-2 transmission and food safety consideration during COVID-19 pandemic

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Abstract

COVID-19 has brought speculations on potential transmission routes of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causal agent of the pandemic. It is reported that the main route of virus transmission to be person-to-person by respiratory droplets; however, people have raised concerns on the possible transmission of SARS-CoV-2 to humans via food and packaging and its potential effects on food safety. This review discusses food safety issues in the COVID-19 pandemic and reveals its possible transmission in cold-chain food. The first outbreak of COVID-19 in late 2019 was associated with a seafood market in Wuhan, China, while the second outbreak of COVID-19 in June 2020 was also related to a seafood market in Beijing, China. As of 2020, several frozen seafood products linked with SARS-CoV-2 have been reported in China. According to the current survey and scientific studies, the risk of infection by SARS-CoV-2 from cold-chain food, food products, and food packaging is thought to be very low. However, studies on food cold chain contamination have shown that SARS-CoV-2 remained highly stable under refrigerated (4°C) and even in freezing conditions (−10 to −80°C). Since one mode of SARS-CoV-2 transmission appears to be touching contaminated surfaces, it is important to clean and sanitize food contact surfaces properly. Understanding food safety hazard risks is essential to avoid potential negative health effects and SARS-CoV-2 transmission in the food supply chain during the COVID-19 pandemic.

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1 | INTRODUCTION

On December 31, 2019, the first case with pneumonia caused by a novel coronavirus was detected in Wuhan, China (Huang et al., 2020). On January 7, 2020, the new virus was identified as 2019-nCov (Francesco, 2020). A few days later, China announced the first death of COVID-19, which led to placing Wuhan under quarantine on January 23, 2020. Unfortunately, COVID-19 spread out worldwide rapidly due to the extensive public transport network. On February 11, 2020, World Health Organization (WHO) announced that the disease caused by the novel coronavirus would be named COVID-19. On March 11, 2020, WHO declared COVID-19 a pandemic and warned all countries to prepare for this disease (Cucinotta & Vanelli, 2020). COVID-19 outbreaks had been confirmed in 222 countries on the six continents in 2020. In July 2021, the global COVID-19 cases exceeded 200 million, and the death reached almost four million (WHO; https://covid19.who.int/). COVID-19 is becoming one of the deadliest pandemics in history.

2 | TRANSMISSION OF SARS-CoV-2 IN FOOD AND FOOD SUPPLY CHAIN

Although the coronavirus is mainly transmitted through respiratory droplets from sneezing, coughing, and talking during close contact among humans (Anderson, Turnham, Griffin, & Clarke, 2020; Galbadage, Peterson, & Gunasekera, 2020; Zhang et al., 2020), the possibility of transmission through water, bioaerosols, and food should not be ignored (Carducci, Federigi, Liu, Thompson, & Verani, 2020). COVID-19 can also be transmitted via the contact-oral route with contaminated objects and surfaces, although it seems less significant (Chan et al., 2020; van Doremalen et al., 2020). Nevertheless, it is possible that a person can get COVID-19 by touching a surface or object, including food or food packaging, that has the virus on it and then touching their own mouth, nose, or possibly their eyes. Therefore, U.S. CDC (CDC, 2020) also reminded the importance of following good food safety practices to reduce the risk. One major question pertains to the survival of SARS-CoV-2, the causative agent of COVID-19, on food and food contact surfaces, and the potential risk to consumers and essential workers (Lacombe, Quintela, Liao, & Wu, 2020).

In the previous outbreak of SARS-CoV (SARS outbreak in 2003) and Middle East respiratory syndrome virus (MERS; an outbreak in 2012), food was considered less likely to be a route of transmission (EFSA, 2020; Olaimat, Shahbaz, Fatima, Munir, & Holley, 2020). According to authoritative literature, the general agreement is that there is no evidence that SARS-CoV-2 is a food safety risk currently. From a hazard-risk perspective, the overall potential risk of acquiring COVID-19 from contaminated food or food packaging appears to be very low (ANSES, 2020; FDA, 2020; FSA, 2020; WHO, 2020). SARS-CoV-2 is, therefore, not considered a foodborne virus (Anelich, Lues, Farber, & Parreira, 2020).

On the other side, much research has shown that SARS-CoV-2 is more stable on plastic and stainless steel than copper and cardboard, and the artificially contaminated virus can be detected within 72 hr after being applied to these surfaces (van Doremalen et al., 2020). Thus, as evidenced by positive results in solid surfaces (table, floor, or window), the risk of transmission from infected persons to food products is likely high (Zhang, He, Zhu, Liu, & Wu, 2021). Food products are often traded in supermarkets, wholesale markets, and chain stores with large crowds in enclosed rooms, making it easy for the virus to be transmitted through droplets or aerosols from infected humans (Lacombe et al., 2020; Zhang et al., 2020). When one employee is infected with SARS-CoV-2, it would be risky for people visiting the area (Ahmed et al., 2020). An infected person can uncontrollably sneeze or cough coronavirus on food products or food packaging. For example, it was reported that contaminated SARS-CoV-2 RNA was detected on the surface of a salmon chopping board (Hayashi, Aboko, Mandan, Yaegashi, & Konishi, 2020). In this regard, the food supply chain is likely to have the potential spread of the virus. However, limited attention has been focused on the transmission of SARS-CoV-2 in the food supply chain (Galanakis, 2020).

In addition, several studies have concluded that diarrhea is likely caused when the virus infiltrates the body through other mechanisms, for example, via the gastrointestinal tract from ingestion of contaminated food (Amirian, 2020; Wang, Zhou, Jiang, Zhou, & Ma, 2020; Xiao et al., 2020). However, whether the COVID-19 virus resists passage through the gastrointestinal tract and the fecal-oral virus transmission still needs to be explored (Bogler et al., 2020). During the COVID-19 pandemic, therefore, the Agency for Food, Environmental, and Occupational Health and Safety of many countries have conducted one of the first risk assessments related to food safety and SARS-CoV-2 (ANSES, 2020). Additional hygienic practices are listed in all such standards to ensure that food handlers practice proper hygiene to prevent transmission of any potential microbiological contamination to food (ANSES, 2020; CAC, 2020). It has become commonly accepted that foods, packages, and food contact surfaces play an insignificant role in transmitting SARS-CoV-2. The workers should operate the food according to HACCP and GMP principles. Proper wearing masks and frequent hand washing are sufficient to eliminate the virus and other common foodborne pathogens from workers' hands (Finger et al., 2021). Therefore, consumers absorbedly needed to properly wash hands after touching potentially virus-contaminated surfaces and especially before eating or touching the face.

3 | COLD-CHAIN AND FOOD CONTAMINATION IN CHINA

A cold chain is a temperature-controlled supply chain. A complete cold chain is an uninterrupted series of refrigerated production, storage, and distribution activities, along with associated equipment and logistics, which can maintain quality via a desired low-temperature range. It is used to preserve, extend, and ensure the shelf life of products, such as fresh agricultural produce (Kohli, 2020), seafood, frozen food, chemicals, and pharmaceutical products (Gyesley, 1991). As the primary method for extending shelf life and providing high-quality food, cold-chain food means to control the temperature through

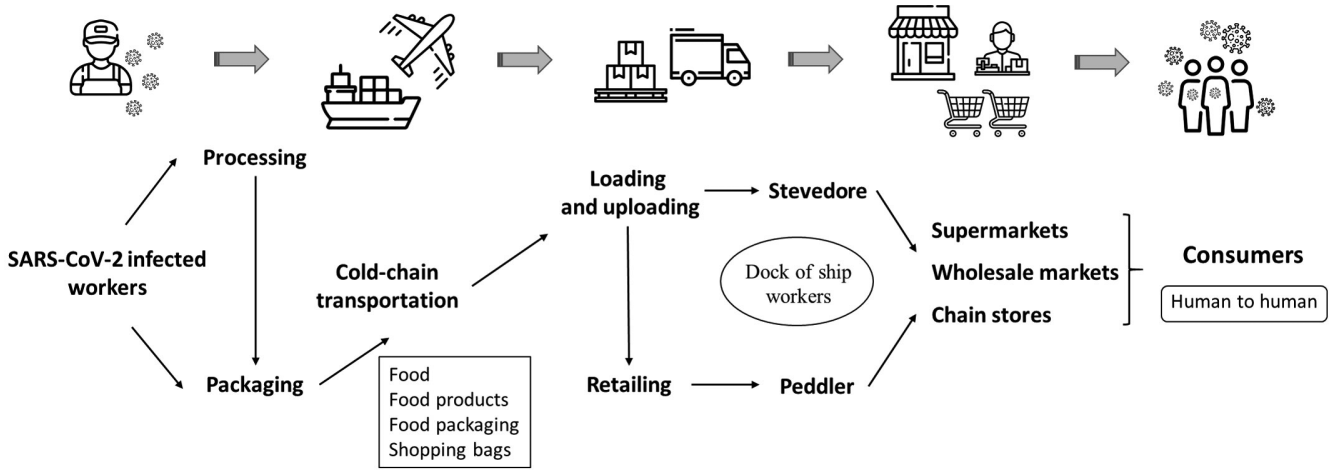

FIGURE 1 Probable route of transmission for SARS-CoV-2 through cold-chain transportation in the frozen food industry

refrigeration in the food supply chain during transport, storage, and distribution (Duret et al., 2019). This temperature-controlled measure covers a series of steps from harvesting to consumption, and the contamination risk of SARS-CoV-2 exists throughout the whole procedure (Han, Zhang, He, & Jia, 2020; Figure 1).

The first outbreak of COVID-19 in late 2019 and early 2020 was associated with the Huanan Seafood Market in Wuhan, China, while the second outbreak of COVID-19 in June of 2020 was also related to the Xinfadi Seafood Market in Beijing, China (Global Times, 2020). Most recently, in China, several frozen seafood products contaminated with SARS-CoV-2 have been reported (IntraFish, 2020), raising the concern that imported frozen seafood and meats with SARS-CoV-2 could be a source of international transmission (Dai et al., 2021). Since June 2020, more than 10 provinces and cities, including Beijing, Liaoning, Anhui, Fujian, Jiangxi, Shandong, Guangdong, Shaanxi, and Jiangsu in China, have discovered SARS-CoV-2-positive samples taken from imported frozen food or food packaging (Table 1). To prevent imported food from potentially infecting people, the State Council of China required all imported cold-chain food to be thoroughly disinfected before going to the market. Related equipment and warehouses, including loading and transporting carriers, are also required to be thoroughly sanitized (Chi, Zheng, Liu, & Wang, 2021). However, in the XFDM event, the investigation ignored the possibility that the retailing workers may get the SARS-CoV-2 infection from international traders. As pointed out by Finger et al. (2021), the COVID-19 contamination could have happened via international workers that came into close contact with local personnel, including retailing workers in the market.

Cold-chain contamination as the possible origin of COVID-19 resurgence in Beijing city (China) since June has been investigated and scientifically reported by Pang et al. (2020) and Xing, Wong, Ni, Hu, and Xing (2020). On June 11, 2020, a retailing worker at Xinfadi Market (XFDM) was diagnosed with COVID-19 in Beijing after a 56-day zero new case interval (Ceylan, Meral, & Cetinkaya, 2020; European Commission, 2020). One hundred twelve close contacts of the index case and 242 environmental samples collected from the places he had visited were tested by quantitative reverse transcription-polymerase chain reaction (qRT-PCR). All close contacts were negative, but two environmental samples from Xinfadi Market (XFDM) were positive for SARS-CoV-2. The results led to an in-depth investigation to confirm the role of XFDM in virus spread. Therefore, a large-scale screening campaign of SARS-CoV-2 infection was implemented over the city by Beijing Center for Disease Prevention and Control. A total of more than 10 million citizens and 5,342 environmental samples were screened and analyzed. The results indicated the infections demonstrated spatial clusters in the basement, and highly clustered cases were identified in the seafood section (Pang et al., 2020). Pang et al. (2020) speculated that the COVID-19 resurgence in Beijing was likely initiated by an environment-to-human transmission originating from contaminated imported food via cold-chain logistics. Cold-chain food contamination had raised an alert in China even before this cluster of cases was reported (Sun, Cheng, Zhao, Chen, & Ayaz, 2021). However, they did not provide evidence of whether the viral load on the frozen salmon surface is sufficient to establish an infection, but the risk from the cold-chain food and environment contamination exists (Fisher, Reilly, Zheng, Cook, & Anderson, 2020; Hoseinzadeh et al., 2020).

On July 3, 2020, the Dalian and Xiamen Customs in China claimed that the container surface of the frozen South American white shrimp manufactured by an Ecuadorian enterprise was detected with SARS-CoV-2 (GAC, 2020). Three local COVID-19 cases were reported in Dalian City, Liaoning Province, China. All three patients informed that they did not leave Dalian 14 days before the onset of the disease and had no COVID-19 case contact history and no foreign personnel contact history. Throat swab samples were taken from COVID-19 patients, and asymptomatic infections were collected for the phylogenetic analysis of virus genomic sequences. Judging from the timing and phylogenetic analysis, the virus was likely to be imported from outside of Dalian City. The report suggested that the Dalian outbreak was probably related to the processing of cold-chain seafood products, especially those contaminated imported products (Zhao et al., 2020). After epidemic investigation, 87 confirmed cases were reported between July 9, 2020, and August 3, 2020; among those

TABLE 1 Imported cold-chain food tested positive for COVID-19 virus in China in 2020

Date	Product	From	Found by	Note
June 11	Frozen salmon	Not reported	Xinfadi market (XFDM), Beijing city	SARS-CoV-2 was found on frozen seafood in China for the first time.
July 3 to August 13	Frozen white shrimp	Ecuador	Dalian, Xiamen, and five other cities in Shandong Province	For the second time, SARS-CoV-2 was found on frozen seafood in China following a month after the COVID-19 outbreak in Beijing.
August 9	A variety of frozen seafood	Not reported	Dalian in Liaoning Province, Yantai in Shandong Province	
August 13	Frozen chicken wings	Brazil	Guangdong Province	
September 18	Frozen hairtail	Indonesia		
September 23	Frozen deepwater redfish	Norway		
September 24	Frozen cod outer package's surface	Not reported	Qingdao city, Shandong Province	This is the first time worldwide, SARS-CoV-2 was isolated from the frozen fish outer package's surface. The virus has not been isolated due to the low nucleic acid concentration of the samples (from the outer package's surface) tested.
September 25	Frozen hairtail	Brazil		
October 1	Frozen boneless beef	Brazil		
October 17	Frozen cod	Not reported	Qingdao Port, Shandong Province	
October 31	Frozen pomfret	Ecuador		
November 6	Aquatic product	Russia and Netherlands		
November 7–8	Frozen pork and frozen hairtail	Germany and India	Tianjin city	No community transmission has occurred.
November 10	Frozen pomfret	Indonesia		
December 9	Frozen boneless beef	Brazil		
December 17	Frozen cod	Not reported	Dalian in Liaoning Province	No community transmission has occurred.

Note: Most of the messages have been reported on the globaltimes, China (https://www.globaltimes.cn/).

infected, at least 38 individuals had links to local seafood importing companies (CGTN, 2020).

On September 24, 2020, two stevedores at Qingdao Port were identified as asymptomatic infected patients. After epidemiological investigation, it revealed that both cases had no COVID-19 case contact history and no foreign personnel contact history. However, both carried out loading and unloading works of frozen cod in bulk on September 19, 2020. Subsequently, the surface swab samples of the frozen cod outer package were collected and tested; out of 421 surface samples, 50 were tested SARS-CoV-2 nucleic acid positive (Liu et al., 2020). This is the first time worldwide wherein SARS-CoV-2 was isolated from the imported frozen cod outer packaging surface. However, the live virus has not been isolated from the samples of the outer packaging surface due to the low nucleic acid concentration of the samples tested. A total of 10.9 million people had been tested by qRT-PCR before October 16, and another nine cases related to the initial cluster were identified for a total of 12 cases (Xing et al., 2020). Presumably, the frozen food-importing industry could bring in the SARS-CoV-2 virus (Liu et al., 2020; Pang et al., 2020; Sun et al., 2021). Despite this, SARS-CoV-2 has been isolated from the samples of the outer packaging surface of frozen cod and its packages. It is still a lack of directly strong evidence of cold-chain food contamination with the COVID-19 virus. It is well established that the main route of virus transmission to be person-to-person by respiratory droplets (Anderson et al., 2020; Zhang et al., 2020). Therefore, it cannot be excluded that the cold-chain food contamination is transmitted by the stevedores or international workers in Qingdao Port.

4 | SURVIVAL AND INACTIVATION OF SARS-CoV-2 IN FOOD

WHO has recommended hand hygiene formulations and alcohol-based sanitizers to inactivate SARS-CoV-2 (Kratzel et al., 2020; Suchomel et al., 2020). SARS-CoV-2 appears to be stable at different pH (3–10) at room temperature. Heat, sunlight, and UV light appear

TABLE 2 Inactivation of SARS-CoV-2 by different types of disinfecting agents or treatments

Disinfectants/methods	Working concentration or condition	Treatment time	Reduction of the virus titer	References
Heat treatment	>75°C	45 s to 5 min	N/A	Chen (2020)
Sodium hypochlorite	0.05% (500 ppm)	5 min	SARS-CoV-2 reduced by about three logs	Chen (2020)
Simulated sunlight	Simulated saliva on stainless steel coupons	~7 min	90% of the virus inactivated	Ratnesar-Shumate et al. (2020)
Silicon nitride	15 wt% aqueous suspensions	1 min	Inactivate 99% of SARS-CoV-2	Pezzotti et al. (2020)
Heat treatment	70°C	5 min	SARS-CoV-2 reduced by about seven logs	Chin et al. (2020)
Short-wavelength ultraviolet light (UV-C)	Irradiation	15 min	>99.9% reduction of infectious titers	Criscuolo et al. (2021)
UV-C	Irradiation 3.7/16.9 mJ/cm^2	Accumulated irradiation by 3.7/16.9 mJ/cm^2	Three-log inactivation for 3.7 mJ/cm^2 and complete inactivation by 16.9 mJ/cm^2	Biasin et al. (2021)
Ozone (O_3)	4 ppm (gas exposure)	90 min	>98.2% viral titer reduction	Criscuolo et al. (2021)
275 nm UV-C LEDs	83.1 J/m^2 (irradiation)	1 min	Inactivate 99.9% of SARS-CoV-2	Trivellin et al. (2021)

Abbreviation: N/A, not applicable.

to inactivate the virus (Chin et al., 2020; Pressman, Naidu, & Clemens, 2020). At refrigeration temperatures (4°C), no loss of infectious titer for SARS-CoV-1 was found (Rabenau et al., 2005). Similarly, there was hardly any reduction in infectious SARS-CoV-2 noted in transport medium held at 4°C for 14 days (Chin et al., 2020; Harbourt et al., 2020). Dai et al. (2021) reported that SARS-CoV-2 in fish products could still be detected for more than 1 week at 4°C. Moreover, the virus may exist in food for a long time, and the virus infectivity may remain up to 2 years during frozen storage and transport at −20°C (Chin et al., 2020; Ling et al., 2020). Even so, a lack of enough evidence supports that cold-chain food can transmit SARS-CoV-2 (Finger et al., 2021). Therefore, some experts on food safety assume that it is highly unlikely that food consumption or touching food packages will result in the spread of SARS-CoV-2 (FDA, 2021; ICMSF, 2020). Therefore, the possibility of transmission of the COVID-19 virus through the food chain still needs to be investigated.

The U.S. Environmental Protection Agency, Health Canada, and the European Union Open Data Portal (EU ODP 2020) have a list of approved disinfectants for use to control or destroy harmful microorganisms, for example, SARS-CoV-2. SARS-CoV-2, like other viruses, cannot propagate in food; therefore, the number of infectious virions is expected to decrease if the virus is present on the surface of a food product (Pressman et al., 2020). Air disinfection could be considered in food-related environments. There are two practical methods, including room air cleaners, such as filters or UV light, and upper-room germicidal UV fixtures (Nardell & Nathavitharana, 2020). It has been shown that SARS-CoV-2 is sensitive to artificial sunlight when suspended in simulated saliva on stainless steel coupons; that is, 90% of the virus was inactivated in ~7 min (Ratnesar-Shumate et al., 2020). Irradiation by short-wavelength ultraviolet light (UV-C) is an effective method to inactive SARS-CoV-2 on solid surfaces, such as glass and gauze (Biasin et al., 2021; Criscuolo et al., 2021). A 275 nm UV-C LED has been used to inactivate 99.9% of SARS-CoV-2 by 83.1 J/m^2 irradiation for only 1 min (Trivellin et al., 2021; Table 2).

It was found that SARS-CoV-2 could be reduced by about seven logs after heat treatment of 70°C for 5 min (Chin & Poon, 2020). Furthermore, ANSES (2020) reported sufficient heat treatment and concluded that exposing food to 63°C for 4 min would be adequate to kill the virus (Table 2). A qualitative risk assessment conducted by the Food Standards Agency of the United Kingdom acknowledged that despite several uncertainties, temperatures used for cooking should be sufficient to inactivate any virus present in food (Anelich et al., 2020; FSA, 2020).

The issue of survival and inactivation of SARS-CoV-2 on inanimate surfaces is also important (Anelich et al., 2020), although the U.S. CDC and the New Zealand Food Safety Science & Research Centre (NZFSSRC) do not consider contracting SARS-CoV-2 via contaminated surfaces a main route of transmission (CDC, 2021; NZFSSRC, 2020). Therefore, many disinfectants for inactivating SARS-CoV-2 are under investigation. The results have shown that silicon nitride (Si_3N_4) can inactivate 99% of the SARS-CoV-2 virus after exposure for 1 min, which showed it to be as effective as copper (Pezzotti et al., 2020). Thus, placing Si_3N_4 particles into the fabric of personal protective equipment or other materials could effectively limit viral spread and transmission. Sodium hypochlorite is also a potential virus disinfectant; 0.05% (500 ppm) treatment for 5 min could reduce SARS-CoV-2 to around three logs (Chen, 2020). Ozone (O_3) exposure is another alternative method to treat SARS-CoV-2 contaminated

goods that 4 ppm of O_3 exposure for 90 min can reach >98.2% viral titer reduction (Criscuolo et al., 2021; Table 2).

5 | CONCLUSION

While more data on how long the SARS-CoV-2 could remain viable and infectious under refrigerated and frozen temperatures are needed, we should still be highly alert to the possible risk of spreading SARS-CoV-2 through contaminated refrigerated or frozen food. At the community level, people may be exposed to contaminated food when buying groceries. At the national or regional level, the risk of transmission by cold-chain logistics of food between countries and regions cannot be completely ruled out. Therefore, the enhanced surveillance, regular SARS-CoV-2 detection, and fast identification of SARS-CoV-2-infected individuals among food industry workers may be warranted (Lacombe et al., 2020; Sun et al., 2021).

The successful SARS-CoV-2 virus isolation from the cold-chain seafood and the packaging surface proves that the imported virus that re-infected humans and caused the outbreaks through cold-chain transportation is possible. In the future, we should strengthen the inspection and quarantine of imported cold-chain food and pay more attention to the personal protection of relevant workers to better prevent and control COVID-19 (Liu et al., 2020; Pang et al., 2020).

According to the current survey and scientific studies, below are six key points that outline the impact of COVID-19 on cold-chain food contamination and food safety.

1. Cold-chain transportation in the frozen food industry may have caused the recurrence of COVID-19 cases in shipping destinations primarily due to the isolated SARS-CoV-2 from the imported frozen food and food package surfaces that were tested.
2. Although SARS-CoV-2 has previously infected some people who work in food production and processing facilities, no evidence showed that the virus spread and infected consumers via food or food packaging handled by those workers in these facilities.
3. Currently, there is no evidence that food is associated with the spreading of SARS-CoV-2, the virus that causes COVID-19.
4. The risk of infection by the virus from food products, food packaging, or bags is thought to be very low. Currently, no cases of COVID-19 have been identified as infected by touching food, food packaging, or shopping bags.
5. The current consensus is that SARS-CoV-2 will not or rarely spread through food or food packaging materials. However, it is very important to clean and sanitize food contact surfaces properly, since one mode of transmission of SARS-CoV-2 appears to be touching contaminated surfaces and then touching the mouth, nose, or eyes.
6. It is always important to follow good food safety practices to reduce the risk of illness from the COVID-19 virus and common foodborne pathogens.

In summary, although current evidence suggests that SARS-CoV-2 does not cause foodborne illness, the virus has caused significant disruptions to the global food supply chain. Thus, issues such as food security and food sustainability have been brought to the forefront in this pandemic, as well as the health of food workers from the farm through to retail and foodservice. For preventing the potential spread of the COVID-19 virus in the food chain, laws and regulations related to the production and sales of foods should be evaluated. Relevant departments of the food enterprise should strengthen the training of employees on epidemic prevention knowledge, using the epidemic prevention equipment rationally to avoid personal and food infection.

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DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs

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