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REVIEW

Can the coronavirus disease be transmitted from food? A review of evidence, risks, policies and knowledge gaps

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Abstract

The coronavirus disease 2019 (COVID-19) has brought speculations on possible transmission routes of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causal agent of the pandemic. Air pollution has been linked to increased risks of COVID-19 infection and mortality rates in regions with poor air quality, yet no retrospective study has been reported on foodborne transmission of COVID-19. While studies have shown that low temperature could dramatically prolong the persistence on SARS-CoV-2 and other coronaviruses, frozen and refrigerated foods have been widely overlooked as potential vectors in policy frameworks and risk mitigation strategies. Food transmission evidence has been disclosed in China early July 2020 by the detection of SARS-CoV-2 on frozen foods, including their packaging materials and storage environments, with two re-emergent outbreaks linked to contaminated food sources. The contamination risk is augmented by a complex farm-to-table process, which favors exposure to food workers and ambient environments. Moreover, the food cold-chain also promotes contamination because laboratory studies showed that SARS-CoV-2 remained highly stable under refrigerated, at 4 °C, and freezing conditions, from − 10 to − 80 °C, on fish, meat, poultry, and swine skin, during 14–21 days. While data are lacking on long-term survival and infectivity under these conditions, ample evidence has been shown on other coronaviruses, including SARS-CoV-1. We therefore hypothesize that contaminated cold-storage foods may present a systematic risk for SARS-CoV-2 transmission between countries and regions. Here, we review the evidence, risk factors, current policy and knowledge gaps, on food contamination and foodborne transmission of SARS-CoV-2.

Keywords Refrigerated · Frozen · Food · Coronavirus · Cold chain · Logistics

Abbreviations

ATP	Agreement concerning the international carriage of perishable footstuffs and on the special equipment to be used for such carriage
BCoV-88	Bovine coronavirus strain 88
CDC	Centers for Disease Control and Prevention
COVID-19	Coronavirus disease 2019
EEC	European Economic Community
EVOH	Ethylene vinyl alcohol
FDA	Food and Drug Administration
GB/T	Chinese GB standard
HCoV-229E	Human coronavirus 229E
MERS	Middle east respiratory syndrome
NHCC	National Health Commission of China
OSHA	Occupational Safety and Health Administration
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PVC	Polyvinylidene chloride
RNA	Ribonucleic acid
SARS-CoV-1	Severe acute respiratory syndrome coronavirus 1

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SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
$TCID_{50}$	Median (50%) tissue culture infectious dose
USDA	United States Department of Agriculture
WHO	World Health Organization
WP.11	Working party on the transport of perishable foodstuffs

Introduction

The coronavirus disease 2019 (COVID-19) pandemic was first identified in December 2019 in Wuhan, China, then identified as a public health emergency of international concern on January 30, 2020 (https://en.wikipedia.org/wiki/COVID-19_pandemic). On April 7, 2020, an interim guidance of the World Health Organization (WHO) and Food and Agriculture Organization stated that "It is highly unlikely that people can contract COVID-19 from food or food packaging. COVID-19 is a respiratory illness and the primary transmission route is through person-to-person contact and through direct contact with respiratory droplets generated when an infected person coughs or sneezes. There is no evidence to date of viruses that cause respiratory illnesses being transmitted via food or food packaging. Coronaviruses cannot multiply in food; they need an animal or human host to multiply (WHO-FAO 2020)." At that time food contamination appeared very unlikely since there were few relatively cases and fatalities, yet evidence of transmission by food is now mounting.

Eight months since the onset of the COVID-19 pandemic, more than 25.5 million confirmed cases, including 852,000 deaths, have been reported to the WHO (2020a). Understanding how the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causation agent of COVID-19, spreads within and across different communities and adopting appropriate control measures is imperative. Based on the current knowledge, SARS-CoV-2 is thought to spread principally via respiratory droplets—micronized blobs released from human airways as we cough, sneeze, or talk—and contact routes (WHO 2020b). While direct human-to-human transmission may occur by inhaling virus-laden airborne droplets or aerosols, transmission can also occur by SARS-CoV-2 viruses deposited on inanimate surfaces which could infect people via their eyes, noses, and mouths after touching these by hands. Other alternative routes SARS-CoV-2 may take to reach a new host include fecal-oral transmission and airborne transmission (Qu et al. 2020; Sun and Han 2020; Wang and Han 2020). High levels of fine particulate matter in air have been correlated to increased persistence of SARS-CoV-2 and higher infection and mortality rates (Roviello and Roviello 2020; He and Han 2020). Grocery stores, for instance, are considered a high-risk setting for virus transmission during COVID-19 due to a combination of risk factors in presence including their enclosed environments, frequently touched surfaces, high foot traffic and difficulty in maintaining physical distancing (Fig. 1).

Public health authorities including the WHO (2020c), the Centers for Disease Control and Prevention (CDC 2020a) and Food and Drug Administration (FDA 2020) in the United States, and other regional regulatory bodies (FSS 2020) advised that there is currently no evidence the novel coronavirus that causes COVID-19 can spread via foods, and did not expect that certain foods needed to be withdrawn. Although no direct link has been established between COVID-19 infection and foodborne transmission, a series of recent incidents highlighted frozen foods as carriers for the long-range transport of SARS-CoV-2 during the current pandemic. The earliest incident occurred on 12 June 2020 in the Xinfadi agricultural produce wholesale market in Beijing, where SARS-CoV-2 was detected on a cutting board used for processing imported salmon (Global Times 2020a). Although later investigations did not find conclusive evidence on its origin, this particular incident raised awareness by authorities and consumers on frozen foods as possible SARS-CoV-2 carriers. Since the beginning of July 2020, at least nine incidents of food contamination have been reported across the country, where SARS-CoV-2 was detected on imported foods, mostly on their packaging materials (Fig. 2). Most of those incidents traced to frozen shrimps imported from Ecuador, where novel coronavirus was found on their packaging materials, and in one particular case, SARS-CoV-2 was also detected on the interior of a shipping container. Notably, in the latest incident in Shenzhen, Guangdong province on August 12, 2020, local authorities found SARS-CoV-2 on the surface of a frozen chicken wing sample originated from Brazil, which became the first known case where the novel coronavirus was detected on actual food samples (SMHC 2020).

The frequent detection of SARS-CoV-2 in frozen foods suggest that these are not random, isolated incidents but rather alerting signs that viral contamination and foodborne transmission may present a systematic risk in the ongoing pandemic. This is plausible given that food contamination may occur via respiratory droplets, contact or other route, during the farming, processing, storage, transport, and retailing process where foods may contact with different workers and ambient environments in the "farm-to-table" lifecycle. It is particularly noteworthy that prior to the re-emergence of the first COVID-19 case on June 11, 2020, there had been no local transmission reported for 56 consecutive days in Beijing (China Daily 2020a). A total of 256 cases were confirmed over the next two weeks, with 98.8% of those linked to the Xinfadi market where a salmon cutting board was tested positive for SARS-CoV-2 (Xinhua News 2020).

Fig. 1 Routes of virus transmission in food retailing environment during the coronavirus disease 2019 (COVID-19) pandemic. Frozen and refrigerated foods as well as commonly touched surfaces including shared tongs, handles on bakery and refrigerated cabinets, shopping baskets, payment terminals are highlighted for their elevated risk of contamination by the virus. The optional wearing of face coverings by shoppers and staff reflects current regulatory guidelines

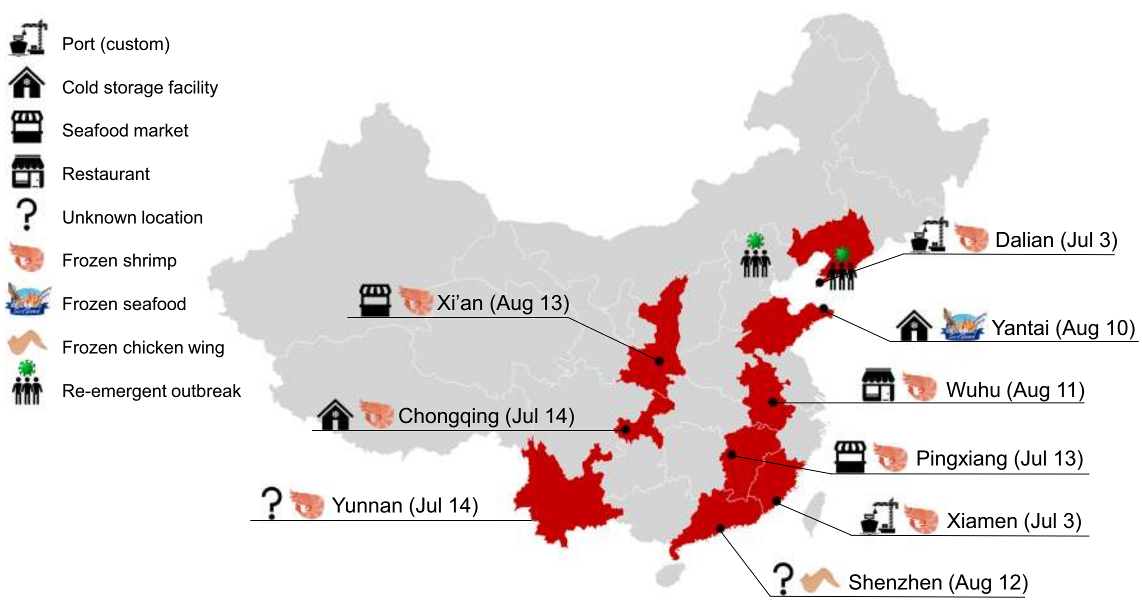

Fig. 2 Detection of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) on imported frozen raw foods across China between early July 2020 and mid-August 2020. Information was compiled from announcements by local authorities. In most cases, the novel coronavirus was found on food packaging materials, although it was also detected in food storage environment (Dalian) and food surface (Shenzhen). The percentage of positive samples found in each investigation was not specified in any of these reported incidents. According to the current standard, customs and public health authorities in China are required to test no more than 10 samples in each importation of animal products with over 10,000 units or 10,000 tons in total weight

Genome sequencing of the SARS-CoV-2 virus sampled from the Xinfadi market identified a European coronavirus strain, providing strong evidence that the re-emergent COVID-19 cases in Beijing may be caused imported sources rather than continued transmission of the local coronavirus strain (CCDC 2020). Similar connection was found in a re-emerged COVID-19 outbreak in Dalian, a coastal city in northeastern China where 87 confirmed cases were reported between July 9, 2020 and August 3, 2020. Among those infected, at least 38 individuals had links to a local seafood importing company (CGTN 2020). The Chinese Center for Disease Control and Prevention commented that given the fact that no new local COVID-19 case had been reported for more than 100 days, and the epidemic in Dalian had no specific connection with the outbreak in Beijing, imported seafoods contaminated with the virus were the more probable cause of the re-emerged outbreak (China Daily 2020b; Global Times 2020b).

It should be noted that prior to the recent detections and outbreaks, the COVID-19 pandemic had prompted speculations that the novel coronavirus may be transmitted via foodstuffs or packages. In the early discussions on COVID-19, foodborne transmission was postulated as a potential risk factor (Sharma et al. 2020), and precautionary measures were recommended for staff involved in preparing and distributing food (Eslami and Jalili 2020; Zuber and Brüssow 2020). In a brief discussion, Ceylan et al. (2020) pointed out that foodborne diseases caused by viral infections are common, and viruses can contaminate food in three pathways, namely via contaminated water in which shellfish grows or used for fruit washing after harvest, poor hand hygiene practices, and the consumption of animal-based products containing zoonotic viruses. The authors further pointed out that foodborne transmission of SARS-CoV-2 needs to be studied, with several tasks suggested for future studies. In a later commentary, Rizou et al. (2020) discussed safety measures needed in the food supply chain during the COVID-19 pandemic, and postulated that transmission may occur via frozen foods or packaging, although the likelihood would be lower after days of shipment.

Nevertheless, none of these scholarly discussions to date has accounted for any actual evidence (Ceylan et al. 2020; Rizou et al. 2020) or presented a focused view on this matter (Eslami and Jalili 2020; Sharma et al. 2020). This is mainly because the situation is rapidly evolving on COVID-19, particularly on viral contamination of foods and associated risks of SARS-CoV-2 transmission, which have only started attracting public and regulatory concerns after the recent events. Most of the evidence on SARS-CoV-2 detection on frozen foods appeared between July–August 2020, weeks or months later after the recent discussions on food-associated transmission of COVID-19 (Ceylan et al. 2020; Eslami and Jalili 2020; Rizou et al. 2020; Sharma et al. 2020; Zuber and Brüssow 2020). Further, studies on the stability of SARS-CoV-2 in food environments only began to appear in early July 2020 (Fisher et al. 2020; Harbourt et al. 2020). These critical developments called for an updated and more informed view on this matter, by reviewing new evidence, scholarly discussions, and current policy and knowledge gaps. In this article, we focus on cold-storage foods and their possible contamination by SARS-CoV-2 through the "farm-to-table" lifecycle, with an particular emphasis on the "cold chain" which plays a central role in the storage and distribution of foods in this category such as seafood, meat, fresh produce, and frozen food varieties. To this end, we present a critical assessment on the up-to-date evidence and information that are most relevant to the hypothesized routes of virus transmission via contaminated cold-storage foods, in the current COVID-19 context. The main points discussed are (1) risks of food contamination by SARS-CoV-2 through the "farm-to-table" lifecycle, including the "cold chain" (2) packaging materials and temperatures used for storing and transporting refrigerated and frozen foods through the "cold chain" (3) persistence of SARS-CoV-2 on food surfaces and in low-temperature environments, with references to other coronaviruses (4) risks and potential transmission routes of SARS-CoV-2 in the retailing environment (5) major gaps in current policies and knowledge to address food contamination and foodborne transmission as a risk factor during the current pandemic. We highlight these gaps to provide a point of reference for future studies and risk assessments on foodborne transmission of COVID-19 and other human respiratory pathogens during pandemics.

Food contamination and the cold chain

Cold-storage foods, including the refrigerated and frozen varieties, are often kept under a low temperature through much of the entire "farm-to-table" lifecycle (Mercier et al. 2017), which caters to the survival of SARS-CoV-2. In this process, they could be exposed to different food workers and ambient environments during their farming, processing, storage, shipment, and retailing (Fig. 3). Depending on the food type and storage condition, the process could take from a few days to several years, before they finally reach the consumers (Gogou et al. 2015; Mack et al. 2014). The logistics of preparing these foods from harvesting to consumption under a specific temperature range is commonly referred to as the "cold chain".

From the very beginning of the "cold chain", contamination may occur. With few exceptions, modern food industry often relies on centralized farming and processing to meet the large and growing demand of food consumption by consumers. Despite the ongoing pandemic, many countries and regions do not implement full mandatory requirements for

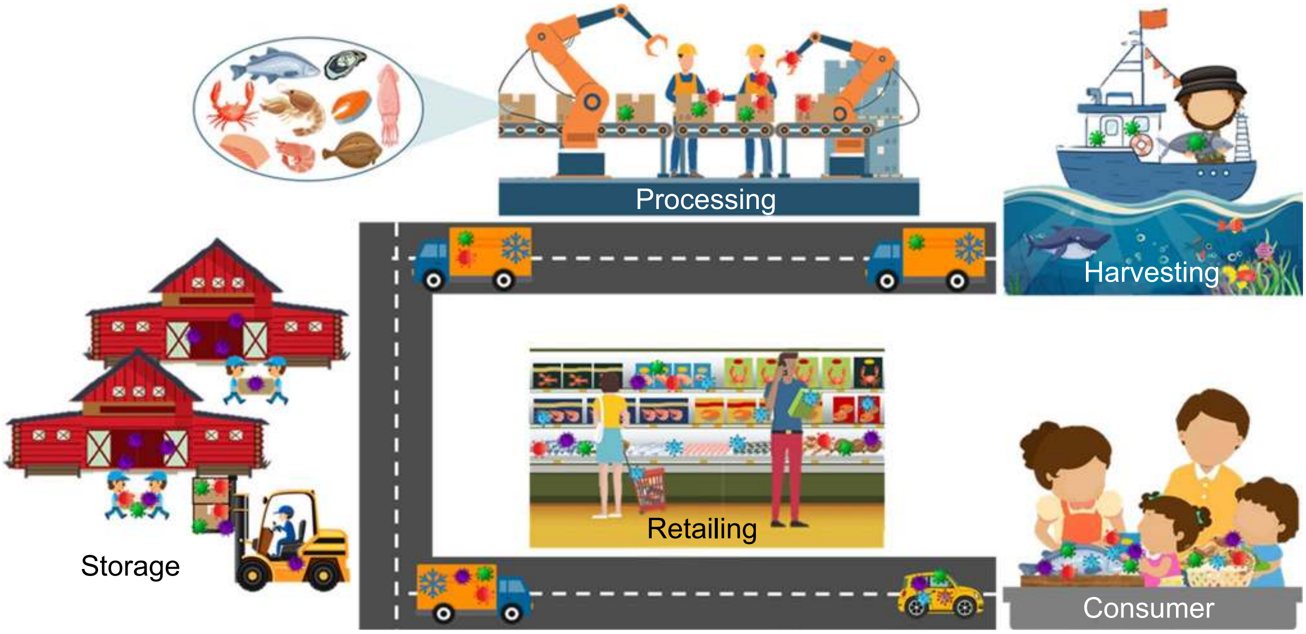

Fig. 3 Possible contamination of refrigerated and frozen foods during the coronavirus disease 2019 (COVID-19) by exposing to various food workers and environments in the entire "farm-to-table" process and the survival of the novel coronavirus throughout the "cold chain" of storage, transport, and retailing of these foods. Contamination may occur via respiratory droplets from infected individuals or contact routes via virus-laden hands, surfaces, and tools

food workers to wear face coverings and gloves when handling or processing food products (EU 2020; FDA 2020; FSS 2020). Food handlers who are infected with COVID-19 may have droplets expelled from their breathing, coughing, singing, sneezing, or talking (Anderson et al. 2020; Morawska and Milton 2020), contaminating foods and their packaging materials in proximity. Without appropriate personal protection equipment, non-symptomatic carriers may act as silent vectors and cause clustered infections in enclosed environments (Huff and Singh 2020; Zou et al. 2020). Since the onset of COVID-19, there have been a number of clustered outbreaks reported in food processing facilities. During April–May 2020, the CDC identified 16,233 cases of COVID-19, including 86 deaths, among the workers at 239 meat and poultry processing facilities located in 23 states (CDC 2020b). Lack of symptom screening, face coverings, and physical distancing were among the main factors that contributed to rapid spread of the virus to large numbers of persons at those facilities. Outbreaks of COVID-19 have also been reported in field workers in the seafood industry. In June 2020, 117 crew members on three commercial fishing vessels of the American seafoods company were tested positive for COVID-19 (KUCB 2020a). The American Dynasty, one of the vessels with 85 crew members on board infected, was a trawler with an onboard factory for processing, packaging, and freezing fish while at sea (KUCB 2020b).

Depending on the type of food processed, frozen foods can be packed in bags, pouches, lidded trays, boxes, cartons, or metal cans. Most of these food packaging materials are made of plastics, while other materials such as paperboard, molded paper pulp, or aluminum are also widely used. Among the types of plastics used, the most common ones are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinylidene chloride (PVC), and ethylene vinyl alcohol (EVOH) (Krochta 2016). Packaging materials create protective barriers between preserved foods and the ambient environment to prolong shelf lives. To maintain the quality of foods, temperature requirements exist in every step of the cold chain. For instance, the current standard in China (GB/T 24616–2019) on packaging, transport, and storage for chilled and frozen foods in logistics require refrigerated foods being kept below 8 °C and frozen foods being kept at or below − 18 °C before they are sold to the consumers. To facilitate international trades on foodstuffs, standardized requirements have also been put in place for transporting cold-storage food products between different countries and regions. On 21 December 1998, the European Commission adopted a Council Directive (89/108/EEC) on the approximation of the laws of the Member States relating to quick-frozen foodstuffs for human consumption, which requires temperatures of quick-frozen foodstuffs to be continuously maintained at − 18 °C or lower at all points, with the exception of edible ices (EU 2013). The United Nations Economic Commission for Europe have set up a working party (WP.11) on the transport of perishable foodstuffs, whose primary functions are to develop and update the “agreement concerning the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (ATP)” (UNECE 2020a). Signed by 49 countries including the USA, the ATP facilitates international transport of perishable foodstuffs by harmonizing regulations and requirements on refrigerated transportation of frozen food and chilled meat, poultry, dairy, fish, seafood, and fresh-cut vegetable products (UNECE 2020b). According to the ATP, the highest temperature of foodstuffs at any point of the load shall not exceed the indicated temperature in Table 1.

The continuous low-temperature environments during the storage and transportation of cold-storage foods create a favorable condition which can drastically prolong the survival of SARS-CoV-2, should they be contaminated during earlier harvesting or processing. Chin et al. (2020) measured the stability of SARS-CoV-2 at different temperatures and found that the virus was highly stable at 4 °C, showing only a 0.7 log-unit reduction of infectious titer after 14 days of incubation with an initial median (50%) tissue culture infectious dose ($TCID_{50}$) of ~ 6.8 log unit per mL. Matson et al. (2020) mixed SARS-CoV-2 with human nasal mucus and sputum and aliquoted the mixture (1×10^5 $TCID_{50}$/mL) onto polypropylene disks stored at 4 °C and 40% relative humidity. Compared with the results at higher temperatures (21 °C and 27 °C), SARS-CoV-2 showed significantly longer viability at 4 °C, and infectious virus can be detected on disk surfaces after 24–48 h. In a similar study, the stability of SARS-CoV-2 (9.6×10^4 $TCID_{50}$/mL, after 1 h drying) was examined on inanimate surfaces at different temperatures at a relative humidity of 30–40% (Kratzel et al. 2020). The virus titers remained stable over the next 8 h with minimal decline on metal disks, then showed a stable, slow decline within nine days at 4 °C. Other coronaviruses, including SARS-CoV-1, also showed prolonged persistence at low temperature (4 °C), ranging from 14 to 49 days when exposed on surfaces or in different media (Casanova et al. 2009, 2010; Gundy et al. 2009; Lai et al. 2005; Wang et al. 2005).

Table 1 Temperature conditions to be observed for the carriage of quick (deep)-frozen and frozen foodstuffs as per the “agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (ATP)”

Class	Temperature
Ice cream	− 20 °C
Frozen or quick (deep)-frozen fish, fish products, molluscs and crustaceans and all other quick (deep)-frozen foodstuffs	− 18 °C
All other frozen foodstuffs (except butter)	− 12 °C
Butter	− 10 °C

Based on version amended on July 6, 2020. Full text of the ATP agreement can be found on UNECE’s website (https://www.unece.org/trans/main/wp11/atp.html). The term “quick-frozen foodstuffs” means foodstuffs for human consumption which have undergone a freezing process known as “quick-freezing” whereby the zone of maximum crystallization is crossed as rapidly as possible, depending on the type of product, and the resulting temperature of the product (after thermal stabilization) is continuously maintained at a level of − 18 °C or lower at all points, as per the European Communities (Quick-Frozen Foodstuffs) regulations 1992

With respect to food environments, there has been only one study to date on the survival of SARS-CoV-2 on food surfaces. In a controlled laboratory study, Fisher et al. (2020) examined the persistence of SARS-CoV-2 on refrigerated and frozen salmon, chicken, and pork over a period of 21 days. The study found that the titers of SARS-CoV-2 remained virtually constant, and the inoculated viruses maintained their infectivity on both refrigerated (4 °C) and frozen (− 20 °C and − 80 °C) samples. In an earlier study conducted by United States Army Medical Research Institute of Infectious Diseases, researchers found that SARS-CoV-2 remained largely stable on swine skin throughout the 14 day experiment at 4 °C (Harbourt et al. 2020). Adding to the currently limited data, earlier studies provided ample evidence that other coronaviruses generally exhibited prolonged survival in food environments when stored at a low temperature. van Doremalen et al. (2014) inoculated the middle east respiratory syndrome coronavirus (MERS) at a $TCID_{50}$ of $10^{5.5}$/mL in unpasteurized cow milk. The study found that 44% of the infectious viruses could be detected after storing at 4 °C for 72 h. Mullis et al. (2012) used a bovine coronavirus strain (BCoV-88) as a surrogate coronavirus to study the persistence of coronaviruses on fresh produce under normal household refrigeration conditions. In diluted bovine fecal suspensions (0.1% and 10%), BCoV-88 retained infectivity for at least 14 days on fresh romaine lettuce in a refrigerator at 4 °C. Yépiz-Gómez et al. (2013) showed that human coronavirus 229E (HCoV-229E) survived well on lettuce, with a 0.2 log reduction after 2 days of storage at 4 °C.

Grocery stores and supermarkets are among the places with elevated risks of COVID-19 transmission due to the concurrent presence of multiple risk factors including an enclosed environment, difficulty in maintaining physical distancing, and many commonly touched surfaces and objects by different individuals (Fig. 1). The United Food and Commercial Workers announced that, as of July 17, 2020, there had been 12,405 grocery workers infected in its members. The results of a national poll of 4000 grocery workers in the USA highlighted the challenges grocery workers faced on the frontlines of the COVID-19 pandemic. Nearly 70% of the survey respondents admitted that employers were not enforcing mask mandates, and customers were not wearing masks or facing coverings during their shopping trips (UFCW 2020). Some retailers recommended their customers to keep social distance while they shop in stores (Tesco 2020; Walmart 2020). While physical distancing is generally effective in reducing direct human-to-human transmission, risk may arise from frequent contacts between customers and various items in store, including fresh produce, packaged foods, cabinets and shelves and some shared tools (Fig. 1). Any prior contamination by SARS-CoV-2 on food surfaces or food packaging materials may cause transmission to shoppers or staff via the contact route. Also, items and surfaces touched by different individuals in store may act as an environmental medium transmitting the virus across those who visited the store. For instance, grocery stores usually require customers to use tools and prevent direct hand contact with certain foods. Shared tools (*e.g.*, tongs, spoons, ladles) are often provided for customers to fetch desired items, such as bakery foods, chilled meat or seafood, live fish or lobsters, or food served at in-store deli bars. Unlike other inanimate surfaces such as shopping carts and weighing benches which must be regularly cleaned and disinfected during the current pandemic (CDC 2020c), these are often overlooked and not disinfected after use despite their frequent contacts with different customers. Others including handles on refrigerated and bakery cabinets, payment terminals (*e.g.*, with keypads or touchscreens), and checkout conveyors are also among the high-touch surfaces in the retailing environment which can be overlooked or difficult to access during routine cleaning and disinfecting. In addition, staff packaging foods, restocking shelves, or working at check-out counters may touch large numbers of items. Without appropriate personal protection equipment, any infected person carrying out these tasks can potentially become a "super-vector" and spread the virus over a large number of items.

Current policy and knowledge gaps

The different onset periods and control measures implemented by governments and regulatory bodies have contributed to a contrasting prevalence of COVID-19 infections in different geographic regions (WHO 2020a). While travel restrictions have been widely put in place for international travels (CAAC 2020; France Diplomacy 2020; INZ 2020; UAE 2020) and in some places, domestic travels (Chicago 2020; CT 2020; MA 2020), few restrictions exist on the freight of consumer goods, including foodstuffs (UNECE 2020b; NZCS 2020). Since SARS-CoV-2 has high stability under low temperatures (Chin et al. 2020; Fisher et al. 2020; Kratzel et al. 2020), consumer goods constantly kept under low temperatures such as chilled and frozen foods may become vectors in the current pandemic allowing long-range transport of SARS-CoV-2 in international trades and inter-regional transport of these goods. Although the likelihood of food-to-human transmission is considered lower when compared with other routes such as respiratory droplets and fomites, these should not be neglected as a risk factor given the large volumes of refrigerated foods being transported across different countries and regions, the personnel and complex environments they could be exposed to through the "farm-to-table" lifecycle, and their eventual human contact with a large consumer base.

Before the recent incidents of food contamination and re-emergence of COVID-19 outbreaks associated with imported foods, the General Administration of Customs of China had directed some of its branches to inspect imported foods for possible SARS-CoV-2 contamination while ensuring normal trade activities (China Daily 2020c). While this precautionary approach was widely applauded by consumers, it should be pointed out that based on current Chinese standards on sampling of imported animal products (GB/T 18088–2000), customs are required to only inspect a maximum of 10 samples for each importation of animal products even in quantities over 10,000 units or 10,000 tons. The rather limited numbers of samples being tested makes it questionable whether such a sampling protocol would make reliable or meaningful predictions on the presence of SARS-CoV-2 on goods under scrutiny, especially when large quantities are present. On the other hand, testing a sufficiently representative number of samples (*e.g.*, $> 1\%$) would create a daunting task for their staff performing such tasks. This creates a dilemma for authorities given their limited capacity in carrying out such tests and the large volumes of freighted goods imported on a daily basis. Also, since health authorities only began to report their inspections on imported foods from July 2020, it remains to be seen if more cases will emerge in the near future on other types of cold-storage foods or foods imported from other geographic regions, other than these reported to date (Fig. 2).

Recent clustered COVID-19 infections at meat and poultry processing facilities also prompted concerns that these locations may be potential "hot spots" of COVID-19 infections which may lead to large-scale food contamination. The National Health Commission of China (NHCC) has ordered domestic meat processing plants to identify the origins of their poultry and livestock and only accept certified imports showing negative nucleic acid test results for SARS-CoV-2 (China Daily 2020d). In a set of guidelines issued on July 21, 2020 for preventing and controlling COVID-19 infection in domestic meat processing facilities, NHCC required facilities located in medium- and high-risk areas to take five environmental samples daily from each of their slaughtering, dissecting, and packaging operations for nucleic acid tests to detect SARS-CoV-2. Those in low-risk areas must conduct tests on environmental samples at least once a week, following the same sampling and testing protocols (NHCC 2020). At the other end of the spectrum, on July 1, 2020, the U.S. department of agriculture (USDA) denied a petition requiring all processing plants operating in the USA and all facilities shipping meat and poultry products into the USA to test their products for the presence of SARS-CoV-2 (USDA 2020). In their response, the USDA food safety and inspection service stated that public health and food safety experts found no evidence to support the transmission of COVID-19 associated with meat and poultry products, and therefore would not require testing on these products and reporting results. To mitigate the risks of COVID-19 spread in meat and poultry processing facilities, the CDC and the occupational safety and health administration (OSHA) issued an interim guidance to meat and poultry processing workers and employers, which recommends wearing face coverings and social distancing (CDC 2020d). However, the current guidance, updated on July 9, 2020, does not require testing for SARS-CoV-2 on food or environmental samples at these facilities. Further, symptom screening was suggested only as an optional strategy that employers may use (CDC 2020d). In an interim guidance addressing food safety control, the WHO noted that reduced capacity in public sector laboratories presented a particular challenge for ensuring food safety during COVID-19, as these had been reallocated to test clinical samples of COVID-19 (WHO 2020c).

Major knowledge gaps exist on understanding the risks of cold-storage foods as long-range carriers and transmitting media of COVID-19. SARS-CoV-2 is the latest member of the coronavirus family of viruses to emerge globally. Based on the current knowledge, both ambient temperature and substrate material significantly impact the persistence of the virus (Aboubakr et al. 2020). In general, low-temperature dramatically prolongs the lifespan of the virus, where a normal refrigeration temperature (4 °C) allowed them to persist for days to several weeks (Chin et al. 2020; Kratzel et al. 2020; Matson et al. 2020). Existing studies on coronaviruses suggest that they are highly stable in a frozen state, which could survive for up to 2 years at − 20 °C, according to the WHO (2020d). However, data are lacking on the long-term survival of SARS-CoV-2 under freezing temperatures (− 10 to – 20 °C) that are frequently encountered on the storage and transport of frozen foods (Table 1). There has been only one study to date examining the persistence of SARS-CoV-2 under freezing temperatures (− 20 and − 80 °C). Since the duration of the study was limited to 21 days, and viral titers remained almost constant for the duration of the experiment, it remains unknown if SARS-CoV-2 would exhibit similar long persistence as other coronaviruses under those conditions. Further, although the study showed similar persistence of SARS-CoV-2 on three food surfaces (salmon, chicken, and pork) with the 21 days study period, earlier studies showed that the substrate material had a significant impact on the viability of SARS-CoV-2 (Aboubakr et al. 2020), even under a low temperature (4 °C) (Harbourt et al. 2020). For instance, low surface permeability of the substrate material may correlate to longer survival of the virus (Chin et al. 2020). Given that fish, meat, and dairy products often contain water, the survivability of SARS-CoV-2 in ice or deposited on ice surface should be investigated which can be particularly relevant when examining the persistence of SARS-CoV-2 on frozen foods. Further, since infectivity is dependent on viral ribonucleic acid (RNA) load (Han et al. 2020), prospective studies detecting SARS-CoV-2 on food surfaces or food packaging materials should also examine the viral loads, preferably on actual food samples. This information will be crucial to determine the likelihood of COVID-19 transmission via contaminated foods.

Consumer behaviors form an integrated part of any risk assessment on contaminated consumer goods. The COVID-19 emerging globally has a profound impact on consumer behavior regarding their food choices and shopping habits (Li et al. 2020; Richards and Rickard 2020; Schmidt et al. 2020). Recent surveys indicated a change of consumers' attitude on frozen foods during COVID-19. A survey commissioned by the American Frozen Food Institute showed that 86% of the survey respondents ($n = 1014$) in the US purchased frozen food items between early March and mid-April 2020, including 7% new frozen food buyers who rarely or never purchased such products pre-pandemic (AFFI 2020). Also, about half of the respondents who bought frozen foods since the onset of COVID-19 anticipated that they would buy a lot more (18%) or somewhat more (32%) frozen foods over the next few months. In the same vein, a study conducted on behalf of the German Frozen Institute found that 98% of German households buy and use frozen food products during normal times. During the lockdown period, a third of those surveyed purchased more frozen products owing to their long shelf life which helped reduce the needs of grocery shopping (Deutsche Tiefkühlinstitut 2020). Whether such trends are representative of a wider change in consumer behavior regarding frozen food consumption during the current pandemic remains unclear. Meanwhile, statistical data on changes on consumers' food purchasing habits (Li et al. 2020; Schmidt et al. 2020), how they store and handle foods at home, and whether they adopt certain precautionary measures when handling raw foods are also critical for assessing the risks of transmission via cold-storage foods and further establishing polices, guidelines, and mitigation strategies during the current pandemic.

We wish to point out that these challenges come at a time when the pandemic has disrupted the global food production. Some communities are at increasing risks of suffering from food shortages (Farias and dos Santos Gomes 2020; Paslakis et al. 2020; United Nations 2020). In this context, viral contamination of foods and foodborne transmission of COVID-19 present even greater of a challenge for regulators and manufacturers to maintain food security and safety. The growing body of evidence on SARS-CoV-2 contamination on frozen foods, including their packages and storage environments, supported earlier postulated links to recent re-emergence of COVID-19 outbreaks in areas with long eradicated local transmission. While it is without any doubt that normal trades and transport of foodstuffs play an essential role in ensuring global food security, it is of utmost importance to attain a better understanding of how foods become contaminated in the "farm-to-table" process, the survivability and infectivity of SARS-CoV-2 in foods and low-temperature food storage environments, and finally, the potential routes of transmission via contaminated foods in different environments from the initial food harvesting to the intermittent storage and handling in households. With recent evidence and studies raising alerts on these issues, regulatory bodies should adopt a proactive approach and lead the current research efforts on assessing and mitigating risks associated with foodborne transmission of COVID-19.

Conclusion

Foodborne transmission has been postulated as a risk factor in early scholarly discussions on COVID-19. While governments and regulatory bodies have taken different stances on this matter, evidence started to emerge since mid-June 2020, with at least two re-emerged outbreaks in China linked to food contamination by SARS-CoV-2, the causation agent of the COVID-19 pandemic. The presence of SARS-CoV-2 was detected on frozen foods, including packaging materials and storage environments, with 9 incidents reported by health authorities across the country between early July and mid-August 2020. Further, latest laboratory studies found new evidence that SARS-CoV-2 remained highly stable on meat, fish, and animal skin for the entire duration of studies (14–21 days) at both refrigerated (4 °C) and freezing temperatures (− 20 and − 80 °C). These new developments necessitated a fresh and closer look at this issue by assessing the risks of food contamination and routes of transmission in the "farm-to-table" lifecycle, including field harvesting, processing and handling, transport, and retailing, with a focus on the "cold chain". The continuous low-temperature environment kept through the storage and transport of refrigerated and frozen foods can dramatically prolong the survival of SARS-CoV-2, a characteristic commonly observed on other coronaviruses. When deposited on surfaces, SARS-CoV-2 showed higher persistence on plastics, which are extensively used in food packaging. Since the onset of COVID-19, focuses have been put on restricting travels, exposure to crowds and frequently touch surfaces in public places, while few restrictions exist on the freight of consumer goods. This leaves a gap for contaminated consumer foods, especially refrigerated and frozen varieties, to become long-range carriers of SARS-CoV-2, posing a systematic risk that has yet to be assessed during the current pandemic. Current sampling protocol greatly limits the capacity for health authorities to assess the true prevalence of SARS-CoV-2 contamination in imported animal products. Although regulatory bodies recently issued guidelines for the food industry, contrasting levels of vigilance are shown in current policy frameworks and control measures, some showing laxed regulations with few mandates issued despite the increasing body of evidence highlighting the risks in those environments. Major knowledge gaps exist in current literature on understanding the lifespan of SARS-CoV-2 in food environments under refrigerated and freezing conditions, especially in ice as a common substrate in frozen fish, meat, and dairy products. Further, information on consumer's changing attitude and behavior regarding the consumption of frozen foods during the pandemic, including shopping habits, storage, and handling at home is needed to assess the risks of virus transmission via contaminated food products. These gaps should be addressed to enable informed decision-making for establishing policy frameworks, risk mitigation strategies, and precautionary control measures on food contamination and foodborne transmission of pathogens. In addition, smart food packaging (Gaikwad et al. 2019; Pandit et al. 2017; Rai et al. 2019), biosensors (Brinda et al. 2018; Jyoti and Tomar 2017) and nanosensors (Kumar et al. 2017) for food safety may be explored as future technological solutions for the food industry to prepare for epidemics and pandemics to maintain a robust supply chain.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest in this work.

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