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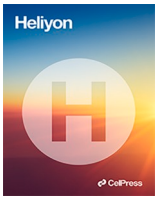

Review article

Lesson learned from COVID-19 pandemic for the future of food industry

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ABSTRACT

With WHO announcing COVID-19 no longer as a public health emergency of international concern (PHEIC) on May 5, 2023, coupled with the fact that the majority of the countries of the world have dropped strict city lockdown or border closure, this perhaps signals the end of the COVID-19 crisis caused by the SARS-CoV-2 virus. However, the COVID-19 pandemic has resulted in far-reaching effects affecting nearly every aspect of our lives and society. Notably, the food industry including agriculture, food manufacturers, food logistics, distributors and retailers have all felt the profound impact and had experienced significant stress during the pandemic. Therefore, it is essential to retrospect the lessons that can be learned from this pandemic for the food industry. This short review aims to address the food safety issues related to the COVID-19 pandemic by focusing on its foodborne transmission potential, innovations of virus detection strategies suitable for food industry; development of phathogenicaidal methods and devices to inactivate SARS-CoV-2 virus (particularly in industrial scale); and the set-up of related food regulations and guidelines as preventive and control measures for preventing the spread of SARS-CoV-2 virus through the food supply chain during the pandemic. This article may provide useful references for the food industry to minimize the food safety impact of COVID-19 (as well as other respiratory virus) and allows them to better prepare for similar future challenges.

1. Introduction

Coronavirus disease 2019 (COVID-19) is a contagious disease caused by the virus SARS-CoV-2. Since the initial outbreak in 2019, the virus quickly spread worldwide and resulted in a global pandemic. Fortunately, implementation of preventive measures including vaccination along with social distancing, quarantining, travel-related control measures, and appropriate personal hygiene help minimize the pandemic impact and bring the pandemic under control. On May 5, 2023, the World Health Organization (WHO) announced that COVID-19 is no longer a public health emergency of international concern (PHEIC).

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However, the COVID-19 pandemic has profoundly influenced our societies and economies. For instance, the impacts of this pandemic on the food industry including agricultural sustainability, food manufacturers, food logistics, distributors and retailers could not be overlooked [1–3]. Particularly, COVID-19 is a contagious respiratory disease and thus transmission can occur in crowded workplaces such as food factories. Although it might be possible to reduce the risk of virus transmission by avoiding direct contact and switching to online work model for certain industries, however, for the food industry, it still requires large quantity of employees to work on-site. Meanwhile, survey also showed that the public was also concerned about potential virus contamination in foods. Thus, insights into these topics may provide valuable experience and guidance for the food industry.

Therefore, it is essential to retrospect the lessons that can be learned from this pandemic for the food industry. Here, by summarizing the available findings related to the following topics (including the risk for SARS-CoV-2 contamination and transmission in food industry; the efforts and security measures to prevent the spread of COVID-19 through the food supply chain; the novel detection methods for SARS-CoV-2 for foods; the development of pathogenicidal methods against SARS-CoV-2 in food production; and the relevant regulations and guidelines for food manufacturers), the collect information may help us better understand the potential sources and transmission pathways of SARS-CoV-2 in the food industry. Meanwhile, it could also provide valuable references for preventing the transmission of SARS-CoV-2 as well as other foodborne microorganisms in food industry, and promote the establishment of effective prevention and control measures to cope with the similar situation in future and protect public health.

2. Methods

To fulfill the above aim, the articles related were searched from Web of Science, PubMed, Google Scholar, CNKI, Baidu Scholar, WIPO, CNIPA up to Aug 2023. Search strategies for each database were developed using the following terms: “COVID-19” or “SARS-Cov-2” or “Coronavirus” or “2019 novel coronavirus”; “detection” or “PCR” or “LAMP” or “CRISPR-Cas” or “Mass”; “disinfection” or “sterilization” or “irradiation” or “Ozone” or “PDT”; “Prevention guideline” or “control guidelines” or “packaging”.

Search results were managed using Endnote to remove the duplicates. Two reviewers (H. Yang and J. Hu) checked the search results to identify papers for inclusion, and any differences resolved through discussion with other two reviewers (B.K. Tan and S. Lin). The narrative review approach was adopted since the collected information covers multiple topics and the results cannot be pooled together for meta-analysis.

3. Results and discussions

3.1. Can food supply chain be a transmission route of COVID-19

COVID-19 is a severe respiratory disease caused by the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). Respiratory droplet and contact transmission were the most common transmission routes of SARS-CoV-2, while aerosol and fecal-oral transmission were also reported [4]. Currently, it is still debatable whether the SARS-CoV-2 virus could be spread through the handling or consumption of food. According to the report released from the Centers of Disease Control and Prevention (CDC), SARS-CoV-2 is highly unstable outside of the host and will die quickly on foods, making the transmission of the SARS-CoV-2 virus

Table 1
Incidents of SARS-CoV-2 contamination in foods.

Country	Date	Contaminated Foods	Key information
Canada	May 2020	Poultry	There were 18 food inspectors infected with COVID-19 at Cargill’s meatpacking plant in High River, Alberta. There were 64 employees infected with COVID-19 at the Cargill-owned processing plant in Quebec [13].
China[a]	Aug 2020	Frozen chicken wings	Cold chain food was ranked and tested in Longgang District. One frozen chicken wing surface sample from Brazil was found to be positive for viral nucleic acid testing.
China[a]	Jan 2021	Ice cream	Three ice creams from Tianjin Bridge Road Food Company tested positive for SARS-CoV-2 nucleic acid.
China[a]	July 2021	Rice	The import of rice was suspended after the virus was found on bags of imported Pakistani rice.
China[a]	Mar 2022	Dairy products	Dairy products tested positive for SARS-CoV-2 nucleic acid on the sample of the outer packaging of the adhesive bundle film. The goods were all destroyed and did not enter the market.
China[a]	July 2022	Mango	Twenty boxes of Mango that were imported from Macau tested positive for SARS-CoV-2. The goods were all destroyed and did not enter the market.
Germany	May 2020	Poultry	Over 200 employees were infected with COVID-19 at a meat packing plant in the city of Coesfeld [14].
Germany	June 2020	Poultry	Six hundred and fifty workers confirmed COVID-19 infections at the meat processing plant Tönnies in North Rhine-Westphalia [15].
UK	June 2020	Poultry	Poultry meat manufacturers 2 Sisters Foods, Rowan Foods, and Kepak Ltd shut down and closed due to the outbreak of COVID-19 [16].
US	Apr 2020	Poultry	By April 23, 115 meat or poultry processing facilities reported COVID-19 cases with 4913 workers were diagnosed of COVID-19 (overall infection rate at 3.0 %). Twenty COVID-19 related deaths were reported among workers [17].

[a] Sources : Chinese Center for Disease Control (www.chinacdc.cn).

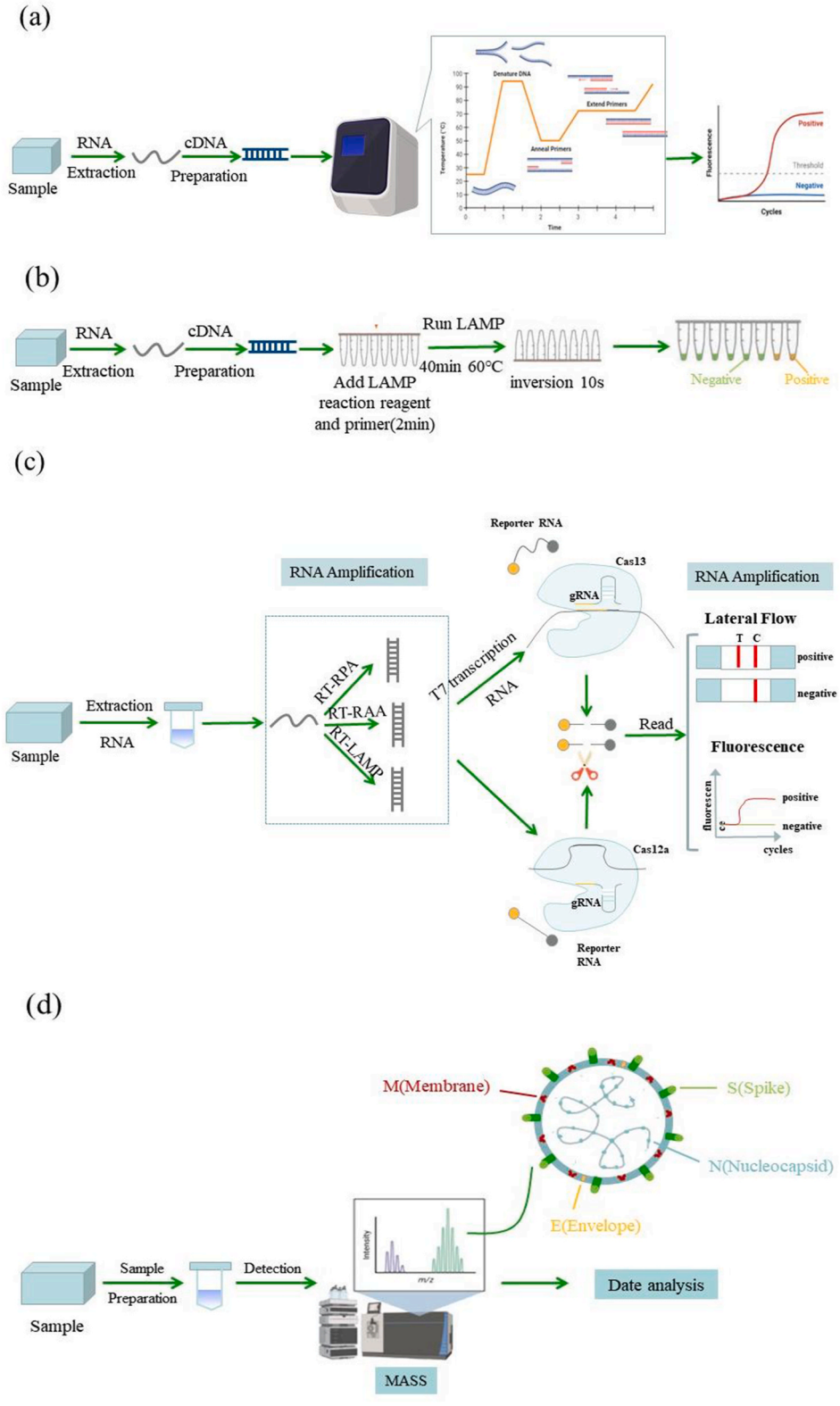

Fig. 1. The schematic illustration of detection methods of SARS-CoV-2
(a) Real-time PCR; (b) Loop-Mediated Isothermal Amplification (LAMP); (c) CRISPR-Cas12/13 system; (d) Mass spectrometry.

Table 2
Primers and probes for the detection of SARS-CoV-2 by Real-time PCR.

Target gene	Forward primer	Reverse primer	Probe	Reference
Orf1ab region	CCCTGTGGGTTTTACACTTAA	ACGATTGTGCATCAGCTGA	5′-FAM-CCGTCTGCGGTATGTGGAAAGGTTATGG-BHQ1-3′	China Association for Quality Inspection [29]
N	GGGGAACTTCTCCTGCTAGAAT	CAGACATTTTGCTTCAAGCTG	5′-FAM-TTGCTGCTGCTTGACAGATT-TAMRA-3′	
E	TGCGTACTGCTGCAAT	GGAACTCTAGAAGAATTCAGAT	5′-FAM-TTAACGTGAGTCTTGTAAAACCTTCTT-BHQ1-3′	
N	AATTCTAATACGACTCACTATAGGG ACTACAGATAGAGACACCAG	GGCTAGACTTTATTATGATTCAA	5′-YakimaYellow-CGCGAAGCTCTATTCTTTGCACTAATGGCATTCGCG-BHQ1-3′	Vahid Kia et al. [34]
RdRp	AATTCTAATACGACTCACTATAGGGAGGTTAATGTTGTCTACTGTT	TGGTTATCTTACTTCTTCTTCTA	5′-FAM-CGCGAAATCCTACCACATTCCACCTAGATGGTCGCG-BHQ1-3′	
RdRP	AGAATAGAGCTCGCACCGTA	CTCCTCTAGTGGCGGCTATT		Myungsun Park et al. [35]
S	GCTGGTGCTGCAGCTTATTA	AGGGTCAAGTGCACAGTCTA		
N	CAATGCTGCAATCGTGCTAC	GTTGCGACTACGTGATGAGG		

through food highly unlikely [5]. However, there are also reports of SARS-CoV-2 contaminated food (Table 1). For example, China National Center for Food Safety Risk Assessment Center reported a positivity rate for tests on food packages that was 0.48 per 10,000 [6]. Routine sampling and surveillance of SARS-CoV-2 on the imported food arriving in Tianjin also reported the positive testing of SARS-CoV-2 in imported pork in November 2020. Furthermore, three COVID-19 cases were traced and confirmed by workers involved in handling these contaminated imported foods [7]. Therefore, there has been widespread concerns regarding food contaminated food by the SARS-CoV-2 virus and the spread of the COVID-19 pandemic.

Admittedly, the number of COVID-19 positive samples in these reports are at a very low level. In addition, evidence to date only demonstrated the presence of virus genetic material but not the live virus [8]. Therefore, many scholars believe that the risk of foodborne transmission of SARS-CoV-2 is low. However, there are also warnings that food may be a pathway for SARS-CoV-2 transmission since COVID-19 may have the potential for "substance-to-human" transmission. An epidemiological investigation of a cluster of COVID-19 cases in the Beijing market suggested that environmental to human transmission might have occurred between a merchant and SARS-CoV-2-contaminated salmon [9]. Similarly, in New Zealand, four COVID-19 infected cases were reported in August 2020 with one of whom being a worker engaged in handling frozen food, while no other new infection was identified for more than 100 days in the country before this outbreak [7]. Meanwhile, infected workers might also spread the virus in the food supply chain. Indeed, the Food and Environment Reporting Network reported that no less than 88,203 workers in at least 1399 meat processing plants and food processing facilities in the United States were tested positive for COVID-19 b y March 11, 2021 [10].

Notably, cooler temperatures could effectively slow the inactivation of SARS-CoV-2, which means frozen foods possess higher risk for SARS-CoV-2 contamination and transmission. Experts had already proved that the SARS-CoV-2 could survive for a long time on cold-chain food overpacks [11]. Furthermore, Dale Fisher et al. reported that SARS-CoV-2 titers remained constant over 3 weeks in chicken, pork and salmon stored at low temperatures [12]. In summary, the majority of SARS-CoV-2 food contamination incidents have been associated with frozen foods (Table 1).

Although the current evidence suggests that the risk of transmission of the SARS-CoV-2 virus through food is low, modern food supply chains have successfully demonstrated its extremely high transmission efficiency resulting from the centralization of food storage and distribution that few modern food factories nowadays could process huge quantify of primary products and distribute processed food nationwide or even globally. Therefore, the virus contaminated foods could rapidly affect large numbers of people in a short time. Therefore, the potential danger of foodborne transmission of the SARS-CoV-2 virus (as well as other foodborne virus in future) remains a significant problem and cannot be overlooked.

Furthermore, concerns about SARS-CoV-2 virus contamination on food raw materials also greatly disrupted the food supply chain [18,19] and induced logistical challenges [20,21], which caused far-reaching economic consequences for national and global levels [22,23]. For example, it has been reported that SARS-CoV-2 could be potentially spread to animals (eg. pets, livestock and poultry) from human, particularly in close contact environments [24,25]. Thus, poultry industry in several major countries such as China, US, UK, and Germany, were significantly influenced by COVID-19 [26] although no evidence was found indicating that SARS-CoV-2 can be transmitted to humans *via* poultry products.

3.2. Current detection methods for SARS-cov-2 in food

Since the frequency of SARS-CoV-2 contaminated food incidents has increased, rapid and accurate detection methods for SARS-CoV-2 virus is in great need to ensure the food safety. Currently, real-time PCR and LAMP techniques are the most common methods to detect the SARS-CoV-2 in foods with other novel methods being also reported. The recent development of detection techniques for identifying SARS-CoV-2 in food products are described below.

3.2.1. Real-time PCR techniques

Real-time PCR was a rapid and accurate method for detecting the virus with high sensitivity, specificity, and well-established technology development. Currently, it is the most widespread method for detecting SARS-CoV-2 (Fig. 1(a)) [27]. According to the World Health Organization (WHO), the gold standard method to detect SARS-CoV-2 is real-time PCR with TaqMan probes [28], which could precisely detect the presence of the SARS-CoV-2 virus in foods and on food packaging surface [29].

Currently, a number of primers and probes have been designed and optimized for real-time PCR analysis of SARS-CoV-2 (Table 2). The commonly selected target genes include RdRp gene and N gene, while E and S genes were also available. Notably, András Zóka et al. [30] reported that the viral Orf1a-related RdRp sequence was less detectable than the N gene, therefore, the real-time PCR targeting viral Orf1a-related RdRp sequence was prone to result false negatives.

In addition, both China and the United States reported the reliability problems of the commercial real-time PCR test kits at the beginning of the COVID-19 outbreak [31,32]. The Czech Republic also reported incorrect results for ~80 % of the test kits purchased from China [33]. Therefore, the specificity and sensitivity of the primer sets should be carefully optimized and validated since the accuracy of real-time PCR for SARS-CoV-2 detection is highly dependent on the choice of primer sets.

3.2.2. LAMP detection techniques

The Loop-mediated Isothermal Amplification (LAMP) technique has become an important molecular tool for the detection of pathogenic microorganisms with a number of advantages such as low-cost, providing a visual readout, operation at a constant temperature. Indeed, this diagnostic tool has also be tailored for the detection of SARS-CoV-2 (Fig. 1(b)).

For instance, Nuttada Panpradist et al. [36] established a highly sensitive visualization method for SARS-CoV-2 detection based on LAMP. It can detect down to 0.38 SARS-CoV-2 RNA copies/μl and can report in 17 min for high–viral load samples (5000 copies/μl).

Detection performance was comparable to real-time quantitative PCR with detectable template concentration. In addition, Yang et al. [37] also proposed a hydrogel-mediated LAMP method for the ultra-rapid and absolute quantitative detection of SARS-CoV-2 on cold-chain fruits. Its applicability was successfully tested in a number of cold chain fruits, including longan, kiwi, dragon fruit, cherries, and bananas with good sensitivity and specificity. Furthermore, LAMP detection techniques also showed an excellent specificity, reproducibility and storage stability, which have been successfully used to test SARS-CoV-2 on various cold chain fruits. In conclusion, the LAMP detection techniques are promising tools for the rapid detection of SARS-CoV-2 and other pathogens in order to ensure food safety.

3.2.3. CRISPR-cas technology

CRISPR-Cas technology has rapidly evolved in the last decades, which has become a cutting-edged technique for rapid, sensitive, specific and field-deployable identification of specific nucleic acids. Therefore, the application of CRISPR-Cas based detection of SARS-CoV-2 has already been approved by FDA [38]. Particularly, the CRISPR-Cas based SARS-CoV-2 detection exhibits high specificity and sensitivity [39] (Fig. 1(c)).

For example, Liang et al. [40] demonstrated CRISPR-Cas12a system could be used to rapidly detect the variant genotypes of SARS-CoV-2 on the basis of CRISPR-Cas12a multiplex allele-specific assays. Jiang et al. [41] also reported CRISPR-Cas12a technology in combination with gold nanoparticle probes for detection of SARS-CoV-2. The results showed that this technical tool was able to clearly distinguish SARS-CoV-2 from other pathogens of high relevance. The results were in 95.12 % agreement with the clinically approved real-time PCR assay. James P. Brougthon et al. [42] also developed a lateral flow analysis on the basis of CRISPR-cas12 technology for easy and rapid detection. In addition, Ahmed Mahas et al. [43] constructed a novel miniature CRISPR-Cas13 system for the better detection of SARS-CoV-2. It is reasonable to predict that the CRISP-Cas based detection methods could be potentially further adapted and used in large-scale screening for diverse pathogens, including RNA and DNA viruses in future.

3.2.4. Mass spectrometry detection

SARS-CoV-2 viral particles contained S (spike), E (envelope), M (membrane), and N (nucleocapsid). They have been proven to be suitable diagnostic targets due to their high expression and accumulation during infection [44]. Therefore, mass spectrometry (Fig. 1(d)) could detect different specific fragments of SARS-CoV-2 (Table 3).

Table 3
Mass spectrometry for detecting different specific fragments of SARS-CoV-2.

Protein	Identified Peptides	Reference
M	VAGDSGFAAYSR	Gouveia et al. [47]
N	ADETQALPQR	
	AYNVTQAFGR	
	NPANNAAIVLQLPQGTTLPK	
	WYFYYLGTGPEAGLPYGANK	
S	LQSLQTYVTQQLIR	
	FQTLLALHR	
	HTPINLVR	
N	ITFGGPSDSTGSNQNGER	Nikolaev et al. [45]
	RPQGLPNNTASWFTALTQHGK	
	GQGVPINTNSSPDDQIGYYR	
	WYFYYLGTGPEAGLPYGANK	
	DGIIWVATEGALNTPK	
	NPANNAAIVLQLPQGTTLPK	
	MAGNGGDAALALLLLDR	
	MAGNGGDAALALLLLDRLNQLESK	
	RGPEQTQGNFGDQELIR	
	GPEQTQGNFGDQELIR	
	IGMEVTPSGTWLTYTGAIK	
	LDDKDPNFK	
	LDDKDPNFKDQVILLNK	
	KADETQALPQR	
	ADETQALPQR	
	KQQTVTLLPAADLDDFSK	
	QQTVTLLPAADLDDFSK	
	QLQQSMSSADSTQA	
M	LNTDHSSSSDNIALLVQ	Zecha et al. [48]
	VAGDSGFAAYSR	
	EITVATSR	
N	ADETQALPQR	
	AYNVTQAFGR	
	GFYAEGSR	
	QQTVTLLPAADLDDFSK	
	GQGVPINTNSSPDDQIGYYR	
	IGMEVTPSGTWLTYTGAIK	
	NPANNAAIVLQLPQGTTLPK	

Specifically, the S protein could generate more peptides for mass spectrometry detection. However, this protein is heavily glycosylated, which may affect its fractionation and ionization. The copy numbers of E, M, and N proteins are much larger than that of S, but the E and M are relatively short and tightly membrane-bound proteins, which makes them difficult to be extracted and detected [45]. N protein has abundant lysine (K) and arginine (R), which together account for 14.3 % of protein amino acid composition (Expasy ProtParam) and implicate 57 theoretical trypsin cleavage sites (Expasy PeptideCutter). Therefore, N protein could be easily for ionization and suitable for mass spectrometry detection [44]. Thus, the main target for the mass-spectrometry-based detection of SARS-CoV-2 is the N protein.

Notably, detecting SARS-CoV-2 virus in foods is often a complex and challenging task in practice. For example, foods such as red meat, poultry, and fish often contains abundant animal proteins, which can interfere the mass spectrometry analysis for virus. Meanwhile, in the case of plants, metabolites such as pigments, sugars, lipids, or waxes in the surface of fruits and vegetables make it necessary to establish cleaning stages before analysis by mass spectrometry. The availability of different resins for solid phase peptide extraction and protocols such as filter aided sample preparation (FASP) and combinatorial peptide ligand library (CPLL) could provide an alternative to digging deep in the proteome, allowing the confident detection of peptides or proteins associated with SARS-CoV-2 [46].

3.3. Disinfection and sterilization methods and devices for food manufacturers

The concern about foodborne transmission of COVID-19 and the presence of SARS-CoV-2 in a range of foods have urged researchers to develop a number of novel disinfection and sterilization methods and devices. As an enveloped virus, SARS-CoV-2 is highly sensitive

Table 4
Relevant studies and results of inactivation of SARS-CoV-2.

Inactivation method	Experimental Methods	Virus titer	Inactivation efficiency	Reference
Thermal inactivation	56 °C 30min 60 °C 60min 92 °C 15min	$3.3 \pm 2.3 \times 10^6$ $TCID_{50}$/ml	SRAS-CoV-2 viral titer reduction > 4 $log_{10}TCID_{50}$	Boris Pastorino et al. [65]
	70 °C 5min	6.8 log_{10} $TCID_{50}$/ml	SRAS-CoV-2 was inactivated effectively and couldn't reproduce	Alex Chin et al. [55]
	56 °C 15min	1.4×10^7 $TCID_{50}$/ml	The viral titer reduction: 3-4 $log_{10}TCID_{50}$	Tony T Wang et al. [66]
	56 °C 30min		The viral titer reduction: 7 $log_{10}TCID_{50}$	
	60 °C 15min		SRAS-CoV-2 completely inactivated and reduced infectivity	
UV inactivation	Waves:254 nm Doses:3.7 mJ/cm^2 Time:5s	MOI 0.05	SRAS-CoV-2 was inactivated effectively	Mara Biasin et al. [67]
	Waves:254 nm Doses:16.9 mJ/cm^2 Time:23s	MOI 5		
	Waves:254 nm Doses:84.4 mJ/cm^2 Time:114s	MOI 1000		
	Waves:280 nm Doses:3.75 mJ/cm^2 Time:1s	3.7×10^4 PFU/mL	The viral titer reduction rate: 87.4 %	Hiroko Inagaki et al. [68]
	Waves:280 nm Doses:37.5 mJ/cm^2 Time:10s		The viral titer reduction rate: 99.9 %	
	Waves:280 nm Doses:≥75 mJ/cm^2 Time: ≥20s		The viral titer reduction rate >99.9	
Ozone Inactivation	$C_{(O_3)}$ = 1 mg/L Time:5s	1.0×10^4 PFU/mL	The viral titer reduction rate: 81.4 %	Hiroko Inagaki et al. [69]
	$C_{(O_3)}$ = 4 mg/L Time:5s		The viral titer reduction rate:93.2 %	
	$C_{(O_3)}$ > 7 mg/L Time:5s		The viral titer reduction rate:96.6 %	
	$C_{(O_3)}$ = 500 ppm Time:20s	5 log_{10} $TCID_{50}$/ml	No reduction	Yohei Takeda et al. [70].
	$C_{(O_3)}$ = 1000 ppm Time:20s		The viral titer reduction rate:94.38 %	
	$C_{(O_3)}$ = 2000 ppm Time:20s		The viral titer reduction rate:98.46 %	
Electron beam inactivation	Radiation doses > 2 kGy	$1.0 \times 10^{4.6}$ $TCID_{50}$/ml	The viral titer reduction rate more than 99.9 %	Zihao Wang et al. [71]

to chemical and physical environmental influences (such as heat, UV rays) outside of the human body. Therefore, a range of traditional disinfectants and sterilization methods were found to be still effective against SARS-CoV-2. However, it is notable more factors (eg. safety, cost, eco-friendliness, speed) other than killing effect should also be considered when evaluate practical value of the sterilization methods in food industry. Therefore, careful evaluation of inactivation methods is required for eradication of SARS-CoV-2 in foods and food packaging. The following was an overview of several ways of disinfecting this virus.

3.3.1. Chemical disinfectants

Chemical disinfectants are widely used in food production processes such as food ingredients, food handlers, food production and food storage. There are common food disinfectants such as peroxide disinfectants, quaternary ammonium disinfectants and chlorinated disinfectants. In fact, most of these chemical disinfectants are proved to be effective in inactivating SARS-CoV-2.

For instance, 30–80 % ethanol, 30–75 % propanol, 0.45–7.5 % povidone-iodine, and 5–6% sodium hypochlorite were all proven to effectively kill SARS-CoV-2 at short exposure times [49]. These are permitted for use in the food industry and successfully tested against SARS-CoV-2. The sterilization effect could reduce viral infectivity by more than four orders of magnitude (99.99 % reduction) [50].

Common quaternary ammonium disinfectants, such as benzalkonium chloride (BAC) at 0.1 %, are also effective against SARS-CoV-2 but their applications often require long contact time. Indeed, previous tests showed that effective disinfection of coronaviruses using quaternary ammonium compounds (such as BAC) often requires 5–30 min [51]. Similarly, Mikrobac Forte, an aldehyde-free surface disinfectant consisting of BAC and dodecylallentriamine, was tested to sterilize SARS-coronavirus [52]. Results showed that, after 30 min, the disinfection was not as effective as using 80 % ethanol with only 30 s of exposure.

Notably, the efficacy of several other common disinfectants, such as hydrogen peroxide, is controversial in the food industry. Although enveloped viruses are more sensitive to hydrogen peroxide than non-enveloped viruses, it has been reported that hydrogen peroxide is inefficient in disinfecting coronaviruses. Hydrogen peroxide had little effect on SARS-CoV-2, achieving a poor viral infectivity reduction of 1–1.8 $\log_{10}$ in a work concentration of 1–6% after 30 s of exposition [53].

3.3.2. Thermal inactivation

Many studies showed that the persistence of SARS-CoV-2 was affected by a variety of environmental conditions, particularly temperature [54]. For example, Alex Chin et al. [55] reported that SARS-CoV-2 was highly stable at 4 °C but sensitive to heat. At 4 °C, there was only around a 0.7 log-unit reduction of infectious titre on day 14. With the incubation temperature increased to 70 °C, the time for virus inactivation was dramatically shorten to 5 min. Therefore, thermal inactivation can effectively reduce the titer of coronaviruses (Table 4). In general, the available data show that coronaviruses survive longer at low temperatures.

Although thermal inactivation is effective in inactivating SARS-CoV-2, there are some problems in the food industry. For example, thermal inactivation is not suitable for use on fresh food. More importantly, the long inactivation time is not adapted for the transport of foodstuffs, especially for the rapid passage of goods through customs.

3.3.3. Inactivation by UV irradiation

UV light is divided into three classifications: UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (200–280 nm). Viruses are susceptible to ultraviolet light at wavelengths approaching 253.7 nm [56]. Therefore, UV-C (200–280 nm) has been suggested to inactivate different viruses [57,58], including SARS-CoV-2 (Table 4). The direct absorption of UV-C photons through the nucleic acid base and/or coat protein leads to the generation of photoproducts that inactivate the virus was suggested to be one of the main UV-C-associated virucidal mechanisms [59,60].

Notably, the use of UV irradiation to inactivate SRSA-CoV-2 in food requires further investigation. The irradiation wavelength and UV dose have to be determined before large-scale application in the food industry. Meanwhile, the effects of UV irradiation on food products should be explored.

3.3.4. Ozone inactivation

SARS-CoV-2 belongs to the β-B group of coronaviruses with a diameter between 50 and 200 nm. Similar to other coronaviruses, the structure of SARS-CoV-2 consisted of core genetic material surrounded by an envelope of protein spikes resembling a crown [61]. Thus, ozone can oxidize the surface lipids of SARS-CoV-2 and subsequent damage to the lipid envelope and proteins，and eventually damage the capsid and genome [62].

Particularly, the ozone molecule could directly attack the stinger protein (*S*-spikes) on the surface of SARS-CoV-2 virus [63]. As a result, the virus was unable to bind to the host cell and lost its infectivity. SARS-CoV-2 had regions rich in cysteine and tryptophan in their membrane S protein [64]. Ozone would directly oxidize the thiol (*R*-*S*-H) groups of cysteine and tryptophan to the *R*-*S*-S-H form, inactivating them, directly blocking their cellular fusion. If the ozone did not arrive directly, its messengers, such as ROS or LOPs (H_2O_2, superoxide, nitric oxide, etc.), still maintain their oxidizing power to inactivate virus [63]. Ozone oxidation of the S protein could inhibit the infection process. Therefore, the infectiousness and pathogenicity of SARS-CoV-2 virus can be greatly reduced. In addition, the inactivation results of SARS-CoV-2 varied with different ozone concentration and processing time (Table 4).

3.3.5. Electron-beam irradiation inactivation

Cold chain food is a vital part of epidemic prevention and control. Therefore, the disinfection of the packaging of cold chain food could not be ignored. Since liquid disinfectants tended to coagulate and settle at lower temperature, therefore, the desirable disinfection effects might could not be achieved and the residues of liquid disinfectants may even contaminate food. In contrast, electron

beam inactivation of SRAS-CoV-2 is more suitable for cold chain foods. Irradiation with electron beams has long history been used for inactivation of cold chain food and presents unique merits over other inactivation methods, including high penetrating power, environmental friendliness, and low harmful effects on the nutritional value of food [72].

Electron beam sterilization technology used an electron gas pedal generated with high energy high-speed electron beam cut the molecular bonds of DNA of the cell nucleus within the microorganism. It could destroy the molecular structure of various microorganisms, including SARS-CoV-2, to achieve the effect of sterilization and effect. Damage to extra-membrane fibronectin (S protein) maybe the mechanism of the inactivation of the replacement virus by E-beam irradiation [73]. In addition, electron-beam irradiation caused relatively complete viral inactivation and less damage to the internal structure and nutritional composition of food. For example, Luo et al. [73] demonstrated the killing effects of electron beam against SARS-CoV-2 virus surrogates on large yellow croaker slices at doses of 4.08 kGy and higher. Moreover, this method also results no significant changes in color, pH, TVB-N, TBARS, and sensory properties of irradiated fish samples at doses below 10 kGy (Table 4).

Particularly, Ouyang S et al. [74] have successfully invented an industrial-scale device (Fig. 2(a) and (b)) that used electron beam to inactivate SARS-CoV-2 for sterilization of cold chain cargo. In non-smooth paper packaging material, it could finish the disinfection process in less than 3 s with disinfection efficiency >99.99 % and no chemical disinfectant residues or secondary contamination.

3.3.6. *Photodynamic treatment (PDT) inactivation*

Photodynamic treatment (PDT) is a novel inactivation method which relies on photosensitizer activated by light to form reactive oxygen species (ROS), particularly singlet oxygen. The generated ROS could further disrupt the structure of the viral lipid envelope and S protein and cause the damages to the viral genome [75].

PDT has been widely used for food disinfection. According to latest studies, PDT could also be used to inactivate SARS-CoV-2. Luisa Zupin et al. [76] investigated the killing effect of the curcumin-mediated photodynamic therapy (Cur-PDT) on SARS-CoV-2. The authors explored the killing effects of curcumin at the following setting K-Laser blue series light irradiation (445 nmλ, irradiance at 0.25 W/cm^2 and fluence at 15 J/cm^2). There was no reduction in SARS-CoV-2 load when treated with 0.05–0.5 μM curcumin; while the viral load was significantly reduced by 4 Log_{10} viral copies/mL when curcumin concentration increased to 1 μM.

Furthermore, Victor A. Svyatchenko et al. [77] studied the effect of methylene blue and Radachlorin-mediated photodynamic therapy on SARS-CoV-2 virus inactivation. The PDT against the 10^3 TCID50 of SARS-CoV-2 suspensions, with light energies of 16 J/cm^2 and 40 J/cm^2, completely inactivated viral infectivity in the presence of photosensitizers ranging from 1.0 to 10.0 μg/ml for methylene blue or 0.5–5.0 μg/ml for Radachlorin. Thus, these results indicate a high effectiveness of PDT in inactivating SARS-CoV-2 viral suspensions when accompanied by low concentrations of photosensitizers.

3.3.7. *Foodstuffs packaging with anti-sars-cov-2 activity*

Food package contaminated with SARS-CoV-2 has become a non-negligible concern in food industry (Table 1). SARS-CoV-2 is stable in the common food packaging, especially on non-porous surfaces. It remained infectious for 3–7 days at room temperature on smooth surfaces such as glass, plastic, and stainless steel [54]. In contrast, the virus was less stable on cardboard and paper [78]. During the COVID-19 outbreak, the Food and Agriculture Organization of the United Nations (FAO) mentioned improved packaging as a policy response to mitigate risks to the food system [79]. Therefore, developing packaging materials with SARS-CoV-2 resistance properties was a promising strategy [80].

Indeed, consumer concerns about SARS-CoV-2 survival on food packaging surfaces. This has already led to increased interest in food packaging with antiviral properties. Pascuta et al. [81] argued that active packaging could be considered a sustainable option for mitigating food system risk during COVID-19. However, up-to-date, the *anti*-SARS-CoV-2 food packaging research still limited

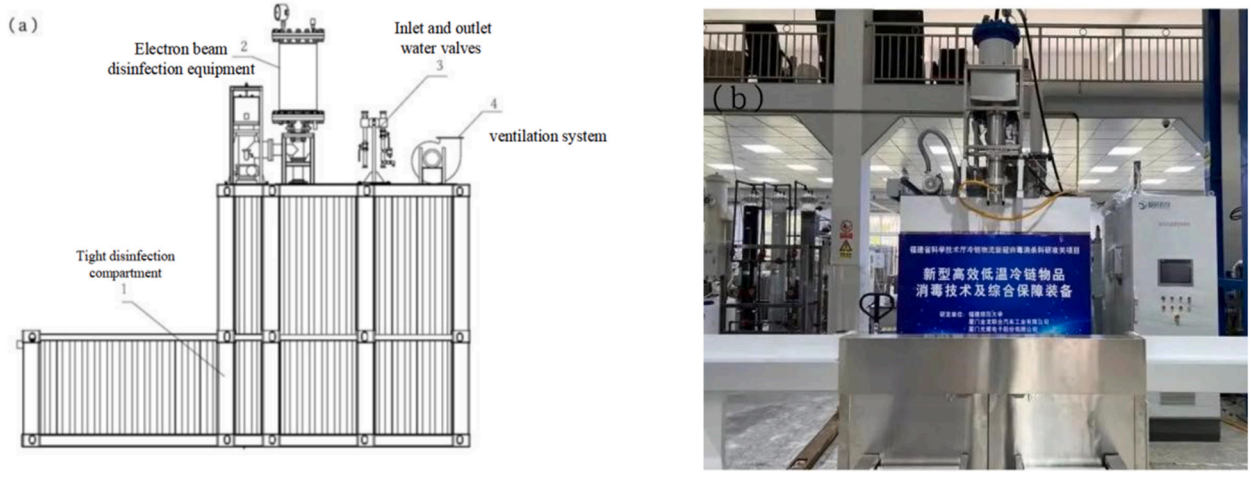

Fig. 2. E-beam irradiation device [74]
(a) Drawing (2D) views of the device side view, (b) Picture of the device.

although development of anti-virus food packaging bloomed in the recent years. Notably, study from related filed offered good lessons for food industry that nanoparticles have an excellent ability to inactivate pathogens and are widely used in the textile industry. Indeed, the result indicated that exposure the virus to that this polymeric composite effectively inhibits the SARS-CoV-2 virus (around 100 % in 2 min) and does not cause any allergies [82]. This could be a useful reference for the future development of antiviral food packaging.

3.4. Prevention and control guidelines

Indeed, since the outbreak of COVID-19, governments and organizations have released a number of guidelines to prevent the spread of the epidemic through the food supply chain. For example, The World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) jointly released *COVID-19 and Food Safety: Guidance for Food Businesses* [83]. It claimed that maintaining the health and safety of all workers in the food production and supply chain was crucial in the present outbreak control scenario. The food industry should establish a Food Safety Management System (FSMS) based on the principles of Hazard Analysis and Critical Control Points (HACCP) to manage the food safety risks and prevent the food contamination. For example, Yin Zhao et al. [84] analyzed the safety management of University canteens during COVID-19 period using HACCP. They successfully identified key control points for food safety and COVID-19 prevention and control.

Ideally, the guidelines should be provided to food-related units and staff operating during the standard control period of the epidemic for production and control. Businesses and governments should consider different perspectives on outbreak prevention in different prevention guidelines. When developing guidelines, they should tailor to the characteristics of the food business itself. They develop prevention and control guidelines to prevent the spread of viruses in food businesses.

Companies and governments have issued guidelines to prevent the spread of COVID-19 b y adapting them to the characteristics of different foods (Table 5) and have set standards for COVID-19 prevention and control in food processing and production.

4. Conclusions

During the COVID-19 pandemic, the SARS-CoV-2 virus infection was transmitted mainly through human-to-human transmission, however, it was also discovered that the SARS-CoV-2 could be detected on food, especially cold-chain foods. There remains no direct evidence that transmission of the SARS-CoV-2 virus is associated with the consumption of contaminated food, hence, COVID-19 is not considered a foodborne disease. However, food or contaminated food packaging should be considered as an important vehicle for indirect transmission of the virus. Further, the food supply chain may create an environment suitable for the spread of cross-infection. Indeed, pre-symptomatic or asymptomatic food operators may be the source of the SARS-CoV-2 virus in the food they handle or on surfaces they come into contact with.

Therefore, a number of efforts and safety measures to prevent foodborne transmission of COVID-19 during this pandemic, such as developing appropriate detection methods for the SARS-CoV-2 virus in foods/food products with ideal speed, sensitivity, specificity, availability, and multiplicity; exploring the potential of conventional disinfection methods and developing novel sterilization methods in food production; and legislating related regulations and guidelines for food manufacturers are still extremely valuable for the food industry. These measures not only reduced the negative impact of COVID-19 on the food industry during the pandemic, but also provide precious experience and guidance for food industry to overcome similar challenges in the future.

Looking ahead, with unceasing innovation of detection strategies for foodborne viruses; development of suitable pathogenicidal

Table 5
Some prevention and control guidelines/measures for COVID-19.

Country/ Organization	Prevention and control guidelines	Prevention and control measures
China	*Prevention and control technology guidelines for SARS-CoV-2 pollution of cold chain food production operation* [85]	Health management of COVID-19 prevention and control for workers, prevention and control requirements for loading, unloading, storage and transportation, prevention and control requirements for production and processing, prevention and control requirements for sales and operation, prevention and control requirements for food and beverage processing, emergency response measures for relevant areas
	Prevention and control technology guidelines for SARS-CoV-2 pollution of Livestock Slaughter and Processing Enterprises [86]	The spread of COVID-19 in livestock slaughter and processing from the perspectives of personnel hygiene, plant hygiene, raw material purchase and storage, slaughter pen hygiene, slaughter, and processing plant hygiene, and plant hygiene and disinfection methods
	Guidelines for the prevention and control of COVID-19 outbreaks in meat processors [87]	Prevention of the spread of COVID-19 in meat processing through control at the source, ventilation of the plant, feeding plant, slaughtering plant, meat cutting plant, packing plant, cold storage, laboratory, and control of public areas
WHO and FAO	*COVID-19 and Food Safety : Guidance for Food Businesses* [83]	Food businesses should establish protective measures to avoid the spread of disease. Specific measures for the prevention and control of epidemics in various types of food businesses include food production, retail, food service, primary agricultural products processing businesses etc.
Japan	*Guidelines for preventing the spread of COVID-19 in the food manufacturing industry* [88]	Measures for infection prevention and health management, cleaning and disinfection of staff

methods for foods with different matrixes/packaging format/transportation methods/etc., as well as establishment of related laws and regulations can effectively prevent the spread of foodborne virus through the food supply chain and better guard food safety, which might be crucial for shaping a sustainable food industry and logistics for future.

Data availability statement

Data included in article/supp. Material/referenced in article.

CRediT authorship contribution statement

Haoqing Yang: Writing – original draft, Visualization, Formal analysis. **Jiamiao Hu:** Funding acquisition, Formal analysis. **Bee K. Tan:** Writing – review & editing, Formal analysis. **Ka-hing Wong:** Writing – review & editing. **Jim Junhui Huang:** Writing – review & editing. **Peter C.K. Cheung:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Shaoling Lin:** Writing – review & editing, Funding acquisition, Conceptualization.

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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