New Zealand FOOD SAFETY SCIENCE & RESEARCH CENTRE

POTENTIAL FOR FOODBORNE TRANSMISSION OF COVID-19: LITERATURE REVIEW UPDATE VERSION 7

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Our understanding of the SARS-CoV-2 virus and the disease it causes, COVID-19, is still evolving. Consequently, international consensus or best practice for the questions asked in this review is still developing. We have provided information according to the current state of knowledge, and within the time available to conduct this review.

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ABBREVIATIONS

ABS	acrylonitrile butadiene styrene
ACE2	Angiotensin Converting Enzyme 2
ANSES	French Agency for Food, Environment and Occupational Health and Safety
BSA	bovine serum albumin
CCV	canine coronavirus
CGMP	Current Good Manufacturing Practices
CI	confidence interval
COVID-19	coronavirus disease 2019 (earlier reported as 2019-nCoV)
DHB	District Health Board
DMEM	Dulbecco’s modified Eagle’s medium
ELISA	enzyme-linked immunoassay
EFSA	European Food Safety Authority
GHP	Good Hygiene Practices
HACCP	Hazard Analysis and Critical Control Points
hCoV	human coronavirus
HCP	health care personnel
HEPA	high-efficiency particulate air
HIT	herd immunity threshold
HSE	health service executive
IANZ	International Accreditation New Zealand
ICMSF	International Commission on Microbiological Specifications for Foods
ICTV	International Committee on Taxonomy of Viruses
MBIE	The Ministry of Business, Innovation and Employment
MERS	Middle East respiratory syndrome-
MERS-CoV	Middle East respiratory syndrome-related coronavirus (causes MERS)
MHV	mouse hepatitis virus
MIQF	managed isolation and quarantine facilities
NZFSSRC	New Zealand Food Safety Science and Research Centre
NZ MPI	New Zealand Ministry for Primary Industries
OSHA	Occupational Safety and Health Administration
PFU	plaque forming units
PHU	Public Health Unit
PIMS-TS	Paediatric Inflammatory Multisystem Syndrome Temporally associated with SARS-CoV-2
PPE	personal protective equipment
RAT	rapid antigen test
RH	relative humidity
RT-qPCR	reverse transcription quantitative polymerase chain reaction
SARS	severe acute respiratory syndrome
SARS-CoV	severe acute respiratory syndrome-related coronavirus (causes SARS)

SARS-CoV-2	severe acute respiratory syndrome-related coronavirus 2 (causes COVID-19)
T99.9	time required for virus titre to decrease 99.9%
$TCID_{50}$	50% tissue culture infectious dose
TGEV	Transmissible gastroenteritis virus
US CDC	United States Centres for Disease Control
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
US FDA	United States Food and Drug Administration
UV	ultraviolet
UVGI	ultraviolet germicidal irradiation
WHO	World Health Organization

1. SUMMARY

The material covered in this report has been based on information available to ESR up to 23 April 2022. This report provides a sixth update to an initial report that was finalised on 16 March 2020, and updated on 1 April 2020, 8 May 2020, 6 July 2020, 15 December 2020 and 1 October 2021.

Our understanding of the SARS-CoV-2 virus and the disease it causes, COVID-19, is still evolving. Consequently, international consensus or best practice for the questions asked in this review is still developing. We have provided information according to the current state of knowledge, and within the time available to conduct this review. New information relevant to the questions addressed in this report may have appeared since 20 April 2022.

The report addresses the following three main research questions:

1. ***What is the latest information on the routes of transmission for COVID-19 (including anything that implicates food as a vehicle)?***

Key findings:

- The primary transmission route for human infection with SARS-CoV-2 is via respiratory droplets. There is growing evidence for airborne transmission, particularly in indoor settings with poor ventilation or during medical procedures that generate aerosols. It may be possible that a person can be infected with SARS-CoV-2 by touching a surface or object (fomite) that has the virus on it and then touching their own mouth, nose, or possibly their eyes. However, there is currently limited evidence for fomite-related transmission and it is not considered to be a significant route of transmission.
- Transmission of SARS-CoV-2 from humans to various species of animals including companion animals has been reported. There is also evidence of transmission from animals (farmed mink, wild deer and rodent) to humans. Experimental infection studies of livestock animals that are used as a food source showed that white-tailed deer were susceptible to infection by SARS-CoV-2, cattle and sheep had low susceptibility, while pigs and poultry were not susceptible. *In silico* studies evaluating ACE2 binding potential suggested sheep, goats, cattle, camels and horses could be susceptible to SARS-CoV-2, pigs would have low susceptibility, while birds (including poultry) and fish are not susceptible.
- There is still no evidence that food is a source or a transmission route for SARS-CoV-2 despite billions of meals having been consumed since the start of the pandemic, and there is very low risk of spread from food products or packaging. SARS-CoV-2 can invade cells in the oral cavity, salivary glands and gastrointestinal tract. However, cooking of food will inactivate SARS-CoV-2. If transmission were to occur via the foodborne route, it is expected that the infectious dose consumed would need to be significantly higher than the infectious dose for airborne transmission to overcome the inhibitory effects of the stomach acid. Significant COVID-19 outbreaks have occurred at food processing facilities and among food service workers, but most transmission has not been attributed to the food products or packaging. Instead, person-to-person transmission exacerbated by a work environment that places workers at increased risk of exposure has been considered the

primary cause of outbreaks at these facilities. There are several reports from Chinese cities where there was a genetic linkage between SARS-CoV-2 found on imported cold-chain products or packaging and from cases that handled them indicating that fomite transmission (but not foodborne transmission) may have occurred. However, the direction of the transmission was not demonstrated and alternative transmission routes were also possible. These are among the relatively few reports where SARS-CoV-2 virus was detected on food and packaging. Most studies report the detection of viral RNA rather than infectious virus which do not show that there actually is a hazard present, but nonetheless, it is prudent to use good hygiene practices to minimise any possibility of food or food contact surfaces as a source for SARS-CoV-2.

2. *What is the international consensus on survival rates of SARS-CoV-2 in and on food products and packaging?*

Key findings:

- Results from experiments that examine the stability of SARS-CoV-2 on foods or surfaces should be considered within the context of the experimental conditions. Researchers typically inoculate small areas of the substrate with far higher concentrations of virus than that expected to be deposited onto a surface, for example, by infectious people sneezing. Incubation is usually carried out in controlled conditions that do not mimic natural scenarios. The length of time that viral infectivity is detected is influenced by the initial virus concentration on a surface and the incubation conditions, so does not necessarily reflect the risk posed under natural contamination situations.
- The persistence of SARS-CoV-2 infectivity has been tested in a wide range of meat, fresh produce and dairy products. Results varied depending on the study and food composition. For example, SARS-CoV-2 remained infectious for up to three weeks on refrigerated deli items, some fresh produce types, and raw meats with high protein, fat and moisture content. SARS-CoV-2 also remained infectious in ice cream stored at -20°C and -80°C for at least eight weeks. However, there were antiviral effects from some processed meats, fresh produce, or acidic products. Studies attempting to replicate natural fresh produce contamination scenarios (low levels of aerosolised SARS-CoV-2 or handling by COVID-19 patients) did not result in viable SARS-CoV-2 being detected on the fruit and vegetables. No studies were identified that reported the stability of the Omicron variant on foods.
- SARS-CoV-2 infectivity has also been assessed in a range of beverage types. The survival of infectious SARS-CoV-2 viruses in different beverages was affected by the characteristics of the liquids, i.e. pH, alcohol content, sugar content, fat content or the presence of inhibitory compounds. For example, there was minimal loss of viral infectivity in beer after 1 hour, while cocoa, coffee, tea, fruit juices, and wine contained antiviral compounds that reduced infectivity, and higher alcohol content spirits immediately inactivated SARS-CoV-2.
- Cooking or pasteurisation inactivated SARS-CoV-2 viruses in or on food and beverages. SARS-CoV-2 remains infectious on food and surfaces for longer periods at lower temperatures, and lower humidity levels. The demonstrated stability of the virus during freezing is expected given that this is how viruses are stored in the laboratory.
- Infectious SARS-CoV-2 has been demonstrated to persist on hard surfaces (e.g. plastic, glass, steel) at ambient temperatures in the dark for several days to at least a month

depending on the experimental setup, although significant log-fold reductions in the amount of infectious virus occurred over that period.

- A non-peer reviewed study reported that infectivity of the Alpha, Beta, Delta and Omicron variants persisted for significantly longer times on surfaces than the Wuhan strain (which is often used in persistence studies).
- The Omicron variant was slightly more resistant to ethanol than earlier variants, but was inactivated by significantly lower concentrations than present in hand sanitisers. The US EPA states that genetic changes to the SARS-CoV-2 genome are not expected to impact the disinfectant efficacy.
- Studies evaluating the persistence of SARS-CoV-2 infectivity in and on food, aerosols and surfaces are summarised in Table 2 and Table 3.

3. *What is international best practice for mitigation options to reduce transfer of COVID-19 from workers to food products, including risk management strategies when a worker is identified as being infected with SARS-CoV-2?*

Key findings:

- Based on available evidence, the best practice for reducing the risk of contamination of food products or packaging continues to be managing the risk of SARS-CoV-2 infection amongst workers. This includes workers getting fully vaccinated, as well as informing their employer, self-isolating, seeking medical advice and getting a COVID-19 test if they have any symptoms of COVID-19 and/or respiratory illness. Employers can recommend and facilitate vaccination, and promote and support good personal hygiene practices for all workers. Because vaccination does not completely prevent infection, particularly with the Omicron variant, and vaccinated people might still have asymptomatic infection, this underscores the importance of adherence to the use of PPE and good hygiene practices.
- Since the last report update in October 2021, New Zealand has moved from a COVID-19 elimination strategy to the current situation where Omicron variant transmission is widespread in the community. Rapid antigen tests (RATs) have overtaken RT-qPCR as the main testing method for people with COVID-19 symptoms, household contacts, and these tests form a key component of ensuring critical workers can remain working even if they are a close contact of a confirmed case. Workplace testing should not be an alternative to the fundamental controls of distancing, hygiene and ventilation.

Overall Conclusion:

- While SARS-CoV-2 can remain infectious and/or detectable on food processing surfaces, packaging and some foods under certain cold-chain conditions, there is still no evidence that food or food packaging are significant transmission pathways for COVID-19.
- Aerosols and respiratory droplets remain the predominant transmission route.
- Vaccination with health checks/status reporting, physical distancing and ventilation, and the use of PPE and good hygiene practices remain the best means of preventing disease transmission between workers. This may be enhanced, but not replaced, by frequent rapid antigen testing.

2. INTRODUCTION AND METHODS

Introduction

This review was commissioned to attempt to answer specific questions submitted by the food industry via the New Zealand Food Safety Science and Research Centre (NZFSSRC) about the current COVID-19 disease pandemic. The questions for the initial review were submitted on 5 March 2020, with the draft review delivered on Thursday 12 March 2020. Updated versions of the document with added questions were finalised on 6 April 2020, 8 May 2020, 6 July 2020, 15 December 2020 and 1 October 2021. This report, submitted on 29 April 2022, comprises the sixth update (seventh version) and includes a set of revised questions, in particular:

1. What new information is available on emerging variants of concern, with respect to transmissibility, modes of transmission, pathogenicity profile, and survival on contact surfaces and food products?
2. What new information is available on the risk of foodborne infection from SARS-CoV-2, and what is the current international consensus on this?

The material in this report is based on information available to ESR up to 20 April 2022. There is significant ongoing research into COVID-19 (the disease) and SARS-CoV-2 (the virus), and new information is appearing on a daily basis. New information relevant to the questions addressed in this report may have appeared since the report date.

Information provided in the earlier versions of this report has been retained, unless it has been superseded. Quotes from websites, articles and reports are given in italics.

Our understanding of the SARS-CoV-2 virus and the disease it causes, known as COVID-19, is still evolving. Consequently, international consensus or best practice for the questions asked in this review is still developing. We have provided information according to the current state of knowledge, and within the time available to conduct this review.

The primary New Zealand sources for information on management of COVID-19 and SARS-CoV-2 are the Ministry of Health website:
https://www.health.govt.nz/covid-19-novel-coronavirus
and the Ministry for Primary Industries website: https://www.mpi.govt.nz/covid-19/

Methods

A systematic approach was undertaken to identify relevant literature from electronic scientific databases (PubMed and Web of Science). References were assessed for relevance (title and abstract screening) and non-duplicates were retained. Details are given in Appendix 1.

Other sources for information included references cited in reviews and other scientific literature.

Information and advice were also obtained from public websites over the dates 4–20 April 2022, including:

- https://www.cdc.gov/coronavirus/2019-ncov/index.html
- https://www.who.int/emergencies/diseases/novel-coronavirus-2019
- https://www.health.govt.nz/our-work/diseases-and-conditions/covid-19-novel-coronavirus
- https://www.efsa.europa.eu/en/news/coronavirus-no-evidence-food-source-or-transmission-route
- https://www.fda.gov/food/food-safety-during-emergencies/food-safety-and-coronavirus-disease-2019-covid-19

Google searches included:

- COVID-19 cold-chain
- COVID-19 food
- SARS-CoV-2 food

2.1. Changes since the previous report update

This seventh version of the report covers much of the same information as the sixth version. The overarching message remains the same; there is still no evidence for foodborne transmission of COVID-19 and the best practice for reducing the risk of contamination of food products or packaging continues to be managing the risk of SARS-CoV-2 infection amongst workers. The main areas of change are as follows:

- The inclusion of general background information on new variants of interest and variants of concern, with a focus on the Omicron variant (Section 3.2). The higher transmissibility and lower efficacy of vaccines for the Omicron variant compared with Delta and ancestral SARS-CoV-2 strains are discussed, which provides context for the more stringent measures required to combat Omicron variant transmission in the community and workplace. Accordingly, new workplace guidance has been provided by MPI and international authorities (Section 6).
- Information has been updated on SARS-CoV-2 diagnostic procedures. In particular, Rapid Antigen Test (RAT) kits have now been approved for use in New Zealand and are the primary test tool for people with COVID-19 symptoms and household contacts. RATs are widely utilised for worker testing by both critical and non-critical businesses and agencies (Section 3.4, Section 6.1).
- Additional studies have been published on the susceptibility of livestock species to infection by SARS-CoV-2. Various studies have reported significant circulation of SARS-CoV-2 in wild and captive populations of white-tailed deer in North America. Evidence has been found for human-to-deer, deer-to-deer and deer-to-human transmission. Mule deer have also been found to be susceptible to SARS-CoV-2 infection. No information was found for susceptibility of other deer species that are farmed or are established in the wild in New Zealand. Two new studies reported experimental infection of sheep with SARS-CoV-2;

susceptibility was minimal to not detected, depending on the study. A study that experimentally inoculated small numbers of other livestock (goats, cattle, alpaca, rabbits and a horse) reported that these were also unlikely to unlikely to contribute to SARS-CoV-2 epidemiology (Section 4.1).

- A new study has reported possible transmission of the Omicron strain via an international mail package. However, the length of time that virus would have needed to have remained infectious is substantially longer than the persistence time of SARS-CoV-2 on paper in laboratory studies. The risk of SARS-CoV-2 infection via fomite transmission is still considered very low (Section 4.2.2).
- New discussion has been added on evidence required to demonstrate foodborne transmission of viruses. Pertinent to the consideration of the likelihood of foodborne transmission, laboratory studies show that SARS-CoV-2 can infect cells in the oral cavity and salivary glands, and in the gastrointestinal tract. However, the risk of infection is considered low due to the fast transit time through the mouth and oesophagus and the mixing with food, which would dilute the virus and reduce viral contact with cell surfaces. Intragastric inoculation of Rhesus monkeys with high concentrations of SARS-CoV-2 resulted in pneumonia and gastrointestinal dysfunction. Inoculated levels of infectious virus were likely higher than would be encountered in a natural situation, and the degree of inactivation that was mediated by the stomach acid or intestinal bile is not known. However, sufficient virus remained infectious following transit through the stomach and gastrointestinal tract to induce symptomatic infections (Section 4.3).
- To date, there are still no documented reports of a direct link between SARS-CoV-2 infection and food consumption. Fomite transmission via food packaging of SARS-CoV-2 has been suggested in another three outbreak reports, all in Chinese cities, involving cases that handled cold-chain products. However, as with previous reports, the chain of transmission is difficult to verify and alternative transmission routes were also possible (Section 4.3).
- Newly published research was identified that examined the persistence of SARS-CoV-2 infectivity in and on a wide range of food and beverage types; data are summarised in Table 2. Infectivity depended on the experimental setup and storage conditions used, with increased maintenance of infectivity at lower temperatures. SARS-CoV-2 remained infectious for up to 21 days on refrigerated deli items, some fresh produce types, and meats with high protein, fat and moisture content. However, there were antiviral effects from some types of processed meat and fresh produce. Infectivity of SARS-CoV-2 in beverages was influenced by the composition, such as pH, sugar, fat or alcohol content, and the presence of preservatives or inhibitory compounds. No studies were identified that examined the stability of the Delta or Omicron variants on food products (Section 5.1).
- Studies have looked at the presence of SARS-CoV-2 in bivalve molluscs; SARS-CoV-2 nucleic acid was detected from shellfish in one of three studies, but no infectious virus was detected (Section 5.1).
- New non-peer reviewed research has compared the persistence of the SARS-CoV-2 Wuhan strain with the Alpha, Beta, Gamma, Delta and Omicron variants on plastic and skin

surfaces. All variants except the Gamma variant persisted for significantly longer periods of time than the Wuhan strain (which is often used in persistence studies), and the Omicron strain persisted for the longest period of time. No significant updates were provided for other inactivation treatments. The Omicron strain was also slightly more resistant to ethanol than the Wuhan strain, but was inactivated by significantly lower concentrations than present in hand sanitisers (Section 5.2).

- Risk management questions relevant to workers have been reviewed and updated, and primarily address changes to guidance based on the COVID-19 Protection Framework, implemented as a consequence of the increased risk and widespread transmission of the Omicron variant within the community (Section 6).
- Not all sections of the report have been updated and there may be new updated information that has not been captured by this report. Specifically, a systematic review was not undertaken for the sections 4.2.1, 4.2.3, 4.2.4, 5.2.2, 5.2.3 and 5.2.4. However, pertinent data was included under these sections when identified from assessed literature.

3. THE PATHOGEN: SARS-COV-2

3.1. Background, nomenclature and classification

The COVID-19 outbreak was characterised as a pandemic by the World Health Organization (WHO) on 11 March 2020.

Coronaviruses, named for the distinct crown-like spikes on their surface, belong to the subfamily *Coronavirinae,* family *Coronaviridae* and order *Nidovirales*. These viruses are enveloped and contain non-segmented, positive-sense, single-stranded RNA ranging from 26 to 32 kilobases which make it the largest known RNA virus genome [1]. The virions are spherical and can measure up to 170 nm diameter[1]. Coronaviruses infect vertebrates, causing a variety of diseases in mammals, including humans, and birds. Interspecies, including zoonotic, transmission of coronaviruses has been reported [2, 3].

In the current classification, in the family *Coronaviridae,* there are 39 species in 27 subgenera, five genera and two subfamilies. The family *Coronaviridae* are currently classified into four main genera known as alpha, beta, gamma and delta (*Alphacoronavirus*, *Betacoronavirus*, *Gammacoronavirus* and *Deltacoronavirus)* [1]. Of the seven identified coronaviruses now known to infect humans, four human coronaviruses (human coronavirus (HCoV)-229E, HCoV-NL63, HCoV-OC43 and HCoV-HKU1) usually cause mild illness consisting of self-limiting upper respiratory infection. The other three (severe acute respiratory syndrome-related coronaviruses, SARS-CoV and SARS-CoV-2, and Middle East respiratory syndrome-related coronavirus, MERS-CoV) can cause severe disease. HCoV-229E and HCoV-NL63 are alphacoronaviruses, while HCoV-OC43, HCoV-HKU1, SARS-CoV, SARS-CoV-2 and MERS-CoV are betacoronaviruses.

SARS-CoV (causing SARS) and MERS-CoV (causing MERS) are both from a zoonotic reservoir and were first detected in humans in 2002 and 2012, respectively [1]. Full genome sequence analysis of SARS-CoV-2 (approx. 30 kilobases) showed that it belongs to the *Betacoronavirus* genus and forms a distinct clade with bat SARS-like coronaviruses (namely bat-SL-CoVZC45, Bat-SL-CoVZXC21 and BatCoV RaTG13) supporting the hypothesis that SARS-CoV-2 originated from bats [4, 5]. There may have been an intermediary animal species that facilitated transfer from bats to humans, with smuggled pangolins being one possibility, but the existence of an intermediary host has not yet been confirmed [6, 7]. It has been noted that most bat species were hibernating at the time the outbreak was reported and no bats were found or sold at the Wuhan seafood market, the officially-recognised point of pandemic emergence (while other non-aquatic mammals were). Consumption of wild animal meat is common in China and another animal sold at the Wuhan seafood market may have acted as an intermediate host responsible for the initial transmission of the virus to humans [8]. However, it has also been suggested that SARS-CoV-2 was already circulating in Wuhan as early as October 2019 and the rapid rise in cases was triggered by mass migration and social gatherings associated with two big celebrations in the region [7]. Predictions based on SARS-CoV-2

[1] https://talk.ictvonline.org/ictv-reports/ictv_9th_report/positive-sense-rna-viruses-2011/w/posrna_viruses/222/coronaviridae; accessed 14 April 2022

molecular sequence data from early cases place the outbreak as starting from late September to early December, with most estimates placing it between mid-November and early December 2019 [9].

The origin of SARS-CoV-2 is not yet known but because the main symptoms in patients are fever and respiratory-related, this suggests that the original mode of transmission was respiratory rather than an oral mode via food [10]. A joint report between WHO and a China-based study group assessed the likelihood of four scenarios for the introduction of SARS-CoV-2 into the human population, concluding that [9]:

- Direct zoonotic spill-over is considered to be a possible-to-likely pathway;
- Introduction through an intermediate host is considered to be a likely-to-very-likely pathway;
- Introduction through cold/food-chain products is considered a possible pathway;
- Introduction through a laboratory incident was considered to be an extremely unlikely pathway.

Angiotensin converting enzyme 2 (ACE2) is an enzyme found on the outer surface (cell membranes) of cells in the lungs, arteries, heart, kidney, and intestines [11]. SARS-CoV-2 attaches to ACE2 and uses this protein to cross the cell membrane and enter cells. Thus, ACE2 is called the receptor, and it is the SARS-CoV-2 spike protein that attaches to this transmembrane protein. Attachment is followed by entry of SARS-CoV-2 into the cell [12].

3.2. SARS-CoV-2 variants with a focus on the Omicron variant

The vast and rapid transmission of SARS-CoV-2 has enabled significant genetic diversity to develop since the virus first entered the human population. Variants have emerged that can differ in their transmission, virulence, ACE2 binding specificity and antigenicity (i.e. how well they are recognised by a host's existing SARS-CoV-2 antibodies). The WHO, in collaboration with other authorities and experts, have been monitoring the emergence of new variants that pose an increased risk to global public health. They have been defined as follows:[2]

- **Variants under Monitoring (VUMs)** include those "*with genetic changes that are suspected to affect virus characteristics with some indication that it may pose a future risk, but evidence of phenotypic or epidemiological impact is currently unclear, requiring enhanced monitoring and repeat assessment pending new evidence*."
- **Variants of Interest (VOIs)** are those:
  - "*With genetic changes that are predicted or known to affect virus characteristics such as transmissibility, disease severity, immune escape, diagnostic or therapeutic escape; AND*
  - *Identified to cause significant community transmission or multiple COVID-19 clusters, in multiple countries, with increasing relative prevalence alongside increasing number of*

[2] https://www.who.int/en/activities/tracking-SARS-CoV-2-variants/; accessed 4 April 2022

cases over time, or other apparent epidemiological impacts to suggest an emerging risk to global public health."

- **Variants of Concern (VOCs)** are those that have been associated with one or more of the following changes at a degree of global public health significance:
  - *"Increase in transmissibility or detrimental change in COVID-19 epidemiology; OR*
  - *Increase in virulence or change in clinical disease presentation; OR*
  - *Decrease in effectiveness of public health and social measures or available diagnostics, vaccines, therapeutics."*

Current VOCs and VUMs are listed in Table 1. There were no circulating VOIs as of 3 May 2022. GISAID, Nextstrain and PANGO nomenclature for variants, as listed in Table 1, are typically used for scientific studies, while a recent designation of variants using the Greek alphabet was implemented as a simpler scheme for non-scientific audiences and to remove the stigma of naming based on the earliest country of documentation.

Table 1. Currently designated Variants of Concern and Variants under Monitoring. Adapted from WHO designations as of 29 March 2022[a].

WHO label	Pango lineage[b]	GISAID clade[c]	Nextstrain clade[d]	Additional amino acid changes monitored	Earliest documented samples	Date of designation
Variants of Concern (VOC)						
Delta	B.1.617.2	G/478K.V1	21A, 21I, 21J	+S:K417N +S:K484K	India, Oct 2020	VOI: 4 Apr 2021 VOC: 11 May 2021
Omicron	B.1.1.529	GR/484A	21K, 21L, 21M	+S:R346K +S:L452R/Q +S:F486V	Multiple countries, Nov 2021	VUM: 24 Nov 2021 VOC: 26 Nov 2021
Variants under Monitoring (VUM)						
–[e]	B.1.640	GH/490R	–	–	Multiple countries, Sep 2021	22 Nov 2021
–	XD	–	–	–	France, Jan 2022	09 Mar 2022

[a] https://www.who.int/en/activities/tracking-SARS-CoV-2-variants; accessed 4 May 2022
[b] https://cov-lineages.org/lineage_list.html; accessed 4 April 2022
[c] https://www.gisaid.org/; accessed 4 April 2022
[d] https://nextstrain.org/sars-cov-2/; 4 April 2022
[e] –, no designation or not applicable at this time

Recombination is common among coronaviruses. One of the current VUMs, the XD Pango lineage, is a recombinant of major subvariants of the Delta (subvariant AY.4) and Omicron (subvariant BA.1) VOCs. There are currently two main subvariants of Omicron (BA.1 and BA.2) as well as minor subvariants. However, the number of cases and countries reporting the detection of the BA.4, BA.5, and BA.2.12.1 subvariants are increasing as of 4 May 2022 [13], and evidence suggests that BA.4 (and likely BA.5) might have a growth advantage and increased transmissibility compared with BA.2 [14]. The first case of BA.2.12.1 was detected at the New Zealand border during the week April 10-23 2022 [15] and the first two cases of BA.4 during the week 18-28 April 2022 [14]. Public health authorities are tracking recombinants of

Omicron BA.1 and BA.2, called XE recombinants; XE was first reported in New Zealand on 23 April 2022[3]. To date, evidence does not suggest that the XD recombinants are more transmissible than other circulating variants although so far there is limited spread within the global population (26 sequences in GISAID).

The Omicron variant (B.1.1.529), including its descendent subvariants, is currently the most predominant VOC worldwide [13]. Of the samples collected during the period 2–31 March 2022, 99.8% were Omicron, <0.1% were Delta and <0.2% were not assigned to a Pango lineage [16]. Internationally, the relative proportions within Omicron include: BA.2, 93.6%; BA.1.1, 4.8%; and BA.1 and BA.3, <0.1%. As of 4 May 2022, both Omicron subvariants were circulating in New Zealand, but the BA.2 subvariant was dominant (96%) [14], and the Delta variant has not been detected in New Zealand since 2 March 2022 although only a small proportion of cases are being sequenced currently [15].

Characteristics of the Omicron variant include:

- A large number of acquired mutations: Relative to the original strain, at least 60 mutations have been identified [17]. Around 30 mutations are in the spike protein region, 15 of which are in the ACE2 receptor-binding domain. Simulations have shown that these mutations confer improved binding to the ACE2 receptor [18]. Mutations around the furin cleavage site might also facilitate the cleavage of the spike into S1 and S2, thereby enhancing fusion and virus infection of cells [17].

- Greater transmissibility compared with the Delta variant: The greater binding of the spike protein to the ACE2 receptor is thought to be responsible for the greater infectivity observed for Omicron [19]. Transmissibility is defined by the reproductive number (R_0)[4] which is a measure of the average number of new infections generated by an infectious person in a totally naïve population in the absence of effective control and vaccines. The Delta variant has been estimated to have an R_0 of 5.08 (range 3.2–8) [20], which is higher than for the ancestral strain which had an R_0 between 2.79 and 2.87, depending on the study [21]. The Delta R_0 of 5.08 is also higher than for other viral infections such SARS, MERS, smallpox, Ebola, seasonal influenza and pandemic influenza [20]. The Omicron variant has been estimated to have an R_0 that is 3.19 or 4.2 times higher than that of Delta, with this transmission advantage being a result of Omicron being more likely to evade existing immunity [22, 23]. An R_0 value as high as 10 has been suggested [24]. A further study has modelled the Omicron variant to be 2.8-times more infectious than Delta and 10-times more infectious than the original SARS-CoV-2 virus [25].

- Different clinical presentation: In tissue culture studies, the Omicron variant has been found to replicate to higher titres in the upper airway cells (bronchi) and less in the lung parenchyma, compared with all other SARS-CoV-2 variants tested [26]. Higher viral loads in the upper respiratory tract of COVID-19 patients may increase person-to-person

[3] https://www.health.govt.nz/system/files/documents/pages/variants-update-27-april-2022_0.pdf; accessed 28 April 2022

[4] Where $R_0 > 1$, the epidemic will grow, and if $R_0 < 1$, the epidemic will decline.

transmission relative to high lung viral loads. The findings may also partially explain the differences in disease severity (discussed below) and symptoms reported for patients infected with the Omicron variant (fewer lower respiratory tract and more upper respiratory tract symptoms) [27].

- A shorter incubation period: The time from infection to symptom onset for the Omicron variant has been reported as three days, compared with five days for the wild-type and four days for the Delta variant [28]. Based on a review of publications, the NZ Ministry of Health has estimated the incubation period to be 3–4 days, and although the maximum incubation period is unclear, 6–8 days has been reported[5].
- Reduced susceptibility to antibody neutralisation: Neutralising antibodies bind to the same region of the spike protein that binds the virus to the ACE2 receptor. Thus Omicron's spike protein mutations that increase ACE2 binding affinity also affect the ability of existing host antibodies (induced from prior infection or vaccination) to bind and neutralise viral particles. This could occur through competitive inhibition, i.e. the Omicron viral particles bind quickly and effectively to ACE2 sites and reduce the ability of antibodies to bind [29]. Mutations may also affect the spike protein conformation, hydrophobicity and charge, also affecting antibody binding [30]. The immune escape characteristics of the Omicron variant have resulted in reduced efficacy of convalescent sera therapy and monoclonal antibody treatments that target the ACE2-spike protein interaction, and increased resistance to neutralising antibodies induced either by vaccination or prior infection, overall leading to increased frequency of reinfection [31, 32], and increased vaccine breakthrough (discussed below) [29, 30, 33].
- A reduced efficacy of vaccines against infection: Comparisons between vaccine effectiveness studies should be interpreted with caution because estimates vary depending on the type of vaccine administered, the number of doses and timing of vaccination. Nonetheless, various studies have reported that vaccination offers less protection for infection by the Omicron variant compared with earlier circulating SARS-CoV-2 strains. One study found that two doses of vaccination (with BNT162b2 or ChAdOx1 nCoV-19) were insufficient to protect against symptomatic infection with the Omicron variant, and although boosting with a third dose provided a substantial increase in protection against mild disease, this protection waned over time [34]. Protection against severe disease was not evaluated in this study. In another study, the effectiveness of vaccination against infection by the Omicron variant was significantly reduced compared with infection by Delta, with efficacy at 64.5% of that observed for the Delta variant [35]. Despite this reduction in vaccine efficacy against the Omicron variant, studies have shown that vaccination still offered significant protection against severe health outcomes following Omicron infection [36, 37]. One study reported the effectiveness of two doses of an mRNA vaccine in preventing hospitalisation with COVID-19 was 85% for the Alpha and Delta variants and 65% the Omicron variant.

[5] https://www.health.govt.nz/system/files/documents/pages/22_february_2022_-_variants_update.pdf; accessed 8 April 2022

Three vaccine doses were required to achieve a similar protective effect against the Omicron variant (86%) as two doses against the Alpha and Delta variants [36].

- Decreased disease severity compared with Delta: Among unvaccinated patients hospitalised with COVID-19 in the United States, severity of disease for people infected with the Omicron variant was lower compared with the Delta variant, but still resulted in significant mortality (7% compared with 12% for Delta) [36]. Significantly decreased hospitalisation and severe outcomes following infection with the Omicron variant relative to Delta were also reported from South African and English studies [37, 38]. The decreased disease severity may at least in part be due to the reduced ability of Omicron to replicate in lungs [26].

The higher transmissibility and lower efficacy of vaccines means that, compared with ancestral SARS-CoV-2 strains, more stringent measures are required to combat Omicron transmission in the community and workplace (as discussed in Section 6).

3.3. Disease signs, symptoms and human susceptibility

3.3.1. *Signs and symptoms*

COVID-19 presentation can range from mild symptoms to severe pneumonia and death [39]. Infection by SARS-CoV-2 may be associated with no signs or symptoms (i.e. asymptomatic infection) and people may be infectious for a period prior to exhibiting symptoms (presymptomatic infection). The New Zealand Ministry of Health has published background information on symptoms.[6]

Signs and symptoms of SARS-CoV-2 infection by earlier variants, including mild respiratory symptoms and fever, occur on an average of 5–6 days after infection (i.e. mean incubation period 5–6 days, range 1–14 days), although this may differ depending on the variant [10, 40]. The incubation period for COVID-19 disease can be longer than for SARS-CoV-mediated disease, which is 2-7 days [40]. As discussed, some data suggest that symptom onset occurs earlier for infection by the Omicron variant. According to data from the ZOE study, a large citizen science health monitoring study in the UK, the most common symptoms of infection by the Omicron variant are[7]:

1. runny nose
2. headache
3. fatigue (mild or severe)
4. sneezing
5. sore throat

[6] https://www.health.govt.nz/our-work/diseases-and-conditions/covid-19-novel-coronavirus/covid-19-health-advice-public/about-covid-19; accessed 14 April 2022
[7] https://joinzoe.com/learn/omicron-symptoms; accessed 21 April 2022

From infection with earlier variants, approximately 80% of laboratory-confirmed patients have had mild to moderate disease and recover (both non-pneumonia and pneumonia cases), 13.8% have severe disease and 6.1% become critical (respiratory failure, septic shock, and/or multiple organ dysfunction/failure) [39]. As discussed earlier, the Omicron variant is associated with a reduced disease severity relative to the Delta variant, but there is still significant morbidity and mortality.

For unvaccinated individuals with infection with earlier variants, asymptomatic infection has been reported, including in infants [41, 42]. In one Chinese study the proportion of asymptomatic cases was 25% [43] and experts have suggested that numbers may actually be higher. Future sero-epidemiology studies will refine this number. Another study in China estimated that 12.6% of cases appeared to be caused by presymptomatic transmission [44]. A further study screened a total of 5,869 people for SARS-CoV-2 at Spanish nursing homes; 768 (23.9%) residents and 403 (15.2%) staff tested positive. Of those testing positive, 69.7% of residents and 55.8% of staff were asymptomatic [45].

More research is required on what the minimum infectious dose of SARS-CoV-2 is for humans (how many infectious virus particles it takes to cause disease), but one review suggests that it is small, at 100 infectious particles [46]. The infectious dose likely varies depending on the route of infection, for example, transmission via aerosols is thought to be more infectious compared with intranasal inoculation (as might occur from fomite transmission). Although foodborne/oral transmission has not been demonstrated (discussed in Section 4.3), the infectious dose would likely need to be significantly higher to overcome the inhibitory effects of the stomach acid. The initial infectious dose of SARS-CoV-2 has been hypothesised to have a bearing on disease severity and disease progression [47]. It is not known how the infectious dose differs for the Omicron variant, but it is possible that it has a lower infectious dose due to the spike mutations increasing the efficacy of ACE2 binding and entry into cells. It is also not known how the infectious dose is influenced by vaccination status but it is also reasonable to assume, as for other viral infections, that the minimum infectious dose will be higher for vaccine breakthrough infections.

3.3.2. *Demographics*

The demographic features and disease outcomes, transmission patterns (including the sources of infection, outbreaks, household transmission) have been published for the first wave of COVID-19 in New Zealand which covered the date range from 2 February to 13 May, 2020 [48].

- Of the 1503 confirmed cases, there were 95 (6.3%) hospital admissions and 22 (1.5%) COVID-19 deaths.
- 1034 (69%) cases were imported or import-related, tending to be younger adults, of European ethnicity, and of higher socioeconomic status.
- 702 (47%) cases were linked to 34 outbreaks.
- 836 (56%) of cases were female and 667 (44%) were male.
- Severe outcomes were associated with:

- locally acquired infection (crude odds ratio [OR] 2.32 [95% CI 1.40–3.82] compared with imported cases). However, this association was strongly confounded by the timing and occurrence of locally-acquired outbreaks in vulnerable-population settings such as aged residential care facilities.
- older age (adjusted OR ranging from 2.72 [1.40–5.30] for 50–64 year olds to 8.25 [2.59–26.31] for people aged ≥80 years compared with 20–34 year olds);
- aged residential care residency (adjusted OR 3.86 [1.59–9.35]); and
- the main ethnicity reported by cases being Pacific peoples (adjusted OR 2.76 [1.14–6.68] relative to European or other) or Asian (2.15 [1.10–4.20]).

A New Zealand study that included cases up to 25 September 2020 calculated that after controlling for age and pre-existing conditions, Māori have 2.50 times greater odds of hospitalisation (95% CI 1.39–4.51) than non-Māori non-Pacific people. Pacific people have three times greater odds (95% CI 1.75–5.33) [49]. An updated Ministry of Health dashboard provides the demographics of confirmed and probable cases of COVID-19 in New Zealand, reported since 16 August 2021[8].

3.4. SARS-CoV-2 detection methods and COVID-19 diagnosis

Nasopharyngeal swabs or back-of-throat/front-of-nose swab (oropharyngeal and bilateral anterior nares) are the standard sample types collected for RT-qPCR diagnostic testing, while less invasive anterior nasal swabs are more commonly used for rapid antigen tests (RATs). Saliva testing has been accredited by International Accreditation New Zealand (IANZ) for surveillance purposes and was initially only implemented for testing people in high-risk workplaces that are regularly tested, such as border workers, and has been offered more widely for workplace assurances[9]. Saliva testing involves collection of drool into a tube with multiple tests within a 7-day period. A positive saliva test is considered only to be "presumptive" and requires an immediate nasopharyngeal test to confirm a diagnosis of COVID-19 and to provide a suitable sample for whole genome sequencing.

The four main methods for SARS-CoV-2 detection or infection diagnosis are:

1. Detection of the RNA from the virus using RT-qPCR. This is the "gold standard" diagnostic test for current infection [50]. RT-qPCR can detect:
   - Intact, infectious virus,
   - Viral particles with damaged capsids that are not capable of infection,
   - Free viral RNA released from damaged capsids,
   - Viral genomes not yet packaged (within a person's cells).

[8] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-data-and-statistics/covid-19-case-demographics; accessed 29 April 2022
[9] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-health-advice-public/assessment-and-testing-covid-19/covid-19-saliva-testing; accessed 14 April 2022

Several RT-qPCR tests have been developed based on different target regions of the SARS-CoV-2 RNA genome, such as different regions within the nucleocapsid phosphoprotein (N), envelope (E), spike (S) or RNA-dependent RNA polymerase (RdRP) genes[10]. These molecular assays can also be used to determine the presence of virus, through the detection of its RNA, in foods and the environment, but do not give any information on its infectivity.

2. Serology, which detects antibodies to indicate that a person has mounted an immune response to SARS-CoV-2 whether or not they actually developed symptoms. Because the earliest that IgM, IgG or IgA antibodies to SARS-CoV-2 can be detected is several days after initial infection [51-53], the test may not detect antibodies in someone with a current COVID-19 infection, depending on the timing of the test relative to the time the person became infected. Serology testing has not yet been extensively validated for SARS-CoV-2 and the growing number and types of tests being developed likely differ in sensitivity and specificity [54]. A range of serology tests have been developed, some of which have been authorised for use by overseas regulatory authorities [50][11]. Several types of serological tests are being used by New Zealand diagnostic laboratories [55]. SARS-CoV-2 serology testing is not centrally funded in New Zealand, but may be funded for selected patients by district health boards. In addition, pre-departure serology testing is undertaken as a fee-for-service by certain New Zealand laboratories to meet entry requirements for some countries.

3. Antigen tests, which are commonly used in the diagnosis of respiratory pathogens, including influenza viruses and respiratory syncytial virus.[12] Antigen tests are immunoassays that detect the presence of a specific viral antigen, which implies current viral infection. Antigen tests are relatively inexpensive, and most can be used at the point-of-care (designated rapid antigen tests (RATs)). Most of the currently authorized RATs return results in approximately 15 minutes. RATs for SARS-CoV-2 are generally less sensitive than RT-qPCR tests, depending on the stage of illness, the viral load of the individual case and the experience of the operator, but sensitivity is potentially as low as 40% to as high as 90%[13]. As such, a proportion of true COVID-19 cases will be missed, which is not ideal when pursuing an elimination strategy. In addition, a low percentage will return false positives, which might be higher than the proportion of true positives in a population with low prevalence of SARS-CoV-2; but in a high-prevalence population (as is the current situation in New Zealand), a positive detection is likely to be a true detection. Since the previous version of this report (1 October 2021), RATs have now been approved for use in New Zealand and are currently New Zealand's primary testing tool for people with COVID-19 symptoms or household

[10] https://www.centerforhealthsecurity.org/resources/COVID-19/COVID-19-fact-sheets/200410-RT-PCR.pdf; accessed 14 April 2022

[11] https://www.fda.gov/medical-devices/coronavirus-disease-2019-covid-19-emergency-use-authorizations-medical-devices/in-vitro-diagnostics-euas-serology-and-other-adaptive-immune-response-tests-sars-cov-2; accessed 14 April 2022

[12] https://www.cdc.gov/coronavirus/2019-ncov/lab/resources/antigen-tests-guidelines.html; 14 April 2022

[13] https://www.beehive.govt.nz/sites/default/files/2021-10/COVID-19%20Testing%20Rapid%20Review%20Report.pdf; accessed 22 April 2022

contacts. A list of the approved RATs as of 1 April 2022 can be found on the Ministry of Health website[14].

4. The virus can also be grown in cell culture. However, this can only be undertaken in highly-contained specialist laboratories and hence is rarely performed, and not used for diagnostics. Culturing SARS-CoV-2 is important for demonstrating whether the virus is infectious, and thus is mainly used for survival and persistence studies [50].

[14] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-health-advice-public/assessment-and-testing-covid-19/rapid-antigen-testing-rat; accessed 14 April 2022

4. WHAT IS THE LATEST INFORMATION ON THE ROUTES OF TRANSMISSION FOR COVID-19 (INCLUDING ANYTHING THAT IMPLICATES FOOD AS A VEHICLE)?

Key findings:

- The primary transmission route for human infection with SARS-CoV-2 is via respiratory droplets. There is growing evidence for airborne transmission, particularly in indoor settings with poor ventilation or during medical procedures that generate aerosols. It may be possible that a person can be infected with SARS-CoV-2 by touching a surface or object (fomite) that has the virus on it and then touching their own mouth, nose, or possibly their eyes. However, there is currently limited evidence for fomite-related transmission and it is not considered to be a significant route of transmission.
- Transmission of SARS-CoV-2 from humans to various species of animals including companion animals has been reported. There is also evidence of transmission from animals (farmed mink, wild deer and rodent) to humans. Experimental infection studies of livestock animals that are used as a food source showed that white-tailed deer were susceptible to infection by SARS-CoV-2, cattle and sheep had low susceptibility, while pigs and poultry were not susceptible. *In silico* studies evaluating ACE2 binding potential suggested sheep, goats, cattle, camels and horses could be susceptible to SARS-CoV-2, pigs would have low susceptibility, while birds (including poultry) and fish are not susceptible.
- There is still no evidence that food is a source or a transmission route for SARS-CoV-2 despite billions of meals having been consumed since the start of the pandemic, and there is very low risk of spread from food products or packaging. SARS-CoV-2 can invade cells in the oral cavity, salivary glands and gastrointestinal tract. However, cooking of food will inactivate SARS-CoV-2. If transmission were to occur via the foodborne route, it is expected that the infectious dose consumed would need to be significantly higher than the infectious dose for airborne transmission to overcome the inhibitory effects of the stomach acid. Significant COVID-19 outbreaks have occurred at food processing facilities and among food service workers, but most transmission has not been attributed to the food products or packaging. Instead, person-to-person transmission exacerbated by a work environment that places workers at increased risk of exposure has been considered the primary cause of outbreaks at these facilities. There are several reports from Chinese cities where there was a genetic linkage between SARS-CoV-2 found on imported cold-chain products or packaging and from cases that handled them indicating that fomite transmission (but not foodborne transmission) may have occurred. However, the direction of the transmission was not demonstrated and alternative transmission routes were also possible. These are among the relatively few reports where SARS-CoV-2 virus was detected on food and packaging. Most studies report the detection of viral RNA rather than infectious virus which do not show that there actually is a hazard present, but nonetheless, it is prudent to use good hygiene practices to minimise any possibility of food or food contact surfaces as a source for SARS-CoV-2.

4.1. Animal-to-human transmission

As discussed in Section 3, SARS-CoV-2 has a zoonotic origin, likely originating from bats and there may have been an intermediary animal species such as pangolins that facilitated transfer from bats to humans. A non-peer reviewed preprint reported that bat-to-human spill-over of SARS-related coronaviruses may be a relatively common occurrence, and estimated that approximately 400,000 people may be infected with SARS-related coronaviruses annually in South and Southeast Asia [56]. Although viruses are generally species-specific, there is evidence that SARS-CoV-2 can also infect other animals as well as humans. At present this evidence is largely limited to companion animals, farmed mink and wild deer, and shows that the direction of transmission (at least initially) is from humans to animals. However, there is also evidence of transmission from animals back to humans, involving farmed mink, rodents and wild white-tailed deer [57-59]. The ability of the virus to infect animals is particularly relevant to assessing the risk from livestock and derived food products. Early reports of transmission for different animal species are discussed below. A global open-access database has recently been produced that provides an overview of all reported SARS-CoV-2 transmission events to animals [60][15].

Passage of SARS-CoV-2 from humans to animals was first reported for a tiger in a New York zoo, which tested positive for SARS-CoV-2 following exposure to a handler that was shedding the virus[16]. The tiger was tested after several lions and tigers at the zoo showed signs of respiratory illness.

Two pet cats with mild respiratory illness have tested positive for COVID-19 in New York[17]. In Belgium, a pet cat owned by a person with COVID-19 showed signs of the disease (diarrhoea, vomiting and breathing difficulty) a week after the owner showed symptoms. The cat subsequently tested positive[18]. Reports of cats testing positive for COVID-19 are increasing internationally[15].

Two out of 15 dogs from households with confirmed human cases of COVID-19 in Hong Kong were found to be infected with SARS-CoV-2 [61]. This was demonstrated using RT–qPCR, serology, sequencing the viral genome, and in one dog, the virus was also isolated. The dogs remained asymptomatic. The first case of a dog testing positive for SARS-CoV-2 infection in the United States occurred in New York, involving a dog showing respiratory signs[19]. An owner of the dog had previously tested positive with symptoms occurring before those of the dog. A second dog in the household did not have respiratory symptoms but was seropositive, indicating exposure.

In laboratory studies, SARS-CoV-2 RNA and infectious virus were detected in upper respiratory tract tissues from cats three and six days post-infection, and viral RNA was also detected in

[15] SARS-ANI VIS (csh.ac.at); accessed 14 April 2022
[16] https://www.aphis.usda.gov/aphis/newsroom/news/sa_by_date/sa-2020/ny-zoo-covid-19; accessed 14 April 2022
[17] https://www.cdc.gov/media/releases/2020/s0422-covid-19-cats-NYC.html; accessed 14 April 2022
[18] https://promedmail.org/promed-post/?id=20200327.7151215; accessed 14 April 2022
[19] https://www.aphis.usda.gov/aphis/newsroom/stakeholder-info/sa_by_date/sa-2020/sa-06/sars-cov-2-dog; accessed 14 April 2022

faeces. Cats were also susceptible to airborne transmission from other infected cats [62]. Dogs had a lower susceptibility to SARS-CoV-2.

SARS-CoV-2 was detected in mink from two farms in the Netherlands in April 2020 [63]. The mink showed respiratory symptoms (watery nasal discharge and in some, severe respiratory distress) and the farms also experienced an increase in mink deaths due to pneumonia. Because workers on these farms had signs and symptoms of COVID-19 prior to the mink signs, it is likely that infected farm workers were the source of the mink infections. The animals were housed individually in cages with solid walls, preventing animal-to-animal contact, so transmission between mink was more likely facilitated by the workers, respiratory droplets, dust or fomites (e.g. bedding and food provided by the workers). On each farm, the viral sequences were similar between the mink and infected workers, but sequencing suggested no infection link between the farms. Based on sequence comparisons, at least one worker was presumed to have become infected from the minks. Seven of 24 stray farm cats sampled from the mink farms also developed antibodies to this virus, suggesting they had been exposed to the virus at some point. Inhalable dust in the mink houses contained viral RNA, which might indicate possible exposure for workers.

By 25 October 2020, mink had tested positive on 69 mink farms in the Netherlands[20], and as of 18 November 2020, SARS-CoV-2 had also been reported in mink on farms in Denmark, Spain, Italy, Sweden, the United States and Greece[21]. Since June 2020, 214 human cases of COVID-19 have been identified in Denmark with SARS-CoV-2 variants associated with farmed minks. This included 12 cases with a unique variant (containing four genetic changes in the spike (S) protein encoding region; Cluster 5), reported on 5 November 2020 [59][22]. In the Netherlands, at least 66 of 97 farm employees have tested positive for SARS-CoV-2 and at least 47 human cases were identified by whole genome sequencing to have been infected with mink-related variants [59, 64]. To date, patients infected with the SARS-CoV-2 variants from mink were not found to have more severe clinical presentations. However, preliminary experiments suggested that the spike protein variants affected the antigenicity of SARS-CoV-2 [65]. Concern has been raised over how this mutation might affect reinfection with SARS-CoV-2, vaccine efficacy or treatment efficacy using plasma from convalescent patients or with monoclonal antibodies [59][23]. In addition, there is a risk that variants causing increased disease severity could eventually emerge if SARS-CoV-2 infects a very large number of animals and/or is sustained over long periods of time. Following the demonstration that mink farms may act as reservoirs for SARS-CoV-2, authorities have introduced new guidance including response and containment measures for mink farms[24,25,26]. In the Netherlands, these include screening of

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[20] https://www.wur.nl/en/Research-Results/Research-Institutes/Bioveterinary-Research/show-bvr/COVID-19-detected-on-two-mink-farms.htm; accessed 14 April 2022
[21] https://www.cdc.gov/coronavirus/2019-ncov/daily-life-coping/animals.html; accessed 14 April 2022
[22] https://www.who.int/emergencies/disease-outbreak-news/item/2020-DON301; accessed 14 April 2022
[23] https://www.nature.com/articles/d41586-020-03218-z; accessed 14 April 2022
[24] https://www.government.nl/latest/news/2020/05/19/new-results-from-research-into-covid-19-on-mink-farms; accessed 14 April 2022
[25] https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov-2-guidance-for-farmed-mink.pdf; accessed 14 April 2022
[26] https://www.aphis.usda.gov/publications/animal_health/sars-cov-2-mink-guidance.pdf; accessed 14 April 2022

mink on all farms for antibodies, use of personal protective equipment (PPE) for farm staff, banning transport of animals and manure from infected farms and ensuring cats cannot enter or exit the site. From 5 June 2020, the Dutch government has called for culling of infected mink and a mandatory closing scheme for Dutch mink farms was introduced early in 2021[20]. Mass mink culls have also been planned or are underway in Ireland[27], Denmark[28], Spain [29], Sweden, Italy and the United States[30].

Laboratory studies have evaluated the susceptibility to SARS-CoV-2 of different model laboratory animals (ferrets, which are a commonly used laboratory model for respiratory infections in humans, and are closely related to minks) [62, 66]. In one study, ferrets were inoculated intranasally with one of two strains of SARS-CoV-2. SARS-CoV-2 was able to replicate in the upper respiratory tract of ferrets, with viral RNA (detected by RT-qPCR) and infectious virus (using Vero E6 cells) detected in the nasal turbinates, soft palate, and tonsils of all four ferrets four days post-inoculation [62]. SARS-CoV-2 RNA was not detected in other tissues (trachea, lung, heart, liver, spleen, kidneys, pancreas, small intestine or brain). Viral RNA and infectious virus were detected from nasal washes of six infected ferrets up to eight days post-infection; RNA was also detected from some rectal swabs but no infectious virus was isolated from this source. Two ferrets also developed a fever. Similar findings were reported elsewhere, and ferret-to-ferret transmission was also documented [66]. Susceptibility to SARS-CoV-2 infection has also been demonstrated for a growing number of model laboratory species such as Rhesus macaques [67] and golden Syrian hamsters [68].

Some laboratory studies are available for livestock, with challenge studies so far showing that pigs, ducks and chickens are poor hosts for SARS-CoV-2. Pigs, chickens and ducks were not susceptible to infection (no SARS-CoV-2 RNA detected from swabs of inoculated animals, and all animals remained seronegative for SARS-CoV-2 when tested by enzyme-linked immunoassay (ELISA)) [62]. One study examined the susceptibility of five-week old pigs via oral/intranasal/intratracheal challenge [69]. Although SARS-CoV-2 was shown to replicate in some porcine cell lines, inoculated pigs showed no evidence of clinical signs, viral replication or SARS-CoV-2-specific antibody responses. Another study challenged chickens, turkeys, ducks, quail, and geese with SARS-CoV-2 and MERS, administered in the nasal cavity [70]. No disease or virus replication was observed, and poultry did not produce serum antibodies, supporting that poultry are unlikely to serve a role in maintenance of either virus. Consistent with the findings of others, a further study also found that pigs and chickens were not susceptible to SARS-CoV-2 infection, while fruit bats had transient infection and ferrets resembled a subclinical human infection with efficient spread [71]. In further support of these results, the ACE2 receptor was not detected in pig nasal mucosa or lung tissues [72]. Furthermore, SARS-CoV-2 did not replicate in *ex vivo* respiratory organ cultures of pigs [73].

[27] https://www.dw.com/en/coronavirus-ireland-plans-mink-cull/a-55668127; accessed 14 April 2022
[28] https://en.fvm.dk/news/news/nyhed/covid-19-all-mink-in-denmark-must-be-culled/; accessed 15 September 2021
[29] https://www.euronews.com/2020/07/17/coronavirus-spain-to-cull-90-000-mink-after-farmworkers-test-positive; accessed 14 April 2022
[30] https://www.sciencemag.org/news/2020/11/mutant-coronaviruses-found-mink-spark-massive-culls-and-doom-danish-group-s-research; accessed 14 April 2022

Among other livestock animals, the ACE2 receptor was detected in the bronchiolar epithelium of sheep and cattle but not samples of nasal mucosa epithelium from these animals, suggesting a reduced potential for infectivity but potential susceptibility to pneumonia if infection occurs [72]. Consistent with this, another study reported that *ex vivo* respiratory organ cultures from sheep and cattle sustained replication of SARS-CoV-2 [73]. A SARS-CoV-2 strain containing the D614G mutation (also present in the Delta variant) replicated at higher magnitude than the D614 strain in tissues from both sheep and cattle, as has also been seen in human respiratory cells [74]. A further study found that SARS-CoV-2 was able to replicate in sheep primary and immortalised kidney cell cultures, but not from bovine kidney or foetal fibroblast cell lines; the study did not test respiratory organ cell cultures from these species [75].

Experimental infections with SARS-CoV-2 have also been conducted in cattle and sheep. Viral replication and specific seroconversion (increase in specific antibodies) was observed in two of six calves that were experimentally infected with SARS-CoV-2, with the evidence for viral replication and an immune response being relatively stronger in one of these calves [76]. However, no calves showed clinical symptoms of infection and there was no transmission to SARS-CoV-2-naive contact calves, supporting that cattle have a low susceptibility to SARS-CoV-2 infection. A second study inoculated six six-week-old calves with SARS-CoV-2 via intratracheal or intravenous routes [77]. While these are not typical routes of infection by SARS-CoV-2, they exploit potential routes that would be most directly associated with tissues found to have the greatest ACE2 receptor distributions in cattle, i.e. the liver and kidneys. Nasal and rectal swab samples, as well as blood and urine samples, were collected at 12 dates over the course of the study (21 days) to evaluate viral shedding, viraemia and seroconversion. Only two nasal swabs from two calves and one tissue sample tested positive for SARS-CoV-2 by RT-qPCR; however SARS-CoV-2 RNA levels were low, there was a lack of evidence of viral replication in the calves, and no infectious virus was recovered. In another study, three calves were intranasally inoculated with SARS-CoV-2 but live virus was only subsequently detected in a trachea sample from one (a nasal and/or oral swab from one calf was also RT-PCR positive for SARS-CoV-2 but the report does not indicate if this was the same calf) [78]. The results suggested a local infection of the upper respiratory tract and no clinical signs of disease or fever following inoculation were noted.

Experimental inoculation of sheep resulted in limited infection, with SARS-CoV-2 RNA detected from nasal swabs at one day post-inoculation (7 of 8 sheep) and three days post-inoculation (1 of 8 sheep), and from respiratory and lymphoid tissues four and eight days post-inoculation [75]. Two sentinel sheep were co-mingled with the inoculated sheep; viral RNA was detected in the respiratory tract of these sheep at 21 days post-infection, but they remained seronegative. Neither the sentinel nor the inoculated sheep showed clinical signs of disease (weight loss, lethargy, diarrhoea, lack of appetite or respiratory distress). Four sheep were intranasally inoculated in another study; none of these sheep shed detectable virus, no viral RNA was detected from oral/nasal swabs, and animals did not display clinical symptoms [78]. In that study, results were similar for small sample sizes of inoculated rabbits, alpaca, goats and a horse; although there were positive RT-PCR results from oral/nasal swabs taken from two of three goats and one of four rabbits. Two further studies reported no evidence of SARS-CoV-2

infection (via antibody or RT-qPCR testing of animal samples) in sheep with close daily contact with people that had diagnosed with COVID-19 [79, 80]. There was also no evidence of SARS-CoV-2 infection of a range of other livestock species (horses, buffalo, poultry, cattle, goats, rabbits and pigs) following exposure to COVID-19-positive handlers [80]. Therefore, despite *in vitro* studies indicating that cattle and sheep may be minimally susceptible to SARS-CoV-2 infection, studies involving natural exposures and *in vivo* infection studies suggest that these species are unlikely to be relevant intermediary hosts of SARS-CoV-2.

Susceptibility to SARS-CoV-2 has also been studied in white-tailed deer (*Odocoileus virginianus*) [81]. The susceptibility to both SARS-CoV-2 infection and replication was first demonstrated *in vitro*, using deer lung cells which have a high degree of similarity of ACE2 to humans. Consistent with the *in vitro* findings, experimental infection carried out in four six-week-old deer via intranasal inoculation resulted in subclinical infection; the four deer did not display any clinical signs of infection over the entire 21-day experimental period other than a slightly elevated temperature (at the higher end or just above the expected physiological range). Viral RNA and infectious virus were detected in nasal secretions and intermittently in faeces from all inoculated animals. Furthermore, infected deer transmitted the infection to both non-inoculated deer that were housed in the same room but in a separate pen, separated by a plexiglass screen to prevent nose-to-nose transmission. Thus, transmission likely occurred via infected droplets or aerosols. White-tailed deer are abundant in North America, including in urban areas. There have now been numerous reports of spill-over from human populations to wild and captive white-tailed deer populations in North America, detected using serosurveillance or RT-qPCR-testing [82-86]. In addition to evidence for human-to-deer and deer-to-deer transmission, a further non-peer reviewed study has provided phylogenetic evidence of deer-to-human transmission [58]. The results indicate that white-tailed deer species are a potential source or reservoir for SARS-CoV-2 infection.

White-tailed deer are one of seven deer species established in the wild in New Zealand and are found in two main locations: 1) Stewart Island; 2) a 350 km^2 area at the head of Lake Wakatipu which includes the lower sections of the Rees River and Dart River valleys. The other species include red deer *(Cervus elaphus scoticus*; most common), elk (wapiti; *C. elaphus nelsoni)*, sika deer *(C. nippon)*, sambar *(C. unicolor)*, rusa deer *(C. timorensis)* and fallow deer *(Dama dama)*[31]. Red deer are also the most commonly farmed deer in New Zealand, followed by different subspecies of elk and European fallow deer[32]. Less information is available about the susceptibility of other deer species to SARS-CoV-2. One UK study did not detect spill-over into wild populations of six different deer species, which included three of the species found in New Zealand, but did not include white-tailed deer [87]. In laboratory studies, both white-tailed deer and mule deer (*Odocoileus hemionus*) primary lung cells were susceptible to infection and replication by SARS-CoV-2, but the results from elk lung cells suggests this species is not susceptible [88]. SARS-CoV-2 infection of wild mule deer has also been detected in the United

[31] https://www.doc.govt.nz/nature/pests-and-threats/animal-pests/deer/; accessed 11 April 2022
[32] https://www.mpi.govt.nz/dmsdocument/46027/direct; accessed 11 April 2022

States; the Delta variant was detected by positive nasal swab from one deer, and other deer were seropositive[33].

To further inform on the potential host range of animals that may be capable of harbouring SARS-CoV-2, a study assessed cross-species conservation of the ACE2 receptor (the main host cell receptor for SARS-CoV-2) from 410 vertebrates to predict its likelihood to function as a SARS-CoV-2 receptor [89]. Related approaches based on analysis of ACE2 orthologs have also been taken by other researchers [90-94]. The species assessed included 252 mammals, 72 birds, 65 fishes, 17 reptiles and four amphibians [89]. The study examined twenty-five amino acids corresponding to known SARS-CoV-2 S-binding residues for their similarity to the residues in human ACE2. The authors cautioned not to over-interpret the predictions made and that any predictions should be tested experimentally. Nonetheless, various predictions were consistent with published results on degrees of infectivity discussed above; for example, Rhesus macaques scored “very high” for ACE2 conservation and hence predicted risk of SARS-CoV-2 infection, cats scored “medium” and dogs and pigs scored “low”. The only discrepancy with experimental studies was for ferrets which had a “low” binding score.

Fish had a very low ACE2 conservation score (less than 18/25 ACE2 residues identical to human ACE2) thus were unlikely to be infected by SARS-CoV-2 via the ACE2 receptor; similar conclusions were also reached in another study [91]. Monotremes (egg laying mammals such as echidna), marsupials, birds (including poultry), amphibians and reptiles also had very low scores [89]. For other animals that may be domesticated and/or consumed as food sources, pigs had a low score; sheep, goats and cattle had a medium score, and deer had a high score. Another *in silico* study evaluating ACE2 binding potential suggested sheep in particular, as well as goats, cattle, camels and horses, could be susceptible to SARS-CoV-2 [91].

Although companion animals might have a role in disease transmission, and may theoretically become a reservoir for SARS-CoV-2, transmission from domesticated pets to humans is currently considered to be minor in the epidemiology of COVID-19 [95]. However, until more is known, the United States Centres for Disease Control and Prevention (US CDC) recommends limiting interaction with pets and other people or animals outside of the household. They also recommend that people with COVID-19 (either confirmed or suspected) should restrict contact with pets and other animals, as they would around other people[21]. The United States Department of Agriculture (USDA) has similarly produced guidance for zoos and captive wildlife facilities to protect susceptible animals from SARS-CoV-2 infection[34].

The likelihood for exposure of humans to SARS-CoV-2 through handling or consuming raw product from livestock or wildlife species from COVID-19-affected areas has been deemed to be low-to-negligible depending on the species and food hygiene standards, and negligible for heat-treated product where further cross-contamination cannot occur [96]. However, to limit the risk of transmission from wildlife and their derived meat, international agencies recommend that countries suspend the sale of captured live wild mammals in food markets, and they emphasize the importance of monitoring wildlife populations for SARS-CoV-2 infection [97]. They

[33] http://outbreaknewstoday.com/utah-confirms-first-case-of-covid-19-in-mule-deer-38746/; accessed 11 April 2022
[34] https://www.aphis.usda.gov/animal_welfare/downloads/ac-tech-note-covid-animals.pdf; accessed 12 April 2022

recommend that hunters should not track animals that appear sick, or harvest those that are found dead. Appropriate butchering and food preparation techniques, including proper hygiene practices to limit transmission of SARS-CoV-2 and other zoonotic pathogens is also paramount for processing both wildlife and livestock. The World Organisation for Animal Health has also produced guidance for working with farmed animals susceptible to SARS-CoV-2 infection (note that cervids are not mentioned) [98]. The guidance centres on reducing the risk of spill-over from humans to farmed animals.

4.2. Human-to-human transmission

4.2.1. *Transmission via airborne particles and respiratory droplets*

According to preliminary data from Guangzhou Center for Disease Control and Prevention (Guangzhou CDC) as of 20 February 2020, SARS-CoV-2 can initially be detected in upper respiratory samples 1-2 days prior to symptom onset [39]. From a systematic review of 79 studies, the mean duration of RNA shedding in the upper respiratory tract was 17.0 days (95% CI 15.5–18.6; 43 studies, 3229 individuals) with a maximum shedding duration of 83 days, peaking within the first week of infection [99]. The mean duration of shedding in the lower respiratory tract was 14.6 days (9.3–20.0; seven studies, 260 individuals) with a maximum duration of 59 days. However, infectious virus was not detected in respiratory samples beyond 9 days of illness, even when RNA shedding loads were high, which suggests that people are most infectious to others during the first 1–2 weeks of infection. Viral loads were similar between asymptomatic and symptomatic individuals infected with SARS-CoV-2, although most studies demonstrated a faster viral clearance among asymptomatic compared with symptomatic individuals. Note that these data were taken from studies before the Delta and Omicron variants came into prominence.

Transmission from asymptomatic and presymptomatic people can also occur [100-104]. From four clusters of COVID-19 in Singapore for which the date of exposure could be determined, presymptomatic transmission occurred one to three days before symptom onset in the presymptomatic source patient [104]. The relative importance of presymptomatic and asymptomatic transmission in the overall spread of COVID-19 disease is not well quantified but is considered to be important. Two models attempted to estimate the number of infections caused by asymptomatic, presymptomatic, or mildly symptomatic infected people (reviewed by [105]). While the modelling estimates varied widely (50% and 80%), both models and the described studies suggest that a significant number of people with asymptomatic or mildly symptomatic infections were not detected by the health system and these people meaningfully contributed to ongoing community transmission. However, symptomatic people are still considered to be more contagious. Dr. Charles Chiu (Professor of laboratory medicine in the Division of Infectious Diseases at University of California, San Francisco) was reported as saying:[35]

[35] https://www.nbcnews.com/health/health-news/can-coronavirus-be-spread-people-who-don-t-have-symptoms-n1140106; accessed 14 April 2022

""When somebody sneezes or coughs, the respiratory secretions are aerosolized, and if you're near, typically within 6 feet, you may be at risk of being exposed. That's the most common route of transmission. Patients who have minimal symptoms or no symptoms may be infectious — they may have the virus in their mucus or their secretions — but unless they're actually coughing or sneezing, it's unlikely that they would transmit to someone else." He said it's possible that someone who is infected but not sneezing or coughing could spread the virus by touching their nose, mouth or eyes and then contaminating a surface such as a doorknob that someone else then touches, but that's not the likeliest way the virus is spread."

Increasing evidence points to a high degree of heterogeneity in transmissibility between individuals, as captured by the 'k' parameter in transmission models. This indicates that more transmission comes from a small number of people, i.e. super-spreader events[36]. Adam Kucharski of London School of Hygiene and Tropical Medicine estimated that k for COVID-19 is as low as 0.1. "Probably about 10% of cases lead to 80% of the spread," Kucharski says [106]. Also, a non-peer reviewed study from Japan found that the risk of infection indoors is almost 19 times higher than outdoors [23]. This has important implications for the food industry as many outbreaks in meat packing plants and other food processing plants have now been reported (as discussed in Section 4.3.2).

Coronaviruses are generally thought to be spread from person-to-person through respiratory droplets, usually generated by coughing or sneezing. The viruses become associated with expelled droplets of different sizes. The traditional definition of respiratory droplets, which is used by WHO, refers to droplet particles that are relatively large (>5-10 µm in diameter)[37]. Such droplets are mostly associated with sneezing and coughing and they usually travel less than 1-2 m as they fall from the air more rapidly than droplet nuclei.

If the droplet particles are <5 µm in diameter, they have been referred to instead as droplet nuclei or aerosols and these particles can remain suspended in the air for longer periods of time and be transmitted over distances greater than 1-2 m. They are highly concentrated near an infected person, so they can infect people most easily in close proximity. If a virus can be spread in this manner it is referred to as being capable of airborne transmission. Recently, there have been calls to change the terminology to distinguish between aerosols and droplets using a size threshold of 100 µm, not the historical 5 µm [107]. This size more effectively separates their aerodynamic behaviour, ability to be inhaled, and efficacy of interventions.

Airborne transmission of SARS-CoV-2 was originally presumed to be limited to healthcare settings where aerosols are created by medical and dental procedures on infected people [108-112]. However, the scientific community has led active discussions evaluating whether SARS-CoV-2 may also be spread through aerosols in the absence of aerosol-generating procedures, particularly in indoor settings with poor ventilation [113-115].

[36] https://www.sciencemag.org/news/2020/05/why-do-some-covid-19-patients-infect-many-others-whereas-most-don-t-spread-virus-all; accessed 14 April 2022
[37] https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions; accessed 14 April 2022

Several super-spreading transmission events involving transmission between cases that were distanced more than 1 m apart support that airborne transmission may be occurring; early evidence includes the following:

- 94 out of a total of 216 employees working on the same floor in a South Korean call centre tested positive for COVID-19 (attack rate of 44%); most cases worked on the same side of the building [116]. The duration of the interaction between the workers was thought to be the main facilitator of transmission.
- In Guangzhou, China, 10 people from three families tested positive for COVID-19 after dining at the same restaurant [117]. Two of the families sat at neighbouring tables to the family containing the index case. The tables were >1 m from the index case, but were seated in the airflow of a recirculating air conditioning unit; no cases were reported amongst other diners that were not seated in the airflow.
- In the Zhejiang province of China, 23 out of a total of 67 people tested positive for COVID-19 (attack rate of 34%) after sharing a bus with an index case. The bus had recirculated air conditioning. Proximity to the index case did not result in a significantly higher risk for COVID-19 compared with those seated further from the case, suggesting that airborne transmission was occurring [117].

Probable cases of airborne transmission have also been reported in New Zealand managed isolation and quarantine facilities (MIQF) [118][38,39]. One transmission event was originally hypothesised to have occurred via a rubbish bin based on CCTV footage showing that Case C, who later tested positive but may have been infectious at the time of contact, contacted the same bin before Case D, who also later tested positive for SARS-CoV-2 that was genetically linked[40]. However, the time span between the two bin contact events was >20 hours, and no environmental testing of the rubbish bin surfaces was conducted to support the hypothesis. Instead, airborne transmission is now considered to be the more likely transmission scenario, which is thought to have taken place within the doorway of the adjacent hotel rooms of the cases when there was a 50-second window between closing the door to Case C's room and opening the door to Case D's room. The enclosed and unventilated space in the hotel corridor is thought to have facilitated this event. At least four additional transmission events at two other New Zealand MIQF were also likely due to airborne transmission; at least two of which were likely through exposure to aerosols in a poorly ventilated lift or lift lobby, and one via hotel room doors open at the same time[38,39]. Similar events have been reported in Australian MIQFs[41]. MIQF transmissions have been reported to be a consequence of using non-purpose built facilities with confined, poorly ventilated shared spaces, and practices resulting in relatively unrestricted funnelling of returnees through poorly ventilated shared indoor transit areas such

[38] https://www.miq.govt.nz/assets/MIQ-documents/case-incident-review-pullman-march-2021.pdf; accessed 14 April 2022
[39] https://www.stuff.co.nz/national/health/coronavirus/300383287/covid19-delta-transmission-at-aucklands-jet-park-miq-hotel-via-opening-of-doors; accessed 14 April 2022
[40] https://www.health.govt.nz/news-media/media-releases/no-new-cases-covid-19-50; accessed 14 April 2022
[41] https://theconversation.com/more-than-a-dozen-covid-leaks-in-6-months-to-protect-australians-its-time-to-move-quarantine-out-of-city-hotels-159808; accessed 14 April 2022

as lifts and lift lobbies. Based on the findings, new recommendations and guidelines were made to improve the safety and effective functioning of the MIQF system[38].

The recognition that airborne transmission may be more relevant than originally thought has important implications for transmission mitigation strategies. The current guidance from numerous international and national bodies to reduce transmission of SARS-CoV-2 is based on transmission being predominantly via respiratory droplets (hand washing and maintaining physical distancing). Mitigation based on transmission being airborne has only focussed where aerosol-generating procedures are performed in healthcare settings. Therefore, it has been suggested that while hand washing and social distancing are appropriate, these might be insufficient to provide protection from virus-carrying respiratory microdroplets released into the air by infected people. In addition to mask wearing, measures that have been suggested to mitigate airborne transmission risk include [113]:

- Provide sufficient and effective ventilation (supply clean outdoor air, minimize recirculating air) particularly in public buildings, workplace environments, schools, hospitals, and aged care homes.
- Supplement general ventilation with airborne infection controls such as local exhaust, high efficiency air filtration such as high-efficiency particulate air (HEPA) filters used on commercial aircraft, and germicidal ultraviolet lights.
- Avoid overcrowding, particularly in public transport and public buildings.

4.2.2. *Transmission via contaminated surfaces (fomites)*

Respiratory droplets expelled by infected individuals can land on surfaces and objects, creating contaminated surfaces (fomites). Infectious SARS-CoV-2 and/or RNA can be detected on contaminated surfaces for periods ranging from hours to days under experimental conditions, depending on the concentration of infectious SARS-CoV-2 present to begin with, surface material, ambient environment and disinfection procedures (see Section 5). While it may be possible that a person can become infected with SARS-CoV-2 by touching a surface or object that has the virus on it and then touching their own mouth, nose, or possibly their eyes, there is currently little formal evidence of this occurring. Each transfer step will involve reduction in the number of infectious particles. However, self-inoculation is considered to be an important mechanism for transmission of other respiratory viruses [119, 120]. Evidence of transmission of SARS-CoV-2 via fomites is challenging to demonstrate, but there is circumstantial evidence of it occurring [104, 121-124]. As such, this is the basis of handwashing and limiting hand-to-face touching as preventative measures for transmission of SARS-CoV-2 [125]. The US CDC have provided a science brief on the potential for fomite transmission, published on 5 April 2021[42]. This concluded that: "*People can be infected with SARS-CoV-2 through contact with surfaces. However, based on available epidemiological data and studies of environmental transmission factors, surface transmission is not the main route by which SARS-CoV-2 spreads, and the risk is considered to be low.*"

[42] https://www.cdc.gov/coronavirus/2019-ncov/more/science-and-research/surface-transmission.html; accessed 14 April 2022

The majority of experiments looking at SARS-CoV-2 infectivity on surfaces inoculated high virus amounts (4–7 log_{10} of 50% tissue culture infectious dose ($TCID_{50}$), or plaque forming units (PFU)) onto a small surface area, which is necessary to measure sufficient log reductions in infectivity over time (see Section 5). The experiments were also performed under ideal conditions. In real-world contamination events, other factors will play a significant role in the persistence and infectivity of SARS-CoV-2 on surfaces, such as ultraviolet (UV) light, air flow and mechanical forces. As discussed by Goldman [126, 127], these experimental concentrations are likely higher than those in droplets in real-life situations, with the amount of virus actually deposited on surfaces likely to be several orders of magnitude lower. In their opinion, because the concentration of viral particles surviving on food or packaging surfaces is likely to be orders of magnitude lower than from respiratory droplets from an infected person, the chance of transmission through inanimate surfaces is very small. They consider that this is most likely to occur when an infected person coughs or sneezes on the surface, and someone else touches that surface soon after the cough or sneeze (within 1–2 h). Kanamori (2020) and Mondelli *et al.* (2020) have also suggested that environmental contamination studies should be interpreted with caution [128, 129]. Support for their statement was based in part on various studies that evaluated real-life contamination of hospital surfaces and equipment using both RT-qPCR and viral culture; infectious SARS-CoV-2 was rarely detected despite detection of SARS-CoV-2 RNA on surfaces [130-133].

A US CDC science brief has reviewed quantitative microbial risk assessment approaches to estimate and compare COVID-19 infection risks after single hand-to-fomite-to-mucosal membrane contacts[42]. The studies reviewed suggest that the risk of SARS-CoV-2 infection via fomite transmission is low, and generally less than 1 in 10,000, i.e. each contact with a contaminated surface has a <1 in 10,000 chance of causing an infection. However, both the US CDC and Kanamori (2020) noted that until more information is available about fomite transmission of SARS-CoV-2, cleaning and disinfection procedures for surfaces using agents effective against SARS-CoV-2 is pertinent, particularly in indoor settings where there has been a suspected or confirmed case in the previous 24 hours.

In light of the concerns around the potential for transmission via cold-chain products (discussed in Section 4.3.2), a study quantified the risks attributed to fomite-mediated SARS-CoV-2 transmission among workers in a representative frozen food packaging facility under cold-chain conditions [134]. They calculated that the risk to susceptible workers of fomite-mediated transmission from contaminated plastic packaging under cold-chain conditions was extremely low, below an infection risk threshold of 1.5×10^{-3} per 1-hour period. Mitigation approaches such as hand-washing, masking, vaccination or disinfection of the packaging, all reduced the infection risk >100-fold. The mitigation approaches continued to significantly control the risk of fomite transmission when modelling simulated increased infectiousness and transmissibility of new variants (including Delta and Omicron; 2–10-fold increased viral shedding). Additional decontamination of frozen food plastic packaging would reduce the infection risk even further, but because the risks were so low with the standard mitigation methods, the study concluded that the decontamination provided minimal benefit.

There are studies that suggest transmission via fomites but these lack evidence of infectious virus being detected on the shared surfaces (although such evidence is very difficult to obtain). In addition, airborne transmission could not be ruled out in some of these studies:

- Transmission within an elevator was the suspected cause of a large (>71 cases) outbreak that occurred in Heilongjiang Province, China [121]. The initial case appeared to be an asymptomatic carrier, previously infected in the United States, and who had no physical contact with the second case, a downstairs neighbour. The investigators believed that the second case was infected by contact with surfaces in the elevator in the building where they both lived. Other residents in the building tested negative for SARS-CoV-2 infection, both by RT-qPCR and testing for serum antibodies. Whole genome sequencing of the viral RNA confirmed the linkages between the cases. Subsequent transmission from the second case was via person-to-person transmission at gatherings and within a hospital. No sampling of the elevator surfaces was reported.

- A study of a cluster of COVID-19 cases in a shopping mall in Wenzhou, China, suggested that indirect transmission may have occurred via fomites (e.g. elevator buttons or restroom taps, although these were not tested) [135]. Most cases reported symptom onset within the same concentrated time period. The mall consisted of several floors and besides cases that shared an office on one floor, there was no known contact between cases. However, the authors could not rule out transmission from asymptomatic carriers or virus aerosolisation within confined spaces within the mall.

- Transmission of the Omicron variant via an international mail package sent from Canada to China was reported [123]. The index case, who had no recent travel history, received the package two days before symptom onset. Although disinfection of the package exterior was carried out when the package arrived in Beijing, 12 of 22 swabs (2 from outside the package, 2 from inside, and 8 from papers within the package that were untouched by the case) tested positive by RT-qPCR for SARS-CoV-2. All positive samples from the package, the index case and five close contacts of the index case who also tested positive in health screenings, carried the Q498R mutation present in the Omicron variant. Viral genetic material obtained from inside the package was genomically linked with that from the case and close contacts that also tested positive, and was distinct from other strains circulating in China at the time. The presence of infectious virus on or in the parcel was not tested. Although the period of time between the package being mailed and being opened by the case was not reported, the package was delivered from abroad four days prior to receipt by the case. The time period for which SARS-CoV-2 would need to remain active for the reported transmission to have occurred is considerably longer than the reported 30 minutes persistence time on paper of an earlier SARS-CoV-2 strain, reported by Chin *et al.* (2020) [136] and discussed in Section 5.1.

- Further reports involving transmission via cold-chain food packaging are discussed in Section 5.3.2

Transmission via contaminated surfaces was originally hypothesised to have occurred in two New Zealand quarantine facilities, via a lift button in one instance and a rubbish bin in the other[39,43]. However, as discussed Section 4.2.1, the transmission event thought to be due to the rubbish bin contact is now suspected to have occurred by an airborne route, which is also a likely scenario for the transmission where the lift button was originally suspected.

4.2.3. *Faecal-oral transmission*

The role and significance of the faecal-oral route for COVID-19 remains to be determined and is not thought to be a main driver of COVID-19 transmission. While person-to-person transmission by respiratory droplets is considered the primary transmission route, it is still possible that faecal-oral transmission could occur. Faecal-oral transmission could hypothetically occur directly, or indirectly via contaminated food, water, aerosol or fomites.

The first indication that faecal-oral transmission might occur is that various studies have reported that many COVID-19 patients experience gastrointestinal symptoms, which is also common for foodborne diseases. Only a small percentage of COVID-19 cases were reported with nausea or vomiting (1-5%), or diarrhoea (2-10%) in early studies [39, 137-140]. One review of 23 published and 6 preprint studies, including results from 4805 patients, reported a pooled rate of 12% of patients with COVID-19 that manifested GI symptoms [141]. Another review, collating data from 2023 patients where presence or absence of gastrointestinal symptoms had been reported, showed that the prevalence of gastrointestinal symptoms varied [142]. This review did not pool data. Anorexia was the most frequent digestive symptom in adults (40-50%), while diarrhoea was the most common symptom both in adults and children (2-50%), and vomiting was more common in children (4-16% of adult patients vs. 7-67% of child patients). Nausea was experienced by 1-29% of patients, and gastrointestinal bleeding by 4-14%. Abdominal pain was relatively rarer (2-6%) and associated with severely ill patients. Patients can present with diarrhoea and vomiting with only low-grade or no fever, and without a cough [143]. Of 1472 symptomatic COVID-19 cases in New Zealand, approximately 5% presented with abdominal pain, 11% with nausea or vomiting, and 14% with diarrhoea [48]. Note that studies were reported before the emergence of the Delta and Omicron variants. However, the occurrence of symptoms at a particular body site does not necessarily imply that the virus is replicating at or directly targeting that site; it is also possible that symptoms might instead be indirect. Indeed, Rhesus monkeys that were intranasally inoculated with SARS-CoV-2 were found to have infection and pathologic changes not only in respiratory tissues but also in digestive tissues [144].

The presence of SARS-CoV-2 RNA, as detected by RT-qPCR, has been frequently reported in faeces, as well as the oesophagus, stomach and duodenum of COVID-19 cases [39, 52, 145-151]. The percentage of COVID-19 patients in which SARS-CoV-2 RNA was detected in faeces varied depending on the study (reviewed by [152]). One systematic literature review which

[43] https://www.stuff.co.nz/national/health/coronavirus/122512325/coronavirus-mystery-rydges-case-possibly-linked-to-use-of-hotel-elevator; accessed 14 April 2022

pooled data from eight studies reported detection of SARS-CoV-2 RNA in faeces from 40.5% (95% CI, 27.4%-55.1%) of patients confirmed as being infected by SARS-CoV-2 [141]. A similar approach that pooled data from 26 publications reported that 53.9% (291 of 540) of faecal samples tested for SARS-CoV-2 RNA were positive [153]. However, higher faecal detection rates of 55% (41/74) [145], 59% (55/96) [150] and 67% (28/42) of SARS-CoV-2 in patients [151] have been reported. By comparison, SARS-CoV RNA was highly prevalent in faecal samples from SARS patients (87% (82/94) of samples) [154]. However, the detection rate was lower for MERS-CoV RNA in faeces from MERS patients (15% (12/82) of samples) [155, 156].

The amount of SARS-CoV-2 detected in faeces by RT-qPCR is highly variable depending on the day of sampling post-onset of COVID-19 disease. Concentrations up to 10^8 genome copies per gram of faeces have been reported [52, 157-159]. Concentrations of SARS-CoV-2 in faeces were at their highest level when peak levels were detected in nasopharyngeal swabs and sputum, which was around the time of, or in the first week of symptom onset [52, 160].

From 26 studies, the duration of faecal viral shedding ranged from 1 to 33 days after a RT-qPCR-negative nasopharyngeal swab was obtained, with one patient remaining RT-qPCR-positive 47 days after onset of symptoms [153]. Another systematic review of 13 studies comprising 586 individuals reported a mean duration of faecal shedding of 17.2 days (95% CI 14.4–20.1 days) with a maximum of 126 days [99]. In one study, faecal samples from 43 out of 55 patients still tested positive for SARS-CoV-2 RNA 1–4 days after throat swabs were negative [161]. SARS-CoV-2 viral RNA could also be detected in anal swabs taken over a 42-day period from a child who remained asymptomatic [162].

For faecal-oral transmission to occur, the virus must remain infectious in faeces. It is not clear whether the detection of SARS-CoV-2 RNA by RT-qPCR in faeces always correlates with the presence of infectious virus. Researchers from one publication found high concentrations of SARS-CoV-2 in 13 faecal samples from four patients in their study, but they were unable to grow the virus in cultured cells which would have demonstrated virus infectivity [52]. Although it is fairly common to detect SARS-CoV-2 RNA in faeces, the presence of infectious SARS-CoV-2 in faecal samples has only been demonstrated for a small number of patients [146, 152, 163, 164]. One study suggested that this might be due to the cytotoxicity of urine and faecal specimens in cell culture [165]. Although the study was unable to isolate infectious SARS-CoV-2 directly from stool and urine samples, they detected infectious virus from nasal washes from ferrets that had been inoculated with urine and stool samples from COVID-19 patients. Studies indicate that infectious SARS-CoV-2 could be present in faeces, but the concentration of infectious particles over time in any one patient, and the prevalence among patients, have not been quantified.

It is possible that the viral RNA detected in faeces arises from virus-containing mucus that has been swallowed from the upper respiratory tract. Coronaviruses, like influenza viruses, are enveloped viruses and therefore can be inactivated by low pH and are vulnerable to surfactants such as bile [166]. The mucus might protect the virus from inactivation or degradation by the gastrointestinal environment; this has also been proposed to describe the presence of influenza

A virus in faeces [167]. However, as an infected person can be RT-qPCR-positive for SARS-CoV-2 in faeces for many days or even weeks after they become RT-qPCR-negative in a throat swab, this suggests that either viral replication in the gastrointestinal tract is occurring [52] or there is a slow clearance of residual RNA fragments. Intestinal epithelial cells express the ACE2 receptor, which the virus uses to enter cells [168]. SARS-CoV-2 could be reaching the ACE2-rich intestinal epithelial cells of the small and large intestine via the blood rather than the gastrointestinal tract. SARS-CoV-2 RNA could be detected in plasma or serum from a low proportion of COVID-19 patients, with prevalence estimates of 3/307 [146], 2/9 [169] and 9/323 [170] having been reported.

In a study published in September 2020, Kang and colleagues report circumstantial evidence for faecal-aerosol transmission of SARS-CoV-2 involving nine infected individuals from three families residing in three vertically aligned flats with interconnected drainage pipes in a high-rise apartment building in Guangzhou, China [171]. Members from family A contracted COVID-19 following travel to Wuhan, while the other two families had no travel history and developed symptoms later than family A. No evidence was found for direct contact between the families, nor transmission via other sources such as the elevator. The viral particles were hypothesized to have been carried on air streams within the drainage pipe network and entered the building interior from the wastewater system. The infectious aerosols may have been formed as the result of toilet flushing or turbulent flows within a wastewater plumbing system containing virus-laden faeces, with transmission occurring either by inhalation of aerosolised virus or from contact of contaminated surfaces. Although there was no direct evidence for the presence of virus-laden bioaerosol of faecal origin in the drainage pipe system, surface samples tested positive for SARS-CoV-2 RNA from the bathrooms used by family A, and a bathroom from another vertically aligned flat that had been uninhabited since before the outbreak. Furthermore, tracer gas used as a surrogate for virus-laden aerosols, was released into the drainage stack of family A's bathroom, which was detected in bathrooms from all vertically aligned flats tested.

To our knowledge, this is the first report of potential faecal transmission of SARS-CoV-2, although transmission via other excreted body fluids such as nasal mucous or urine cannot be excluded. Similar evidence implicating the wastewater plumbing system was also provided for the transmission of SARS-CoV in the high-rise Amoy Gardens housing complex in Hong Kong, which led to the infection of 321 people and resulted in 42 deaths [172, 173]. The World Health Organization Consensus Document on the epidemiology of SARS previously stated:[44]

"The role of faecal-oral transmission is unknown; however, there is no current evidence that this mode of transmission plays a key role in the transmission of SARS though caution was expressed on this point because of the lack of surveys and transmission studies among children where this is a common mode of transmission of other viral infections."

[44] https://www.who.int/publications/i/item/consensus-document-on-the-epidemiology-of-severe-acute-respiratory-syndrome-(-sars); accessed 14 April 2022

4.2.4. *Transmission via breast milk*

The transmission of disease via breastfeeding is a specific person-to-person pathway when a mother is directly feeding an infant, but transmission via breast milk can also be considered foodborne, more-so when the milk is collected for later consumption. Currently, there is limited information regarding mother-to-infant vertical transmission, and no evidence of SARS-CoV-2 transmission through breast milk. Understanding the risk posed by SARS-CoV-2 present in human milk has implications for ensuring the safety of breast-fed babies as well as human milk banks that provide donor human milk to vulnerable infants who lack access to their mother's own milk. However, Holder pasteurisation, which is a common process in milk banks worldwide, has been shown to inactivate SARS-CoV-2 in human milk (see Section 5.1).

SARS-CoV-2 RNA has been detected in breast milk of women with COVID-19 by a number of studies; however, infectious virus was either not detected or not tested for [174-178]. For example, a non-peer reviewed preprint reported the detection of SARS-CoV-2 RNA in milk from 6 of 65 women (9.2%) with recent confirmed infection, but neither infectious virus nor sub-genomic RNA (a potential marker of virus infectivity) were detected in any of the samples [178]. One study reviewed 37 articles that had analysed breast milk samples from 77 mothers with COVID-19 who were breastfeeding their children; 19 of 77 children were confirmed COVID-19 cases, including 14 neonates and five older infants [174]. Nine of 68 breast milk samples from mothers with COVID-19 were positive for SARS-CoV-2 RNA; four of the six infants exposed to the SARS-CoV-2-positive milk were positive for COVID-19. One study reported that one baby was inadvertently fed SARS-CoV-2-positive breast milk but did not develop COVID-19 [177]. In most instances, demonstrating that the milk was the vehicle of transmission is challenging due to the close contact between the mother and infant, meaning that airborne transmission could not be ruled out; other possible routes of transmission for neonates might include trans-placentally or during birth.

SARS-CoV-2 IgA, IgG and or IgM antibodies have been detected in milk from mothers that had recovered from COVID-19 [179]. Rather than being a source of transmission, it has been postulated that breast milk might instead provide a protective effect against SARS-CoV-2 transmission, but there is currently no evidence of this effect.

4.3. Foodborne transmission

The predominant ways in which SARS-CoV-2 is likely to contaminate food and packaging is directly from respiratory droplets emitted by people infected with COVID-19, via sneezing, coughing, talking and shouting, or indirectly from contaminated hands or surfaces. As discussed, other pathways include food sourced from infected animals (see Section 4.1), faecal-oral contamination of food either directly or via contaminated water used for irrigation or food processing (Section 4.2.3), or human breast milk sourced from infected mothers (particularly if it is collected for later consumption; Section 4.2.4). The persistence of infectious virus after a contamination event is discussed later in Section 5.

Specific evidence is needed to confirm that COVID-19 infection has occurred via a foodborne route. Such evidence includes:

1. The occurrence of more than one person developing COVID-19 following the consumption of a common food during an epidemiologically relevant time period (with stronger evidence for foodborne transmission being when the cases are not close contacts, i.e. person-to-person transmission is unlikely),
2. Detection of SARS-CoV-2 RNA and/or culture of infectious virus from the food (with the latter providing stronger evidence), and/or
3. Demonstration of a genetic linkage between the SARS-CoV-2 found in the food and from an epidemiologically linked case.

In contrast to the rare reports of SARS-CoV-2 detection from foods, foodborne viruses such as norovirus are commonly detected from food [180]. Thus, while an outbreak of norovirus infection (for example) would trigger food testing as part of outbreak investigations, an outbreak of COVID-19 is unlikely to trigger the same epidemiological approaches; food that cases may have consumed would rarely, if ever, get tested for SARS-CoV-2 [181]. Unlike SARS-CoV-2, foodborne viruses are commonly non-enveloped viruses, and show high stability toward environmental stresses, e.g. high temperatures, desiccation and pH extremes. As is common for foodborne diseases, and as discussed in Section 4.2.3, COVID-19 patients often experience gastrointestinal symptoms. However, the occurrence of symptoms at a particular body site does not necessarily imply that the virus is replicating at or directly targeting that site; it is also possible that symptoms might instead be indirect.

Two mechanisms by which food could hypothetically act as a source or vehicle for transmission of SARS-CoV-2 were considered in this report:

1. **The potential for development of COVID-19 via ingestion of SARS-CoV-2-contaminated food.** When food is consumed, any pathogens that may be in or on the food are also consumed. The ability of these pathogens to cause infection or illness depends on a number of factors related to the food, the pathogen, and the person consuming the food. Laboratory studies have shown that SARS-CoV-2 can infect cells in the oral cavity and salivary glands, and in the gastrointestinal tract [182-184]. Therefore, it is possible that infection of the oral mucosa could occur, or possibly of cells in the pharynx as the food passes through to the oesophagus. However, there is a low likelihood of this as the virus would be mixed and diluted with food, and the transit time in the mouth and oesophagus is relatively quick, so the bolus does not stay in contact with cells in the mouth and throat for long.

   The ability to retain infectivity in gastrointestinal fluids would be one prerequisite for SARS-CoV-2 to establish infection in the human alimentary tract. Coronaviruses are considered to be sensitive to acidic pH and bile [185] and for this reason it is conceivable that a higher infectious dose would be necessary compared with a respiratory route of infection. Researchers have postulated that there may be an increased risk of infection following

ingestion of SARS-CoV-2 under conditions that increase stomach pH [186, 187]. This might occur following ingestion of certain foods, for individuals taking medication to reduce gastric activity, or for individuals with low stomach acid (hypochlorhydria) as a result of aging or a medical condition such as atrophic gastritis or *Helicobacter pylori* infection. A study whereby Rhesus monkeys were inoculated with an intragastric challenge (via gavage) of very high titres (10^7 PFU in 1 ml buffer) of SARS-CoV-2 resulted in infection of digestive tissues and inflammation in both the lung and digestive tissues [144]. Although sufficient virus remained infectious following transit through the stomach to cause infection, inoculated concentrations were significantly higher than would likely be present in or on food. Furthermore, the inoculum was not mixed with food so the results do not represent a realistic food consumption scenario.

2. **The potential for indirect transmission via food or food packaging acting as a fomite.** Transmission might occur when one touches virally-contaminated food or packaging and subsequently touches one's mouth, nose or eyes, or alternatively, inhales SARS-CoV-2 present on or in food during consumption. However, for this scenario to occur, the SARS-CoV-2 present on the food or packaging would need to still be infectious and in high enough numbers to provide an infectious dose after several transfer steps, and then the person would need to infect him/herself by touching their nose, mouth, or eyes. Even if this hypothetical scenario was proven to lead to infections, in terms of overall transmission, this route of infection is considered to be very minor[45].

4.3.1. *International consensus on the likelihood of foodborne transmission of SARS-CoV-2*

The consensus from international organisations and regulatory authorities is that there is currently no evidence for foodborne transmission of SARS-CoV-2 and it is highly unlikely that food or food packaging are sources or routes of transmission of SARS-CoV-2. The International Commission on Microbiological Specifications for Foods (ICMSF) has stated (3 September 2020) that "*Despite the many billions of meals consumed and food packages handled since the beginning of the COVID-19 pandemic, to date there has not been any evidence that food, food packaging or food handling is a source or important transmission route for SARS-CoV-2 resulting in COVID-19*". [46]

The most recent restatement of this view from international authorities is from the Food and Agriculture Organisation (2 August, 2021).[47] From this report:

"Current data indicates that neither food nor food packaging is a pathway for the spread of viruses causing respiratory illnesses, including SARS-CoV-2. In other words, SARS-CoV-2 is

[45] https://www.foodsafetymagazine.com/enewsletter/sars-cov-2-and-the-risk-to-food-safety/?mobileFormat=false; accessed 14 April 2022
[46] https://www.icmsf.org/wp-content/uploads/2020/09/ICMSF2020-Letterhead-COVID-19-opinion-final-03-Sept-2020.BF_.pdf; accessed 14 April 2022
[47] http://www.fao.org/3/cb6030en/cb6030en.pdf; accessed 14 April 2022

not a direct food safety concern. However, it is important for the food industry and authorities regulating the food industry to protect all workers from person-to-person spread of these viruses by providing a safe work environment, promoting personal hygiene measures and providing training on food hygiene principles."

MPI have also released a statement (13 August 2020) describing the risk of transmission through food packaging as negligible.[48]

4.3.2. *Outbreaks associated with food service, production and wholesale facilities*

Food service workers represented a high proportion of the infected crew members involved in a large outbreak on a cruise ship (in Japan) during February 2020 [188]. A total of 15/20 of infected crew members were food service workers who prepared food for other crew members and passengers. These workers lived on the same deck and congregated with other crew in the shared dining area. It was considered that transmission was probably through contact or droplet spread, which is consistent with the current understanding of COVID-19 transmission.

Internationally, multiple outbreaks of COVID-19 have occurred among meat, poultry, seafood, fruit and vegetable processing facility workers. Early examples include:

- A meat-processing facility in Melbourne, Australia (111 cases as of 23 May 2020)[49].
- A meat-processing facility in Germany (more than one thousand cases)[50].
- Three meat and poultry-producing facilities in England and Wales (although the high number of cases in one facility was likely to reflect the high prevalence in the community)[51].
- A seafood-processing plant in Ghana (534 cases)[52].
- Multiple meat, poultry and seafood processing facilities in the United States [189-192]. Data submitted during the week of 20-27 April 2020 showed that COVID-19 was diagnosed in approximately 3% (4913/130578) of workers in 115 meat and poultry processing plants, and that there were 20 COVID-19–related deaths [189]. As of 21 July 2020, the total excess of COVID-19 cases and deaths associated with proximity to livestock plants in the US was estimated to be 236,000-310,000 cases (6-8% of total cases) and 4,300-5,200 deaths (3-4% of total deaths) with the majority related to community spread outside these plants [193]. The association was mainly focused around large processing facilities.
- Multiple fruit and vegetable producing and packing facilities in the United States [190].

Workers were not thought to be exposed to SARS-CoV-2 through the food products they handled. Instead, aspects of their work environments, including processing lines, and other

[48] https://www.mpi.govt.nz/dmsdocument/41614/direct accessed 14 April 2022
[49] https://www.dhhs.vic.gov.au/coronavirus-update-victoria-23-may-2020; accessed 14 April 2022
[50] https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/Situationsberichte/2020-06-21-en.pdf?__blob=publicationFile; accessed 14 April 2022
[51] https://www.bbc.com/news/uk-england-leicestershire-53100321; accessed 14 April 2022
[52] https://www.reuters.com/article/us-health-coronavirus-ghana/president-says-one-person-infected-533-with-coronavirus-at-ghana-fish-factory-idUSKBN22N02J; accessed 14 April 2022

areas in busy plants where they have close contact with co-workers and supervisors, were thought to place them at increased risk of exposure [193, 194][53]. Depending on the industry, many workers also had close contact via shared transportation and housing. In addition, the working environment in facilities (particularly, meat-processing) are favourable to SARS-CoV-2 persistence (metallic surfaces, low temperatures and relative humidity). Such noisy environments can also result in raised voices to overcome noise, increasing SARS-CoV-2 aerosolisation. The pace and physical demands of factory work also make it hard for workers to wear face coverings properly, and CDC observers have noticed that workers tended to cover just their mouths, not their noses, and frequently readjusted their masks[53]. In some industries, a vulnerable, low-paid workforce may be under pressure to keep working despite having symptoms of COVID-19. The US Department of Labor has produced guidance on mitigating and preventing the spread of COVID-19 in the workplace, including in meat and seafood processing facilities[54]. The NZ meat industry and seafood industry have both instituted protocols to manage risk of COVID-19 for continuation of meat processing[55,56]. In addition, given the greater risk associated with larger meat processing facilities, it has been proposed that ensuring both public health and robust essential supply chains might require an increase in meatpacking oversight and a shift toward more decentralized, smaller-scale meat production [193].

Auckland August 2020 Cluster involving Americold cool store employees

After 102 days with no community cases, a New Zealand COVID-19 outbreak occurred in which the index case was an employee at an Auckland Americold cool store[57] which distributes frozen goods that are manufactured both domestically and overseas[58]. The outbreak designated the Auckland August Cluster involved a total of 179 cases[59] as verified by contact tracing and/or whole genome sequencing of the virus from cases; all 145 sequenced positive cases belonged to a single cluster [195]. Ten of the cases were workers or contractors at the Americold plant[60].

The outbreak strain belongs to a lineage that is in multiple continents around the world and has only been observed once before in New Zealand, in a pair of cases in mid-April who were in managed isolation in Auckland (although the complete genome information is not available for all cases in New Zealand; around 40% contain too little or too degraded RNA to obtain a full genome sequence) [195, 196]. The mid-April case was not thought to be the progenitor of the Auckland August Cluster because although the genomes are only one mutation different, the

[53] https://www.cebm.net/covid-19/what-explains-the-high-rate-of-sars-cov-2-transmission-in-meat-and-poultry-facilities-2/; accessed 14 April 2022
[54] https://www.osha.gov/coronavirus/safework; accessed 7 September 202114 April 2022
[55] https://mia.co.nz/covid-19-response/mia-protocol/mia-protocol/; accessed 7 September 202114 April 2022
[56] https://www.seafoodnewzealand.org.nz/industry/covid-19-information/; accessed 7 September 202114 April 2022
[57] https://www.stuff.co.nz/national/health/coronavirus/300082948/coronavirus-earliest-known-case-in-covid19-cluster-was-americold-employee; accessed 14 April 2022
[58] https://www.stuff.co.nz/business/industries/122432186/americolds-covidlinked-coolstore-facility-supplies-supermarkets-and-fastfood-outlets; accessed 14 April 2022
[59] https://www.health.govt.nz/our-work/diseases-and-conditions/covid-19-novel-coronavirus/covid-19-data-and-statistics/covid-19-source-cases#clusters-news; accessed 14 April 2022
[60] https://www.rnz.co.nz/news/national/423743/covid-19-ministry-investigating-melbourne-based-americold-cases-to-provide-clues-on-cluster; accessed 14 April 2022

strains are over three months apart in time, which is inconsistent with the known mutation rate of two mutations each month for SARS-CoV-2 (note also that the April genome was incomplete, so genomes may be more different than they appear). It is also unlikely that the infection remained undetected for four months in the community before turning up as the single lineage in the Auckland August Cluster.

Concern was raised that the frozen products imported by the company were instead the source of the outbreak. Cases were also reported among employees in an Americold facility in Melbourne, which raised the question of whether the outbreak strain may have arisen from contaminated freight imported from Melbourne[60]. However, environmental testing at the Melbourne plant did not detect the virus, and the chief executive for Americold in New Zealand and Australia has indicated that the Melbourne site had not shipped freight to the Auckland site[61]. Furthermore, isolates from the Auckland August Cluster and Melbourne Americold cluster were not closely genetically related (Joep de Ligt, ESR, pers. comm.). The cluster is most closely related (one mutation different) to two SARS-CoV-2 genomes from Ecuador that were sampled in August 2020. Although China has reported the detection of SARS-CoV-2 on frozen shrimp from Ecuador (see below), no shipments from Ecuador were received by the Auckland Americold cool store [196]. Environmental testing carried out at the Auckland Americold plant by Ministry for Primary Industries and ESR detected very low levels of SARS-CoV-2 on 4 of the 35 gauze swabs taken at sites likely to be touch zones for Americold employees who had tested positive[62]. In addition, samples taken from a second Auckland Americold plant, from which no cases among employees were reported, all tested negative for SARS-CoV-2. Therefore, no evidence was found that to support that contaminated imported chilled material packaging was the source of infection for the outbreak. To date, the source of the Auckland August cluster outbreak has not been identified, and the most likely scenario is thought to be border incursion from an infected traveller that acquired the disease while overseas [196].

Outbreaks in Chinese cities with reported links to imported cold-chain products and associated repercussions

Seven occurrences of COVID-19 disease re-emergence, involving 689 infected cases, have been documented in Chinese cities with reported links to imported cold-chain products or packaging [197], and are described below. For each report, the direction of the transmission was not demonstrated and alternative transmission routes were also possible. Despite the reporting of cases linked with handling of imported frozen food, there have been no known reports of COVID-19 infection following direct consumption of contaminated foods[63].

A large COVID-19 outbreak was associated with Beijing's largest wholesale market, Xinfadi market. On 11 June 2020, after 56 days with no cases in Beijing, a case with no known travel

[61] https://www.smh.com.au/world/oceania/new-zealand-cluster-grows-to-35-confirmed-cases-melbourne-link-to-outbreak-investigated-20200815-p55m0u.html; accessed 14 April 2022
[62] https://www.health.govt.nz/news-media/media-releases/5-new-cases-covid-19-3; accessed 14 April 2022
[63] https://www.globaltimes.cn/page/202108/1232802.shtml; accessed 14 April 2022

history or contact with a known case was identified[64,65]. As of 18 June 2020, 172 linked cases had been reported[66]. Chinese officials closed the market and carried out SARS-CoV-2 testing of people that had visited the market as well as environmental sampling of market surfaces. Testing found that 40 environmental surfaces tested were positive for SARS-CoV-2. One of these items was a chopping board that had been used to chop salmon imported from Europe (locations of the other positive samples were not given). Whole genome sequencing analysis of viral genomes from samples were reported to be closely related to European-derived SARS-CoV-2 genomes; the genomes of three have been uploaded to the GISAID repository[67].

It was initially considered more likely that the chopping board was contaminated by infected owner or guests, or other products that carried the virus[68]. However, an investigation into the outbreak by Pang *et al*. (2020) provided some evidence that the imported salmon was the contamination source [198]. The researchers examined the spatial distribution of infected Xinfadi market employees and found that 21% worked in the basement of the market, which was higher than other areas in the market, and they developed symptoms earlier. Within the market basement, highly clustered cases were identified in the seafood section and epidemiological investigations narrowed the source of the cluster to a specific booth (S14) in which all seven employees tested positive, along with five customers that had not visited any other booths. Cases from booth S14 had among the earliest symptom onset dates, although the earliest was from another seafood booth (S01). The neighbouring bean product section of the market also had a high proportion of positive cases, but cases had later symptom onset dates than some from the seafood section. There were also more environmental detections of SARS-CoV-2 RNA from the seafood section (62/870; 7.9%), but a higher proportion of positive detections from the bean product section (35/230; 15.2%). None of the cases or their close contacts had travel history to high risk areas for COVID-19. Salmon was the only imported commodity sold at booth S14 (however, the report did not specify whether other, locally sourced commodities were present at the booth and were also tested. Product from the seafood booth from which the earliest case worked, and bean products, were also not addressed). Researchers examined salmon inside their original sealed packages from a cold store located outside the Xinfadi market (which presumably had been packed from the supplier and had no contact with the Xinfadi market, although this detail was not provided). Six of the 3,582 samples tested were positive for SARS-CoV-2 RNA, five of which were from fish from the same supplier (infectivity was not reported). Partial genome sequence data obtained from one sample included mutations that were also present in the outbreak strain. The salmon from that supplier had been supplied to the Xinfadi market booth on 30 May 2020, the same day that exposure to early cases was thought to have occurred. The study concludes that although it is unclear whether SARS-CoV-2 levels present on the salmon would have been sufficiently high to cause

[64] https://www.who.int/news-room/detail/13-06-2020-a-cluster-of-covid-19-in-beijing-people-s-republic-of-china; accessed 14 April 2022
[65] https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200614-covid-19-sitrep-146.pdf?sfvrsn=5b89bdad_6; accessed 14 April 2022
[66] https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200618-covid-19-sitrep-150.pdf?sfvrsn=aa9fe9cf_4; accessed 14 April 2022
[67] https://www.gisaid.org/; accessed 14 April 2022
[68] https://news.cgtn.com/news/2020-06-14/Off-the-shelves-in-Beijing-is-salmon-guilty-of-spreading-coronavirus--Rj33sh4b8Q/index.html; accessed 14 April 2022

infection, there is a risk that cold-chain transportation of contaminated items might indeed initiate an outbreak.

On 22 July 2020 in Dalian City, Liaoning Province, a case (Case A) was reported that worked in cold-chain products processing and storage facility, following 111 days of no community transmission in that city [199]. A total of 64 employees that worked at the company were subsequently identified in the outbreak, 63 of whom were exposed to the cold-chain seafood processing workspace, as well as 67 contacts or residents living nearby. Environmental swabs were taken of the cold-chain seafood processing areas; 14 of 39 tested positive for SARS-CoV-2 RNA. Swabs were taken from the inside and outside of all imported cold-chain seafood packages imported during the incubation period for the first case; all 4,963 tested negative. The company also temporarily stored other imported cold-chain product from two ships at the time; the location of these were traced and SARS-CoV-2 RNA was detected on the outer packaging of some cold-chain pollock from one ship (overall prevalence 134/368). Among the 216 dock workers that handled the pollock, 11 had COVID-19. One case (Case B) was the husband of Case A. A retrospective investigation concluded that Case B was infected while handling the imported pollock, who transmitted the infection to his wife (Case A), who then transmitted it to her co-workers and work environment. The whole genome sequence of SARS-CoV-2 from the pollock was closely related to that from the environmental samples and cases, differing at one site, supporting that it was the parental strain of the cases. No infectious virus was isolated from the pollock, but high viral copies were present based on the RT-qPCR.

On 24 September 2020 in Qingdao, two asymptomatic port workers tested positive for COVID-19 during routine surveillance [124]. During October 2020, the Chinese CDC tested the outer packaging of frozen cod that had been handled by the workers five days prior to them testing positive. A total of 50 out of 421 surface swabs from the frozen cod outer packaging tested positive for SARS-CoV-2 by RT-qPCR and infectious virus was obtained from one sample. SARS-CoV-2 genomes from cod and worker samples were reported to be highly homologous. The report does not show that the workers were infected by handling the infected cod packages and it is also possible that they contaminated the packages themselves after contracting the virus somewhere else. However, the workers had no known prior contact history with other COVID-19 cases or foreign personnel. A nosocomial COVID-19 outbreak involving a genetically linked strain occurred around the same time period with one of the port workers considered to be the index case [200]. No mention was made regarding the COVID-19 status of workers on the ship that imported the cod, or whether there was contact between the ship workers and the port workers.

Another reported incident with a link to imported cold-chain food occurred in November 2020 in Tianjin [201, 202]. SARS-CoV-2 was detected on frozen pork packaging during routine sampling and surveillance, and around the same time, infection was confirmed in three port workers that handled these products. No further information was found to assess the direction of transmission, or whether the SARS-CoV-2 from the cold-chain product and cases were genetically linked.

Three additional outbreaks have also been reported where the pathway of infection was reported to be via infection of porters handling cold-chain products [197]. These included a second outbreak in Tianjin in November 2020 involving 10 cases, a second outbreak in Dalian City in December 2020 involving 83 cases, and an outbreak in Liaoning and Anhui provinces in May 2021 involving 43 cases. The SARS-CoV-2 genome from the latter outbreak was highly homologous to that from the July 2020 Dalian City outbreak; cod linked to the earlier outbreak had been stored frozen for 11 months but the report did not state whether infectious virus was isolated from the cod at the time of the 2021 outbreak.

As a consequence of the putative link to Europe and salmon in the Xinfadi market outbreak, China halted all imports of European salmon[69]. A growing list of companies have since either voluntarily halted exports to China or had products banned due to COVID-19 outbreaks at meat processing plants around the world[70]. Experts have spoken out against the restrictions to exports on the basis of COVID-19 transmission risk because there is no evidence that people can contract the disease from food or food packaging[71,72,73]. They argue that the fish itself is unlikely to be a source of SARS-CoV-2 because the virus must rely on the ACE2 viral receptor on the host cell surfaces to infect cells. As discussed in Section 4.1, fish have a very low ACE2 conservation score and were considered unlikely to be a host for SARS-CoV-2. Although the likelihood is low, it remains theoretically possible that the salmon, or its packaging, could act as a vehicle for SARS-CoV-2 because the virus can survive on the surfaces for a limited time, and chilled salmon was transported chilled and by air. The Centre for Food Safety of the Food and Environmental Hygiene Department in Hong Kong tested 16 salmon samples from Norway, Chile, Ireland, Iceland, and Denmark and all were negative for coronavirus (the report did not indicate if the testing was specific to coronavirus in general or specifically to SARS-CoV-2)[74].

To date, the majority of detections of SARS-CoV-2 on food packaging likely involves detection of SARS-CoV-2 RNA rather than infectious virus *per se* (although the methods are not always given and information sources often include newspaper articles rather than peer-reviewed publications).

Ongoing changes to COVID-19-related measures for the import of animal, plant and food products into China have also been occurring. On 26 February 2021, the New Zealand Ministry for Primary Industries (NZ MPI) released the latest information document update that outlines their understanding of some of the impacts of the latest measures and the New Zealand reaction[75]. Measures issued include:

[69] https://www.smh.com.au/world/europe/china-halts-european-salmon-imports-over-suspected-link-to-coronavirus-outbreak-20200615-p552w1.html; accessed 14 April 2022
[70] https://www.scmp.com/economy/china-economy/article/3090396/coronavirus-chinas-food-industry-grapples-fresh-disruption; accessed 14 April 2022
[71] https://www.straitstimes.com/world/united-states/us-rebuffs-china-rejecting-links-between-covid-19-and-food; accessed 14 April 2022
[72] https://fox6now.com/2020/06/25/fda-usda-covid-19-not-transported-on-food-packaging/; accessed 14 April 2022
[73] http://www.fao.org/2019-ncov/q-and-a/impact-on-fisheries-and-aquaculture/en/; accessed 14 April 2022
[74] https://www.foodsafetynews.com/2020/06/u-s-fda-aware-of-china-testing-food-for-coronavirus/; accessed 14 April 2022
[75] https://www.mpi.govt.nz/dmsdocument/42922-F1521-China-Covid-19-import-measures; accessed 14 April 2022

- A request for a COVID-19 declaration that states a willingness to:
    - comply with Chinese laws, regulations and standards and the "COVID-19 and food safety: guidance for food businesses" published by the Food and Agriculture Organization of the United Nations and the WHO to ensure that food imported into China is not contaminated with the COVID-19 virus and to ensure the safety of food imported into China.[76,77]
    - take all necessary measures to eliminate food safety risks and protect consumer health in the event that a new case/suspected case of COVID-19 is detected in a food enterprise, or if there is a risk of contamination of food products exported to China.
- Testing for SARS-CoV-2 nucleic acid by at the Chinese border by Chinese customs on food, packaging and the environment at the border, with an import suspension period following any detection. Importers may request exporters to test products prior to export. NZ MPI understands that some exporters may choose to perform pre-export testing of packaging and/or products in order to mitigate commercial and logistical challenges at the border.
    - Chinese authorities have been testing imported product packaging for the presence of SARS-CoV-2 RNA since February 2020, and the intensity has recently increased in some ports as a consequence of the developments. As of December 2020, there had been various reports of products testing positive, for example packaging of frozen shrimp from Ecuador[78] and Saudi Arabia, fish from India, beef from Brazil and Argentina, and pork from Germany[79]. By September 2020, only 22 positive samples had been detected out of approximately three million tested (a 0.00073% positivity rate). This is lower than reported false positivity rates of the SARS-CoV-2 RT-qPCR tests, e.g. 0.004% reported in one study [203], which means than many or all might have been false positive results[80]. A more recent news article published on 30 August 2021 reported detection of SARS-CoV-2 from cold-chain products from 12 different countries, with the most detections coming products arising from Argentina and Ecuador, and a greater number from seafood compared with meat[63].
    - MPI indicated that shared warehousing facilities with potentially contaminated product may pose an additional risk for New Zealand products even with the current level of confidence that product leaving New Zealand is SARS-CoV-2-free. In November 2020, SARS-CoV-2 was detected by Chinese authorities on beef and tripe packaging from Brazil, Bolivia and New Zealand, and packaging on pork from Argentina[81]. Some New Zealand products had been stored in the same warehouse

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[76] http://www.fao.org/3/ca8660en/CA8660EN.pdf; accessed 14 April 2022
[77] http://www.fao.org/3/cb6030en/cb6030en.pdf; accessed 14 April 2022
[78] https://www.reuters.com/article/us-health-coronavirus-china-anhui-idUSKCN2581D1; accessed 14 April 2022
[79] https://www.foodsafetynews.com/2020/11/china-reports-further-food-related-coronavirus-findings/; accessed 14 April 2022
[80] https://www.reuters.com/article/us-health-coronavirus-china-beef-idUSKBN27T0J0; accessed 14 April 2022
[81] https://www.reuters.com/article/us-health-coronavirus-newzealand-beef-idUSKBN27V0PU; accessed 14 April 2022

in which positive tests were returned from Argentinian product. Cross-contamination from product packaging from other countries would be a more likely source for the virus detected on New Zealand product packaging considering that New Zealand at that time (15 December 2020) had no reports of community transmission of COVID-19. In addition, detection of SARS-CoV-2 on kiwifruit being sold at a supermarket in the Jiangsu province of China, and originating from New Zealand, was reported on 24 September 2021[82]. The kiwifruit had been shipped from Tauranga, New Zealand on 16 August 2021, a day before the latest COVID-19 outbreak was discovered in New Zealand. It had originally tested negative for SARS-CoV-2 upon arrival into China, and was disinfected as per standard China customs protocols before being cleared and distributed. All subsequent testing has come back negative. However, the kiwifruit has been temporarily removed from the supermarket shelves and customers have been tested. Contamination is thought to have occurred from within the distribution channel[83].

- NZ MPI is expected to "voluntarily" suspend exports from any establishment that has a staff member who is diagnosed with COVID-19 through a SARS-CoV-2 positive RT-qPCR test. In a guidance document provided by MPI on 25 August 2021[84], MPI states that "*cold-chain food establishments, packhouses, and cold stores registered with China Customs to produce/store food products for export to China should operate on the assumption that if a staff member returns a positive COVID-19 test result it is possible this will result in China suspending the premises registration. MPI understands that it is an expectation of China Customs that establishment operators will, if they have staff return a positive COVID-19 test, immediately recall any affected exports to China, and suspend all exports to China.*"
- Packaging of imported cold-chain products are also to be disinfected on entry to China prior to storage and distribution.
- Imported cold-chain food production and operation units must have their own traceability system to upload this data through an interface. Customers will be able to scan a QR code to find out whether the product they are buying has been tested for SARS-CoV-2, and other relevant information.
- Tianjin Customs is recommending that cold-chain food importers have commercial contracts with exporters that include COVID-19 protection measures, from 1 March 2021. The protection measures include nucleic acid testing of food and outer packaging before product leaves the factory, with export only after the test is negative; coverage of possible contamination pathways such as ventilation systems, across production and transportation, and environmental disinfection; daily health checks of personnel, personal protection of

[82] https://www.stuff.co.nz/business/126489684/zespri-kiwifruit-tests-positive-for-covid19-in-china; accessed 14 April 2022
[83] https://www.newstalkzb.co.nz/on-air/heather-du-plessis-allan-drive/audio/catherine-beard-covid-positive-zespri-kiwifruit-was-probably-infected-in-distribution-channel/; accessed 14 April 2022
[84] https://www.mpi.govt.nz/dmsdocument/46510-F3921-China-Covid-19-further-guidance-for-exporters; accessed 14 April 2022

employees during production processes, encouraging employees to be vaccinated, and regular nucleic acid testing.

New Zealand Food Safety released a scientific opinion on COVID-19 transmission through food packaging on 13 August 2020, which states[85]:

"*Currently there is general consensus that the risk of COVID-19 transmission by food or food packaging is negligible and does not warrant application of specific risk management measures. This consensus results from epidemiological observations from the large number of global cases, the limited ability of the organism to survive on inanimate surfaces and the unlikely probability that an infectious dose would survive and be transmitted in food packaging scenarios, especially that moving in international trade. In terms of presence only, China implemented a testing programme for imported food packaging in July 2020 and it is our understanding there have only been 6 positives from over 200,000 tests run. Further these testing results do not determine presence of infectious particles.*"

No demonstrated role of frozen wild animal meat in early transmission of SARS-CoV-2

Based on the potential for SARS-CoV-2 to survive on frozen food, the WHO has considered the possibility that SARS-CoV-2 may have been introduced into the Huanan market via frozen wild animals or domesticated wildlife in southern China [9, 204, 205]. Before the market closed in January 2020, 10 of its 653 stalls sold live or frozen wildlife captured in the wild or brought from farms. However, there is no evidence of transmission via frozen meat occurring, and no frozen meat from the market that investigators sampled tested positive for SARS-CoV-2 RNA. SARS-CoV-2 could have just as easily been brought in by live animals or infected people who had handled wild animals.

[85] https://www.mpi.govt.nz/dmsdocument/41614/direct; accessed 14 April 2022

5. WHAT IS THE INTERNATIONAL CONSENSUS ON SURVIVAL RATES OF SARS-COV-2 IN AND ON FOOD PRODUCTS AND PACKAGING?

Key findings:

- Results from experiments that examine the stability of SARS-CoV-2 on foods or surfaces should be considered within the context of the experimental conditions. Researchers typically inoculate small areas of the substrate with far higher concentrations of virus than that expected to be deposited onto a surface, for example, by infectious people sneezing. Incubation is usually carried out in controlled conditions that do not mimic natural scenarios. The length of time that viral infectivity is detected is influenced by the initial virus concentration on a surface and the incubation conditions, so does not necessarily reflect the risk posed under natural contamination situations.
- The persistence of SARS-CoV-2 infectivity has been tested in a wide range of meat, fresh produce and dairy products. Results varied depending on the study and food composition. For example, SARS-CoV-2 remained infectious for up to three weeks on refrigerated deli items, some fresh produce types, and raw meats with high protein, fat and moisture content. SARS-CoV-2 also remained infectious in ice cream stored at -20°C and -80°C for at least eight weeks. However, there were antiviral effects from some processed meats, fresh produce, or acidic products. Studies attempting to replicate natural fresh produce contamination scenarios (low levels of aerosolised SARS-CoV-2 or handling by COVID-19 patients) did not result in viable SARS-CoV-2 being detected on the fruit and vegetables. No studies were identified that reported the stability of the Omicron variant on foods.
- SARS-CoV-2 infectivity has also been assessed in a range of beverage types. The survival of infectious SARS-CoV-2 viruses in different beverages was affected by the characteristics of the liquids, i.e. pH, alcohol content, sugar content, fat content or the presence of inhibitory compounds. For example, there was minimal loss of viral infectivity in beer after 1 hour, while cocoa, coffee, tea, fruit juices, and wine contained antiviral compounds that reduced infectivity, and higher alcohol content spirits immediately inactivated SARS-CoV-2.
- Cooking or pasteurisation inactivated SARS-CoV-2 viruses in or on food and beverages. SARS-CoV-2 remains infectious on food and surfaces for longer periods at lower temperatures, and lower humidity levels. The demonstrated stability of the virus during freezing is expected given that this is how viruses are stored in the laboratory.
- Infectious SARS-CoV-2 has been demonstrated to persist on hard surfaces (e.g. plastic, glass, steel) at ambient temperatures in the dark for several days to at least a month depending on the experimental setup, although significant log-fold reductions in the amount of infectious virus occurred over that period.
- A non-peer reviewed study reported that infectivity of the Alpha, Beta, Delta and Omicron variants persisted for significantly longer times on surfaces than the Wuhan strain (which is often used in persistence studies).
- The Omicron variant was slightly more resistant to ethanol than earlier variants, but was inactivated by significantly lower concentrations than present in hand sanitisers. The US EPA states that genetic changes to the SARS-CoV-2 genome are not expected to have an impact on disinfectant efficacy.
- Studies evaluating the persistence of SARS-CoV-2 infectivity in and on food, aerosols and surfaces are summarised in Table 2 and Table 3.

5.1. Persistence of SARS-CoV-2 in and on food products

Since the last report, new published studies have tested the infectivity of SARS-CoV-2 in or on food products; although no studies were found that reported on the persistence of the Delta or Omicron variants on food. Note also that one non-peer reviewed preprint discussed in a previous report has since been formally withdrawn and content is not included in this version of the report [206].

For practical reasons, experiments that examine the stability of SARS-CoV-2 on food or surfaces typically inoculate small areas of the substrate with far higher concentrations of virus than that expected to be deposited onto a surface, for example, by infectious people sneezing. SARS-CoV-2 concentrations of ~10^5 particles have been reported from a single cough and up to 10^8 RNA copies per ml of saliva, although not all viral particles are infectious and the concentration of infectious virus in secretions and on surfaces declines over time [207, 208]. Experimental incubation is also usually carried out under controlled conditions that do not mimic natural scenarios. Therefore, the length of time that SARS-CoV-2 remains infectious in experimental studies is in part defined by the initial virus concentration on a surface and the incubation conditions, and does not necessarily reflect the risk posed under natural contamination situations. These studies do, however, provide useful indicative data on viral survival in or on foods.

Data for the persistence of SARS-CoV-2 infectivity on different foods and beverages are summarised in Table 2 and described further in this section. There was not a standardised approach taken between studies to assess survival on foods. Studies differed by the concentration of the SARS-Co-V-2 inoculum, the method of inoculation (e.g. immersion in the inoculum or deposition of the inoculum on or into the foods), the approach for recovery of virus from the food (e.g. elution or swabbing), and the methodology for enumeration of infectious virus (e.g. $TCID_{50}$, PFU or detect/non-detect). Furthermore, how the data were recorded also differed between studies; for some studies, data tables were not available so data used in Table 2 were extracted from published graphs. The log-reduction values were subject to information available in the study report; some values were based on the inoculum concentration (e.g. when there was a defined concentration added to food or beverages, there was a high percentage of viral recovery from product, when the product might have an immediate effect on viral infectivity, or when the 0-hour timepoint was not recorded) and others were calculated relative to the 0-hour time point (particularly when studies involved an undefined concentration on product, e.g. following immersion of product in inoculum, or when the food type had a significant effect on viral recovery). Therefore, the results presented in Table 2 provide an indicative picture, but are not directly comparable between studies. For a complete understanding of the studies, we refer readers to the publications.

Table 2. Persistence of SARS-CoV-2 infectivity in or on food products.

Food matrix	Inoculum	Incubation or treatment variables[a]	Effect on infectivity ($TCID_{50}$ or PFU)[b]	Reference
Unpasteurised human milk	4 log_{10} $TCID_{50}$/ml SARS-CoV-2	4°C, 2 days -30°C, 2 days 63°C, 30 min 56°C, 30 min	↓0.0 log (no change) ↓0.4 log ↓≥3.5 log (undetected) ↓≥3.5 log (undetected)	[209]
Unpasteurised human milk	7 log_{10} $TCID_{50}$/ml SARS-CoV-2	62.5°C, 30 min RT, 30 min	↓≥6.0 log (undetected) ↓1.0 log	[210]
Full-fat milk	5.65 log_{10} $TCID_{50}$/ml SARS-CoV-2	72°C, 15 s 63°C, 30 min 80°C, 15 s	↓1.9 log undetected[c] undetected	[211]
Low-fat milk	5.65 log_{10} $TCID_{50}$/ml SARS-CoV-2	72°C, 15 s 63°C, 30 min 80°C, 15 s	undetected undetected undetected	
Cream	5.65 log_{10} $TCID_{50}$/ml SARS-CoV-2	90°C, 1 min	undetected	
Ice cream	5.65 log_{10} $TCID_{50}$/ml SARS-CoV-2	-20°C, 1 week -20°C, 2 weeks -20°C, 4 weeks -20°C, 8 weeks -80°C, 1 weeks -80°C, 2 weeks -80°C, 4 weeks -80°C, 8 weeks	↓<0.25 log (no change) ↓<0.25 log (no change) ↓~1.0 log ↓~1.25 log ↓<0.5 log (no change) ↓~0.75 log ↓~1.0 log ↓~2.0 log	
Doogh (Iranian fermented milk drink)	5.65 log_{10} $TCID_{50}$/ml SARS-CoV-2	5°C, 1 week 5°C, 2 weeks 5°C, 3 weeks 5°C, 4 weeks	↓3.1 log ↓3.5 log ↓~4.0 log ↓≥5.5 log (undetected)	
Salmon	0.5 cm^3 salmon immersed in 6.5 log_{10} $TCID_{50}$/ml SARS-CoV-2 inoculum, salmon recovered and excess inoculum drained before incubation	4°C, 1 day 4°C, 2 days 4°C, 7 days 4°C, 9 days 4°C, 12 days	↓0.5 log[d] ↓0.7 log ↓1.1 log ↓2.0 log ↓≥2.5 log (undetected)	[212]
		25°C, 1 day 25°C, 2 days	↓1.0 log ↓≥2.5 log (undetected)	
Salmon	1-2 g immersed in 10^4 $TCID_{50}$/ml SARS-CoV-2 in DMEM for 10 s.	4°C, 9 days	detected	[213]
		-20°C, 20 days	detected	
Beef	1-2 g immersed in 10^4 $TCID_{50}$/ml SARS-CoV-2 in DMEM for 10 s.	4°C, 9 days	detected	
		-20°C, 20 days	detected	
Pork	1-2 g immersed in 10^4 $TCID_{50}$/ml SARS-CoV-2 in DMEM for 10 s.	4°C, 9 days	detected	
		-20°C, 20 days	detected	
Salmon	1.5 cm^2 (1.7 g) including skin, inoculated on surface with 20 µl (10^5 PFU) SARS-CoV-2	4°C, 1 hour 4°C, 1 day	↓0.5 log (no change) ↓0.4 log (no change)	[214]
Shrimp	1.5 cm^2 (1.7 g) including shell, inoculated on surface with 20 µl (10^5 PFU) SARS-CoV-2	4°C, 1 hour 4°C, 1 day	↓0.7 log (no change) ↓0.4 log (no change)	
Chicken skin	1.5 cm^2 (1.7 g); inoculated surface with 20 µl (10^5 PFU) SARS-CoV-2	4°C, 1 hour 4°C, 1 day	↓0.5 log (no change) ↓0.3 log (no change)	
Spinach	1.5 cm^2; inoculated surface with 20 µl (10^5 PFU) SARS-CoV-2	4°C, 1 hour 4°C, 1 day	↑0.2 log (no change) ↓0.4 log (no change)	

Food matrix	Inoculum	Incubation or treatment variables[a]	Effect on infectivity ($TCID_{50}$ or PFU)[b]	Reference
Apple skin	1.5 cm^2, minimal flesh, inoculated on surface with 20 µl (10^5 PFU) SARS-CoV-2	4°C, 1 hour 4°C, 1 day	↓0.2 log (no change)[e] ↓0.5 log (no change)[e]	
Mushroom	1.5 cm^2; inoculated surface with 20 µl (10^5 PFU) SARS-CoV-2	4°C, 1 hour 4°C, 1 day	↓3.0 log[e] ↓≥3.1 log (undetected)[e]	
Beef steak	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 day 4°C, 1 week 4°C, 2 weeks	↓0.5 log ↓2.0 log ↓≥3.2 log (undetected)	
Ground beef	1.7 g; 20 µl of 10^4 PFU SARS-CoV-2 mixed with 25 g ground beef	4°C, 1 day 4°C, 1 week 4°C, 2 weeks	↓0.5 log ↓1.5 log ↓≥3.2 log (undetected)	
Ground beef	10^4 PFU/g SARS-CoV-2 mixed with 25 g ground beef, formed into 1.25 cm thick patties	Internal temp: 51.2°C 62.5 °C 71.1 °C	 ↓1.1 log ↓2.7 log ↓≥3.2 log (undetected)	
Pork chop	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓0.75 log ↓0.75 log ↓1.75 log	
Ground pork	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓0.75 log ↓1.0 log ↓2.0 log	
Plant-based meat alternative	1.7 g; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓1.75 log ↓2.5 log ↓≥3.2 log (undetected)	
Oyster	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓2.0 log ↓3.0 log ↓≥3.2 log (undetected)	[215]
Deli turkey	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓1.4 log ↓2.1 log ↓2.9 log	
Swiss cheese	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓1.5 log ↓2.0 log ↓2.2 log	
Salami	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks	↓2.5 log ↓≥3.2 log (undetected)	
Cherry tomato	Whole tomato inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓0.25 log (no change) ↓2.25 log ↓2.0 log	
Grape	Whole grape inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 week 4°C, 2 weeks 4°C, 3 weeks	↓0.25 log (no change) ↓2.5 log ↓2.5 log	
Avocado pulp	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 hour 4°C, 1 day 4°C, 1 week	↓1.1 log ↓3.0 log ↓≥3.2 log (undetected)	
Avocado skin	1.5 cm^2; inoculated surface with 20 µl 10^4 PFU SARS-CoV-2	4°C, 1 hour 4°C, 1 day 4°C, 1 week	↓0.0 log (no change)[e] ↓0.25 log ↓≥1.5 log (undetected)	
Apple	Exposed to aerosolised SARS-CoV-2 (3.1 log_{10} PFU/L of air)	4°C, 1 hour 22°C, 1 hour	undetected[d] undetected[d]	[216]
Tomato	Exposed to aerosolised SARS-CoV-2 (3.2 log_{10} PFU/L of air)	4°C, 1 hour 22°C, 1 hour	undetected[d] undetected[d]	

Food matrix	Inoculum	Incubation or treatment variables[a]	Effect on infectivity ($TCID_{50}$ or PFU)[b]	Reference
Jalapeño	Exposed to aerosolised SARS-CoV-2 (3.2 log_{10} PFU/L of air)	4°C, 1 hour 22°C, 1 hour	undetected undetected	
Unspecified fruit and vegetables	Produce handled by, and in close proximity to, COVID-19 patients	34°C, RH 54%, wind 11 kph: 1 hour	undetected by RT-qPCR; infectivity not tested	[217]
Milk (whole, skim, almond or coconut)	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	4°C, 1 hour 4°C, 7 days	↓<0.5 log (no change) ↓0.8-1.0 log	[218]
Chocolate milk	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	4°C, 1 hour 4°C, 7 days	↓1.3 log ↓1.9 log	
Coffee	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour 1 hour	↓2.1 log ↓2.7 log	
Tea	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour	↓>3.6 log (undetected)	
Fruit juice (cranberry, grape, apple)	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour 1 hour	↓2.0->3.6 log (undetected) ↓3.2->3.6 log (undetected)	
Beer (stout, IPA)	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	1 hour	↓<0.5 log	
Beer (porter, lager, light beer	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	1 hour	↓0.6-1.0 log	
Liquor, undiluted (whisky, rum, tequila, gin, vodka)	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour	↓>3.6 log (undetected)	
10% vodka + soda	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour 1 hour	↓<0.5 log ↓0.75 log	
Wine (sweet white, dry white)	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour 1 hour	↓0.7-1.3 log ↓1.8->3.6 log (undetected)	
Wine (sweet red, dry red)	4 log_{10} PFU SARS-CoV-2 added to 1 ml beverage	0 hour	↓>3.6 log (undetected)	

[a] Where data for a number of time points were reported, only a selection of informative time points have been provided in the table, including the final time point. RH, relative humidity; RT, room temperature.

[b] The log reduction for some treatments was approximated from published graphs. Log reduction was rounded to the nearest 0.25 log unit. The log reduction values are subject to information available in the study report; some values are based on the inoculum concentration and others are calculated from the 0-hour time point. $TCID_{50}$, 50% tissue culture infectious dose; PFU, plaque forming units.

[c] The study did not include a higher concentration positive control to confirm the inoculum was viable under the conditions of inoculation (not clear, but appears to be viruses in aerosolised growth media). The detection limit was 1 log PFU/ml.

[d] See footnote 86 for assumption made regarding day numbering.

[e] Concentrations were also significantly lower than the inoculum, even at 0 h.

As discussed in Section 4.2.4, SARS-CoV-2 RNA has been detected in human milk from mothers with COVID-19, which has implications for breast-feeding mothers and human milk banks. Recent studies have examined the effect of common storage temperatures and pasteurisation on the infectivity of SARS-CoV-2 in human milk samples. One study reported little or no loss of infectivity of SARS-CoV-2 that was inoculated into unpasteurised human milk as well as control minimum essential medium (MEM) medium and stored at -30°C or 4°C for two days [209]. They and others also demonstrated that Holder pasteurisation (62.5-63°C for 30 min, which is the most common pasteurisation method among milk banks worldwide) completely inactivated any infectious SARS-CoV-2 in the milk [209, 210]. In comparison, a ~1 log reduction in virus infectivity in inoculated breast donor milk held at room temperature for 30 minutes was observed, compared with virus spiked into cell culture medium alone, although the reduction was variable between milk donors (reduction ranging from 2 log to none).

Another study has examined the infectivity of SARS-CoV-2 in dairy products following common industrial processing treatments including pasteurisation, freezing, frozen storage and acidic conditions (low pH and high titratable acidity) [211]. Five dairy products including raw low-fat milk (1.14% fat content), raw full-fat milk (3.22% fat content), cream (33.76% fat content), ice cream (10.19% fat content), and Doogh (Iranian fermented milk drink with initial pH 3.48 and titratable acidity of 141.56 °D) were inoculated with 5.65 log $TCID_{50}$/ml SARS-CoV-2. SARS-CoV-2 infectivity was tested from cream after pasteurisation (90°C for 1 min) and from the two milk types after three different treatments: high-temperature short-time pasteurisation (HTST, 72°C for 15 s), low-temperature long-time pasteurisation (LTLT, 63°C for 30 min) and extended shelf life pasteurisation (ESL, 80°C for 15 s). All treatments resulted in full inactivation of SARS-CoV-2 infectivity except for HTST-treated full-fat milk, where there was only a 1.9-log reduction in infectivity, possibly due to a protective effect of the fat content. Refrigerated storage under highly acidic conditions (Doogh) also significantly reduced the infectious viral load to undetectable levels by the end of 28 days (>5.5 log reduction). Furthermore, SARS-CoV-2 remained infectious following freezing of ice cream at both -20°C and -80°C for at least eight weeks, although there was an up-to-2-log reduction in infectivity over time. As discussed in Section 5.2.3, SARS-CoV-2 infectivity is retained during frozen storage.

Beverages might become contaminated by SARS-CoV-2 via transfer of saliva during drink sharing by infected individuals. The survival of SARS-CoV-2 has been assessed in 18 non-alcoholic and 16 alcoholic beverages inoculated with 4 log_{10} PFU SARS-CoV-2 per 1 ml volume (including milk, as discussed above) [218]. The ability for SARS-CoV-2 viruses to remain infectious in different beverages (as measured by culture-based methods) appears to be affected by a number of variables such as pH, alcohol content, sugar content and the presence of other inhibitory compounds (the results from a representative subset of the beverage types are shown in Table 2). First, a similar ~1-log reduction in infectious virus was observed for different types of inoculated dairy and plant-based milk (whole milk,3.25% fat; skim milk, 0% fat; almond milk, 1% fat; and coconut milk, 1.9% fat) stored at refrigeration temperature for a week. There was a greater reduction in infectivity (1.9-log) in chocolate milk (1% fat) in the same storage conditions, which is likely due to the presence of cocoa because significant reductions in infectivity were documented in cocoa/water solutions. Tea, coffee, dark soda and fruit juices

(apple, cranberry and grape) all had an antiviral effect on SARS-CoV-2 with some of these beverages immediately inactivating the virus following inoculation. Note that while all beverages were inoculated at the same temperature, tea and coffee are often consumed heated, which would have reduced viral infectivity further. Undiluted liquors similarly inactivated the virus upon inoculation, which is not unexpected due to the high alcohol content (40%), while infectivity was retained for at least one hour in liquor diluted in club soda. Wine and cider also inactivated SARS-CoV-2, with red wine immediately eliminating any measurable viral infectivity, while white wine results were influenced by sugar content. In contrast, a minimal reduction in viral infectivity was seen in different beer types after one hour; thus, the authors postulated that sharing a beer might pose a potential infection risk during social events. However, under such social circumstances (sharing a beer from the same glass or bottle) airborne transmission or person or person contact would appear to pose a much greater risk.

A study has assessed the survival of SARS-CoV-2 on salmon stored at refrigeration (4°C) as well as room temperatures (25°C) [212]. Salmon samples (0.5 cm^3) were immersed in 6.5 log_{10} $TCID_{50}$/ml SARS-CoV-2 inoculum, and the salmon samples were recovered and excess inoculum drained before incubation. Although the inoculum concentration was very high, the amount adhering to the salmon surface was much lower, measured at ~4.5 $TCID_{50}$/ml. The titre of infectious SARS-CoV-2 eluted from the salmon was tested at day 0, and then up to 11 days of incubation[86]. However, SARS-CoV-2 adhering to the salmon was shown to remain infectious for up to one day at 25°C (no detection by two days), and up to 9 days at 4°C (no detection by 11 days). SARS-CoV-2 incubated in culture medium (no salmon) remained infectious for at least seven days at both temperatures, but there was a much greater decline in infectivity at 25 °C (a ~3-log reduction at 25°C compared at with ~0.5 log reduction at 4°C). Infectivity declined at a faster rate on the salmon than in the culture medium at both temperatures, and although infectivity was retained for a longer period of time in the culture medium, there was an approx. 2-log higher titre to begin with.

Feng *et al.* (2021) used a similar inoculation approach to Dai et al.(2021) to study infectivity of SARS-CoV-2 on salmon, beef and pork; however inoculation titres were lower to simulate the viral titres likely to be present in patient respiratory samples [213]. Infectious SARS-CoV-2 was eluted from some technical replicates at most time points tested (up to 9 days incubation at 4°C, and up to 20 days incubated at -20°C for high-level inoculated samples). While quantification of infectious virus was not undertaken, SARS-CoV-2 RNA was quantified. However, the variability in RNA results (including an order of magnitude increase in measured RNA despite the virus not being able to replicate) means that this study had limited value.

A study by Dhakal *et al.* (2021) assessed the survival of SARS-CoV-2 on various refrigerated food types. They first utilised the surrogate Herpes Simplex Virus 1 (HSV-1) to develop and validate testing methods [214]. Approx. 1.5 cm^2 samples of chicken, seafood (salmon and shrimp) and produce (apples, mushrooms and spinach) samples were inoculated at multiple

[86] Note that it was not clear in the study whether Day 1 refers to 1 day post-inoculation or the day of inoculation. For the sake of this review, we presumed that Day 1 refers to the day of inoculation because the Day 1 titre of untreated virus presented matches the reported inoculum level.

sites across the surface with 20 µl and 10^5 PFU of SARS-CoV-2 and incubated at 4 °C. SARS-CoV-2 was washed off food surfaces with 1 ml buffer five times by pipette, and infectivity was tested at 0, 1 and 24 h post-inoculation by plaque assay using Vero-E6 cells. There were no significant changes in the infectious SARS-CoV-2 loads eluted from chicken skin, salmon, or shrimp, and spinach over 24 hours. There was a lower initial recovery of infectious SARS-CoV-2 from apple skin and mushrooms. Infectious loads were significantly reduced after one hour from mushrooms and undetectable after 24 hours, at which time infectious loads were also reduced from apple skin. The authors suggest that differences in persistence in infectivity on the different food types might be related to the amount of protein, moisture content or food pH. Results on the stability of SARS-CoV-2 infectivity on salmon after one day in refrigeration conditions were comparable with those reported by Dai *et al.* [212]. The stability of SARS-CoV-2 infectivity on spinach and decline in infectivity on apples after one day, are also consistent with results obtained using surrogate coronaviruses [219, 220], discussed below.

Using the methodology developed in the Dhakal *et al.* (2021) study, researchers from the same laboratory tested SARS-CoV-2 infectivity on further types of foods that may present a potential risk of infection; ready-to-eat deli foods, fresh produce, and raw or minimally cooked meats [215]. However, the foods were inoculated with a lower concentration of SARS-CoV-2 (4 $\log_{10}$ PFU) to represent viral concentrations that might be found in a cough or sneeze. Foods were held at refrigeration temperature and tested for up to three weeks. No decline in infectious virus titres was recorded on whole grapes and tomatoes after one week, and although infectivity declined after that time, infectious virus was still detected after three weeks. Infectivity declined faster on avocado skins and pulp; infectious virus was detected after one day but not one week. Of the deli foods tested, infectious virus was still detected from turkey and Swiss cheese after three weeks, but was not detected from salami after two weeks, which might be due to inhibitors present in the salami. Survival in uncooked meats was also tested; infectious SARS-CoV-2 was recoverable from beef steak and ground beef for up to one week, plant-based meat and oysters (which are often consumed raw) for up to two weeks, and pork chops and ground pork up to at least three weeks. In the US, burger meat is often consumed rare, medium or well-done, based on the consumer's preference. Infectious SARS-CoV-2 was detected from rare and medium-cooked burgers (internal temperatures of 51.2 °C or 62.5 °C, respectively), but not from well-done burgers (internal temperature of 71.1 °C). The authors generalised that SARS-CoV-2 remained infectious for longer in foods that had higher fat and/or protein content, or higher moisture content, protecting the virus from desiccation.

Studies have also taken more realistic approaches to examine the role of food as a potential SARS-CoV-2 transmission route. One study tested the stability of SARS-CoV-2 on apples, tomatoes, and jalapeño peppers at room temperature (22°C) and refrigeration (4°C) following an aerosol exposure (3.1–3.2 $\log_{10}$ PFU/L air) designed to simulate a low-dose SARS-CoV-2 airborne transmission event involving droplet nuclei [216]. However, no infectious SARS-CoV-2 were recovered following swabbing of any of the produce at 1, 4, 8 or 24 hours post-inoculation so it cannot be certain that the inoculation method successfully transferred viable virus onto the product. Another study assessed whether SARS-CoV-2 could be detected on produce that were handled by patients with COVID-19 [217]. Ten patients were asked to cough into their

hands and handle all fruit and vegetables on a tray at least five times, as well as remove their masks and talk over the tray, which remained in front of them for 30 minutes. The produce was then moved into a shaded area with free flow of natural air for one hour (34°C, humidity 54%, and wind 11 kph) after which time, produce was swabbed and tested by RT-qPCR for SARS-CoV-2 (infectivity was not tested). SARS-CoV-2 RNA was not detected on any samples. The efficiency of transfer other human coronaviruses (229E and OC43) from inoculated gloved hands to food (apples, cucumber) or food contact surfaces (stainless steel, plastic) has also been assessed [221]. The study found no evidence of transfer of infectious coronaviruses to any surface, although transfer was detected in the presence of the supernatant from diluted, autoclaved and centrifuged human faecal material. A final study looked at the potential role of food and packaging acting as fomites for the transmission of SARS-CoV-2 [222]. Viral transfer was assessed based on the percentage transfer of SARS-CoV-2 from inoculated food and packaging surfaces to gloves (as a proxy for transfer to hands; first transfer event), followed by glove-to-glove transfer (as a proxy for hand-to-face transfer; second transfer event). The cumulative transfer rate (i.e. overall transfer through both transfer events) was highest under wet inoculum conditions compared to frozen, while no viral transfer was detected from a dry inoculum on plastic or cardboard. The mean cumulative transfer rates from foods were quite low (1–5%) but the wide confidence intervals showed variability. For example, the cumulative transfer rate from wet lettuce was 4.7%, with a 95% confidence interval of 0.6–38.1. The initial inoculum was high, being 6 $TCID_{50}$ per 25 cm^2 food surface. Taken together, the four studies suggest that, in real-life situations, fruits and vegetables are unlikely to act as a fomite or play a significant role in transmission of COVID-19.

A study examined the stability of HCoV-229E as a surrogate for SARS-CoV-2 on the surface of lettuce, as well as apples, tomatoes and cucumbers [220]. For each sample, a 5 cm x 5 cm square area was inoculated with 100 µl of 5×10^5 plaque-forming units (PFU)/ml, and samples were incubated at ambient temperature. At time points up to 72 h post-inoculation, sample surfaces were swabbed and tested for both infectivity (plaque assay) and for persistence of viral RNA (RT-qPCR). The viral infectivity declined within a few hours post-inoculation on apples and tomatoes, and no infectious virus was detected at 24 h post-inoculation, while the virus persisted in infectious form for 72 h post-inoculation on cucumbers and lettuce. Infectivity of the virus following refrigerated storage of inoculated product was not tested.

Like other viruses, SARS-CoV-2 could contaminate fresh produce via contaminated irrigation water. The above studies show that survival of the virus on fresh produce would be highly variable, especially considering normal environmental conditions (e.g. inactivation of the virus through desiccation or UV). Contamination can also be mitigated via washing and cooking produce.

The risk posed by potential bioaccumulation of SARS-CoV-2 in bivalve molluscs proximal to wastewater overflows, and their consumption, has been assessed [223]. For each individual step that would be required for bioaccumulation to occur, there was considered to be a medium probability of infectious SARS-CoV-2 excretion in faeces, a low probability of viable virus persistence in wastewater, a low probability of viable virus persistence through sewage treatment, and a medium probability of viable virus persistence following discharge to an

aquatic environment (although there was a high uncertainty around these assessments). The assessment concluded that the probability of consuming bivalve molluscs containing bioaccumulated viable SARS-CoV-2 was very low for raw shellfish and negligible for cooked shellfish depending on the extent of cooking.

Surveys have also assessed SARS-CoV-2 RNA detection from wastewater, surface water and bivalve molluscan shellfish from a proximal region. Consistent with the risk assessment findings, surveys from Croatian waters conducted during their second epidemic wave detected SARS-CoV-2 RNA from most wastewater treatment plant influents and some effluents, but did not detect SARS-CoV-2 from 77 bivalve molluscs (mussels, oysters and clams), some taken from sites near wastewater treatment plants [224]. Another study demonstrated that oysters were able to bioaccumulate SARS-CoV-2 (heat-inactivated) in the laboratory [225]. However, they did not detect SARS-CoV-2 nucleic acid from seawater or bivalve mollusc samples collected from the French coast, including following microbiological alerts suspected to be linked to sewage contaminations events when norovirus was detected. A further study detected SARS-CoV-2 RNA but not infectious virus from estuarine sediment and clam samples from natural clam banks in Spain [226].

5.2. Persistence of coronaviruses on inanimate surfaces, in aerosols, and effect of temperature and inactivation treatments

Transmission of non-SARS-CoV-2 from contaminated dry surfaces has been postulated [120, 227]. Understanding the persistence of SARS-CoV-2 on inanimate surfaces is relevant to considering the risks and control of SARS-CoV-2 on foods, food contact surfaces and food packaging. Non-enveloped viruses are usually more resistant to harsh environmental conditions (e.g. heating and drying) and the action of biocides, and persist longer on inanimate surfaces than enveloped viruses such as coronavirus [219, 228, 229].

Persistence studies described in this section use both RT-qPCR and cell culture assays, but only cell culture informs on infectivity. Table 3 summarises data from studies of the persistence of SARS-CoV-2 infectivity on and in different substrates and aerosols, at different temperature and humidity conditions. As discussed for studies assessing the persistence of SARS-CoV-2 infectivity on food, methodologies used to assess persistence on surfaces and the effect of inactivation treatments also differed between studies. As such, findings were not directly comparable between studies. These studies are discussed further in the following sections.

Table 3. Persistence of SARS-CoV-2 infectivity in and on different substrates, aerosols and environmental conditions.

Substrate	Inoculum concentration and presentation	Incubation variables[a]	Persistence time[b]	Half-life	Reference
Polypropylene plastic	50 µl containing 5 log_{10} $TCID_{50}$ /ml	21-23°C, RH 40%	72 hours	6.8 hours	[230]
Stainless steel	50 µl containing 5 log_{10} $TCID_{50}$/ml	21-23°C, RH 40%	72 hours	5.6 hours	
Copper	50 µl containing 5 log_{10} $TCID_{50}$ /ml	21-23°C, RH 40%	4 hours	0.8 hours	
Cardboard	50 µl containing 5 log_{10} $TCID_{50}$/ml	21-23°C, RH 40%	24 hours	3.5 hours	
Aerosol	5.3 log_{10} $TCID_{50}$/ml	21-23°C, RH 40%	≥3 hours	1.1 hours	
Aerosol	2 log_{10} PFU/L of aerosol	23°C, RH 53%	≥16 hours	↓0.0 log (no change)	[231]
Virus transport medium	~6.8 log_{10} $TCID_{50}$/ml	4°C	≥14 days	Not reported	[136]
		22°C	7 days	Not reported	
		37°C	1 day	Not reported	
		56°C	10 minutes	Not reported	
		70°C	1 minute	Not reported	
Paper	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	30 min	Not reported	
Tissue paper	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	30 min	Not reported	
Wood	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	1 day	Not reported	
Cloth	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	1 day	Not reported	
Glass	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	2 days	Not reported	
Banknote	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	2 days	Not reported	
Stainless steel	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	4 days	Not reported	
Plastic	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	4 days	Not reported	
Mask, inner layer	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	4 days	Not reported	
Mask, outer layer	5 µl of ~7·8 log_{10} $TCID_{50}$/ml	22°C, RH 65%	≥7 days	Not reported	
Plastic	50 µl of 6 log_{10} $TCID_{50}$/ml	19-21°C, RH 45-55%	≥4 days	>4 days	[232]
	50 µl of 6 log_{10} $TCID_{50}$/ml + BSA	19-21°C, RH 45-55%	≥4 days	>4 days	
Aluminium	50 µl of 6 log_{10} $TCID_{50}$/ml	19-21°C, RH 45-55%	2 hours	2.5 hours	
	50 µl of 6 log_{10} $TCID_{50}$/ml + BSA	19-21°C, RH 45-55%	≥4 days	>4 days	
Glass	50 µl of 6 log_{10} $TCID_{50}$/ml	19-21°C, RH 45-55%	24 hours	17 hours	
	50 µl of 6 log_{10} $TCID_{50}$/ml + BSA	19-21°C, RH 45-55%	≥4 days	>4 days	
Stainless steel		Dark, RH 50%:			[233]

Substrate	Inoculum concentration and presentation	Incubation variables[a]	Persistence time[b]	Half-life	Reference
	10 µl BSA/tryptone/mucin solution containing 5.5 $\log_{10}$ $TCID_{50}$	20°C	≥28 days	6.0 days	
		30°C	7 days	1.7 days	
		40°C	1 day	4.9 hours	
Polymer note	10 µl BSA/tryptone/mucin solution containing 5.5 $\log_{10}$ $TCID_{50}$	Dark, RH 50%: 20°C	≥28 days	6.9 days	
		30°C	7 days	2.0 days	
		40°C	1 day	4.8 hours	
Paper note	10 µl BSA/tryptone/mucin solution containing 5.5 $\log_{10}$ $TCID_{50}$	Dark, RH 50%: 20°C	≥28 days	9.1 days	
		30°C	21 days	4.3 days	
		40°C	1 day	5.4 hours	
Glass	10 µl BSA/tryptone/mucin solution containing 5.5 $\log_{10}$ $TCID_{50}$	Dark, RH 50%: 20°C	≥28 days	6.3 days	
		30°C	7 days	1.5 days	
		40°C	1 day	6.6 hours	
Cotton cloth	10 µl BSA/tryptone/mucin solution containing 5.5 $\log_{10}$ $TCID_{50}$	Dark, RH 50%: 20°C	7 days	5.6 days	
		30°C	3 days	1.7 days	
		40°C	<1 day	Not calculated	
Vinyl	10 µl BSA/tryptone/mucin solution containing 5.5 $\log_{10}$ $TCID_{50}$	Dark, RH 50%: 20°C	≥28 days	6.3 days	
		30°C	3 days	1.4 days	
		40°C	2 days	9.9 hours	
Glass	10 µl of 6.5 $\log_{10}$ $TCID_{50}$/ml	Dark, 4°C	≥14 days	Not reported	[234]
		Dark, 20-25°C	3 days	Not reported	
		Dark, 30°C	1 day	Not reported	
		Dark, 37°C	<1 day	Not reported	
Solution	6.5 $\log_{10}$ $TCID_{50}$/ml	Dark, 4°C	≥14 days	Not reported	
		Dark, 20-25°C	7 days	Not reported	
		Dark, 30°C	1 day	Not reported	
		Dark, 37°C	1 day	Not reported	
Metal disc	5 $\log_{10}$ $TCID_{50}$/ml in 0.3% BSA solution	4°C, RH 30-40%	8 days	12.9 hours	[235]
		RT, RH 30-40%	5 days	9.1 hours	
		30°C, RH 30-40%	≥9 days	17.9 hours	
Stainless steel, plastic, nitrile glove pieces	Simulated saliva droplets (1-5 µl)	24°C, RH 20%	Not reported	15.3 hours	[236]
		24°C, RH 40%	Not reported	11.5 hours	
		24°C, RH 60%	Not reported	9.2 hours	
		24°C, RH 80%	Not reported	8.3 hours	
		35°C, RH 20%	Not reported	7.3 hours	
		35°C, RH 40%	Not reported	7.5 hours	
		35°C, RH 60%	Not reported	2.3 hours	
Swine skin	50 µl of 4.5 $\log_{10}$ PFU	4°C, RH 40-50%	≥14 days	46.8 hours	[237]
		22°C, RH 40-50%	2 days	3.5 hours	
		37°C, RH 40-50%	4 hours	0.6 hours	
Fabric (35% cotton, 65% polyester)	50 µl of 4.5 $\log_{10}$ PFU	4°C, RH 40-50%	4 days	33.7 hours	
		22°C, RH 40-50%	4 hours	1.0 hours	
		37°C, RH 40-50%	<4 hours	0.2 hours	
	50 µl of 4.5 $\log_{10}$ PFU	4°C, RH 40-50%	4 days ($1) 3 days ($20)	33.2 hours ($1)	

Substrate	Inoculum concentration and presentation	Incubation variables[a]	Persistence time[b]	Half-life	Reference
Bank notes (25% linen, 75% cotton)				15.9 hours ($20)	
		22°C, RH 40-50%	8 hours ($1, $20)	1.3 hours ($1) 1.1 hours ($20)	
		37°C, RH 40-50%	4 hours ($1, $20)	0.4 hours ($1) 0.6 hours ($20)	
Tyvek coveralls	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	14 days	Not reported	[238]
Mask (N95 particulate filter respirator and surgical)	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	21 days	Not reported	
Mask (N-100 particulate respirator)	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	21 days	Not reported	
Cotton t-shirt	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	<1 day	Not reported	
Stainless steel	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	14 days	Not reported	
Plastic face shield	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	21 days	Not reported	
Nitrile medical examination gloves	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	7 days	Not reported	
Chemical-resistant reinforced nitrile gloves	10 µl BSA/tryptone/mucin solution containing 7.88 log $TCID_{50}$/ml on 1.4 cm^2 token	~20°C, RH 30-40%	4 days	Not reported	
Polyethylene terephthalate glycol PPE visor	50 µl containing 4.3 log_{10} PFU on 6.3 mm^2 material	22°C, RH 40–50%	>3 days	10.05 hours	[239]

Substrate	Inoculum concentration and presentation	Incubation variables[a]	Persistence time[b]	Half-life	Reference
Polypropylene-coated nonwoven shroud fabric on PPE hood	50 µl containing 4.3 log_{10} PFU on 6.3 mm^2 material	22°C, RH 40-50%	>3 days	9.12 hours	
Polyester PPE visor	50 µl containing 4.3 log_{10} PFU on 6.3 mm^2 material	22°C, RH 40-50%	>3 days	8.72 hours	
Spunbound polypropylene nonwoven PPE hood shroud fabric, polyethylene outer film	50 µl containing 4.3 log_{10} PFU on 6.3 mm^2 material	22°C, RH 40-50%	>3 days	6.74 hours	
Polyester PPE visor with antistatic and antifog coating	50 µl containing 4.3 log_{10} PFU on 6.3 mm^2 material	22°C, RH 40-50%	>3 days	8.83 hours	
Tyvek 400 coverall	50 µl containing 4.3 log_{10} PFU on 6.3 mm^2 material	22°C, RH 40-50%	>3 days	9.08 hours	
DMEM	4 log_{10} PFU/ml	S-D614 strain:			[240]
		4°C	≥30 days	Not reported	
		-20°C	≥30 days	Not reported	
	4 log_{10} PFU/ml	S-G614 strain:			
		4°C	≥30 days	Not reported	
		-20°C	≥30 days	Not reported	
Human skin	4.7 log_{10} $TCID_{50}$ SARS-CoV-2 in 2 µl PBS placed onto 4 x 8 cm skin	25°C, RH 45-55%			[241][d]
		Wuhan strain	9 hours	0.7 hours[c]	
		Alpha variant	20 hours	1.7 hours	
		Beta variant	19 hours	1.7 hours	
		Gamma variant	11 hours	1.1 hours	
		Delta variant	17 hours	1.5 hours	
		Omicron variant	21 hours	2.0 hours	
Plastic (polystyrene)	4.7 log_{10} $TCID_{50}$ SARS-CoV-2 in 2 µl PBS onto plastic	25°C, RH 45-55%			
		Wuhan strain	56 hours	0.7 hours	
		Alpha variant	191 hours	1.7 hours	
		Beta variant	157 hours	1.7 hours	
		Gamma variant	59 hours	1.1 hours	
		Delta variant	114 hours	1.5 hours	
		Omicron variant	194 hours	2.0 hours	

[a] RH, relative humidity; RT, room temperature; PFU, plaque forming units; BSA, bovine serum albumin; DMEM, Dulbecco's modified Eagle's medium.
[b] The final time points where infectious SARS-CoV-2 was detected is shown. When this was the last time point tested, ≥[given time point] is indicated. Some of these values were estimated from graphs.
[c] Two values for half-lives were given; values shown were based on regression curve when remaining virus titre was 2.0 log_{10} $TCID_{50}$.
[d] Non-peer reviewed preprint.

5.2.1. *Persistence on inanimate surfaces*

Van Doremalen *et al*. (2020) compared the surface stability of SARS-CoV and SARS-CoV-2 at room temperature (21-23°C) and 40% relative humidity (RH) [230]. Stability was quantified by virus infectivity using Vero E6 cells. Four surface types were compared, plastic (polypropylene), stainless steel, copper and cardboard. The concentration of infectious viruses decreased on all surfaces for both viruses. Both viruses survived longest on plastic and stainless steel (below limit of detection after 4 days) and shortest on copper surfaces (below limit of detection after 8 hours). Results for cardboard (below limit of detection after 2 days) were variable because virus recovery was by swabbing rather than washing and the virus would have absorbed into the cardboard, but these data suggest a shorter survival compared to plastic and stainless steel. Specifically, median half-lives for SARS-CoV-2 on the different substrates were 6.81, 5.63, 3.46, and 0.77 hours on plastic, steel, cardboard and copper, respectively. Median half-lives for SARS-CoV on the different substrates were 7.55, 4.16, 0.59 and 1.5 hours on plastic, steel, cardboard and copper, respectively.

Chin *et al.* (2020) has also assessed the stability of SARS-CoV-2 on inanimate surfaces using Vero E6 cells to determine infectivity [136]. Surfaces were inoculated with a 5 µl droplet of virus culture (~7·8 $\log_{10}$ $TCID_{50}$/ml) and incubated at 22°C, 65% RH. Virus was eluted from samples at time periods 0, 30 min, 3 and 6 hours, and 1, 2, 4 and 7 days. No infectious virus could be detected from printing and tissue paper at 3 hours (showing at least a 2.8 log reduction), nor from treated wood and cloth at day 2 (2.8 to 3.7 log reduction). SARS-CoV-2 persisted longer on smooth surfaces, with infectious virus detected from glass and banknotes at day 2 but not at day 4, and detection on stainless steel and plastic at day 4 but not at day 7. Infectious virus could still be detected on the outer (but not inner) layer of a surgical mask on day 7 (~0·1% of the original inoculum). Corpet (2021) had hypothesised that SARS-CoV-2 persists for shorter times on paper because it may be inactivated by dehydration on water-absorbent porous materials but sheltered by long-persisting micro-droplets of water on waterproof surfaces such as plastic, glass or stainless steel [242].

A study by Pastorino *et al.* 2020 [232] compared infectivity of SARS-CoV-2 inoculated onto polystyrene plastic[87], aluminium and glass, with and without the addition of bovine serum albumin (BSA) to mimic the protein content within respiratory body fluids. Surfaces were inoculated with a 0.05 ml droplet of virus culture (at 6 $\log_{10}$ $TCID_{50}$/ml). Incubation conditions consisted of 19-21°C and 45-55% RH, and infectivity was determined using Vero E6 cells. In the absence of BSA (protein concentration 1.8 g/L), there was a 6 log reduction in infectivity in <4 hours on aluminium (half-life 2.5 h), a 3.5 log reduction on glass over 44 hours (half-life 17 hours), but <1 log reduction over 92 hours on polystyrene plastic (half-life >96 hours). However, infectivity persisted longer on all surfaces in the presence of BSA (protein concentration 11.4 g/L) (half-life of >96 hours on all surfaces).

A study by Riddell *et al.* (2020) also compared SARS-CoV-2 infectivity on stainless steel, polymer and paper notes, glass, vinyl and cotton cloth [233]. A 10 µl volume of a BSA, tryptone

[87] In one location in this reference, the plastic was described as polypropylene while all other mentions list polystyrene plastic.

and mucin solution containing 5.5 log_{10} $TCID_{50}$ SARS-CoV-2 was inoculated onto coupons of the different substrates and dried. The authors suggest that this represents a plausible amount of virus that might be deposited on a surface based on concentrations extrapolated from RT-qPCR results from some patient samples. The inoculated coupons were incubated in the dark at RH 50% and temperatures of 20, 30 and 40°C, and infectivity was tested 1 hour, and 1, 3, 7, 14, 21 and 28 days post inoculation. At 20°C, the half-life for SARS-CoV-2 infectivity was the longest on paper notes (9.1 days) and the shortest on cotton (5.6 days). Infectious SARS-CoV-2 could be recovered from most nonporous surfaces (glass, polymer note, stainless steel, vinyl and paper notes) after 28 days at ambient temperature (20°C), while no infectious virus was isolated from cotton cloth after a week. Infectivity decreased as the temperature was increased (while maintaining constant humidity), reducing the duration of infectivity to as low as 24 h at 40°C for most substrates, and less for cotton cloth.

A further study of surface survival of SARS-CoV-2 quantified infectious virus after inoculation onto skin (swine skin with the hair removed), unused US banknotes, and fabric (unused scrub fabric consisting of 35% cotton and 65% polyester) [237]. The samples were incubated for 0, 4, 8, 24, 72 and 96 hours, and 7 and 14 days post-exposure at three different temperatures (4˚C ± 2˚C, 22˚C ± 2˚C, and 37˚C ± 2˚C). The virus exhibited similar initial decay profiles at 4˚C across all surfaces, reducing by 1–2 log_{10} PFU in the first 8 hours. However, after this time the virus appeared to stabilize to varying degrees for the remainder of the experiment. It was detected after 14 days on skin, 96 hours on fabric, and 7 days on banknotes. At 22˚C, the virus appeared to decline by approximately 2–3 log_{10} PFU within the first 8 h across all surfaces. Infectious virus was detectable on bank notes only up to 8 or 24 hours, fabric for 4 hours and skin up to 96 hours. At 37˚C, infectious virus was only detected for 4-8 hours across all surfaces. These results are consistent with previous studies, which showed that the virus survives longer at low temperatures. The demonstration of virus stability on skin (a new substrate) reinforces the importance of hand hygiene.

A study by Kasloff *et al.* (2021) assessed the persistence of SARS-CoV-2 infectivity on PPE samples including porous materials such as N-95 and N-100 particulate respirator masks, Tyvek overall material and cotton t-shirt material, as well as non-porous nitrile medical examination gloves, reinforced chemical resistant gloves, plastic and stainless steel surfaces [238]. Surfaces (1.4 cm^2 coupons) were inoculated with 10 µl 7.88 log $TCID_{50}$/ml SARS-CoV-2 in a BSA/tryptone/mucin solution. Samples were incubated at ambient conditions in a closed cabinet (20°C, RH 30-40%). Persistence of infectious SARS-CoV-2 on samples was assessed for 21 days and RT-qPCR was also performed to assess the efficiency of SARS-CoV-2 elution from surfaces (SARS-CoV-2 RNA compared with infectious particles). Infectious virus was still detected after 21 days on some surfaces such as both mask types and plastic, and up to two weeks on overall material and stainless steel, albeit at significantly reduced levels. In contrast, infectious virus was below the limit of detection from cotton material by one day, and had reduced by over 4 log after only one hour of the sample drying (a 99.995% decrease from input inoculum). SARS-CoV-2 RNA was recovered at slightly lower titres on cotton samples compared with other materials after four hours (~2 log lower, but still reasonably high level at ~7.9 log), followed by a gradual reduction between days 1 and 14 post inoculation. These

results suggest that the rapid decline of SARS-CoV-2 infectivity observed on cotton is not merely due to it being less efficiently eluted from this material. Infectivity results on cotton material are similar to those reported by Chin et al. (2020) [136].

A study by Haddow *et al.* 2021 also assessed persistence on similar PPE surfaces to that used by Kasloff *et a*l. (2021) [239]. However, results were difficult to compare between studies due to different experimental parameters; Haddow *et al.* (2021) used a total incubation time of 3 days compared with 21 days, a lower inoculum load (4.3 log_{10} PFU was used based on reported viral RNA loads in human sputum of samples) and the inoculum did not contain mucin, BSA or tryptone. In this study, SARS-CoV-2 remained infectious on all surfaces tested after 72 hours incubation, but with a reduction in infectivity of 2-3 log PFU depending on the material.

As results from the discussed studies show, the length of time that SARS-CoV-2 infectivity is maintained on different surfaces varies considerably depending on the study and experimental conditions, such as titre of virus used, storage temperature, relative humidity, or the presence of added protein (e.g. BSA and mucin) (Table 3). The presence of added protein (which mimics the protein content present within respiratory body fluids) has been shown in some studies to extend the persistence of infectious SARS-CoV-2 on surfaces, while including nasal mucus or sputum reduced persistence in other studies [232, 243].

SARS-CoV-2 infectivity on common surfaces at ambient temperature was retained for longest periods of time, and half-lives were the longest, in the study by Riddell *et al.* (2020), although the lowest temperature they tested was 20°C [233]. The authors suggest that the duration of detection of infectious virus in their study is likely due in part to the high titre of virus used in their study (at least 2 log $TCID_{50}$ higher than used by van Doremalen *et al.* (2020)). The half-life of infectivity on aluminium in the absence of BSA reported by Pastorino *et al.* (2020) was in between the half-lives reported by van Doremalen *et al.* (2020) for copper and steel, and reduction in infectivity on glass was similar to that reported by Chin *et al.* (2020)[88]. However, the half-life observed on plastic was considerably longer than reported by van Doremalen *et al.* (2020); authors attribute this to different plastic types used in the two studies (polystyrene versus polypropylene). Chin *et al.* (2020) also reported a larger decline in infectivity after four days on plastic (polymer type not indicated) than Pastorino *et al.* (2020).

Earlier studies that examined SARS-CoV-2 stability on surfaces and food typically used earlier circulating strains such as the Wuhan strain. A non-peer reviewed preprint has compared the stability on *ex vivo* human skin samples and polystyrene plastic of the Wuhan strain, and the Alpha, Beta, Gamma, Delta and Omicron variants [241]. The Alpha, Beta, Delta and Omicron variants all remained infectious for significantly longer periods of time on both substrates compared with the Wuhan strain. The Omicron variant persisted for the longest period of time, which was more than two or three times longer than the Wuhan strain on skin or plastic, respectively. However, survival of the Omicron variant was not significantly different than of Alpha and Beta (on both substrates) or Delta (on skin). The apparent higher stability of the

[88] Results are presented in different formats across the three papers; tables by Chin *et al.* (2020) do not report half-lives.

Omicron variant relative to the Wuhan strain may have implications for SARS-CoV-2 stability and transmissibility on fomites but these results need to be reviewed and confirmed.

While persistence as determined by molecular assays (i.e. RT-qPCR) does not inform on infectivity, such studies can be useful to demonstrate potential sources of contamination and identifying high risk areas. For instance, the US CDC reported on a study that used RT-qPCR methods, rather than cell culture, to determine the persistence of SARS-CoV-2 on the surfaces within cruise ship cabins of symptomatic and asymptomatic COVID-19 passengers. The study showed that SARS-CoV-2 could be detected 17 days following the vacation of the cabins and pre-cleaning [244]. Because viral RNA can persist longer than the time over which the virus remains infectious, the presence of RNA does not necessarily show the presence of infectious virus. Based on the findings reported by van Doremalen *et al.* (2020) [230] and Chin *et al.* (2020) [136], it is unlikely that the virus remained infectious after this 17-day period.

A study by Guo *et al.* (2020) sought to determine the presence of SARS-CoV-2 on surfaces in Wuhan, China intensive care and general COVID-19 hospital wards [245]. SARS-CoV-2 RNA was widely detected on floors (including samples from a pharmacy which was accessed by staff and not patients, presumably transmitted on shoe soles), shoe soles of intensive care unit staff, surfaces touched by patients and/or intensive care staff (computer mice, trash cans, and sickbed handrails and doorknobs) and on patient masks. Contamination was greater in intensive care units than general wards. As with the cruise ship cabin study, results do not show that the detected virus was infectious, but instead show potential for SARS-CoV-2 transmission via contact surfaces in the absence of effective cleaning. Furthermore, a recent study that sampled high-contact surfaces and air in close proximity to patients infected with the Omicron variant found high contamination rates based on detection of SARS-CoV-2 nucleic acid (90 of 168 surfaces (57%) and 6 of 49 air samples (12%)) [246]. Rates of contamination were not significantly different between the Wuhan and Alpha variants. Importantly, despite the increased stability of the Omicron variant under laboratory conditions that has been reported in a preprint [241], no infective virus was identified in any of the samples in this study in a real life environment.

Asymptomatic COVID-19 patients were also demonstrated to be capable of contaminating their surroundings [247]. A total of 4 of 14 surface samples taken from a negative-pressure, non-intensive care unit room housing an asymptomatic patient in a hospital ward in Chengdu, China, tested positive for SARS-CoV-2 by RT-qPCR. The samples included the bed sheet and rail, pillow and air exhaust outlet; however, an air sample was negative. Virus infectivity was not tested. A further study sampled inanimate surfaces in areas at high risk for aerosol formation in an emergency unit of a sub-intensive care ward containing COVID-19 patients [248]. Two of 26 samples tested positive by RT-qPCR, but no infectious virus was detected by culture in Vero E6 cells. The authors suggested that although contact with fomites in contaminated areas may be a route for infection, it might be less extensive than hitherto recognised in healthcare settings where PPE is in use and regular surface sanitising occurs.

SARS-CoV-2 RNA has also been detected from environmental swabs from households and accommodations inhabited by cases [133, 249-251]. In one study, SARS-CoV-2 RNA was

identified in three of 19 samples of a COVID-19 patient's apartment, and from three of 50 samples from a department store where a COVID-19 outbreak had occurred, 48 and 57 days after the premises had been vacated, respectively [251]. In another study, fifteen household surfaces were sampled from each of ten households that housed at least one person with COVID-19, and samples were tested for presence and viability of SARS-CoV-2 [133]. These samples were taken within six days of the first household member testing positive. SARS-CoV-2 RNA was detected in six of ten households, and from 23 (15%) of 150 environmental samples, most frequently on nightstands (4/6; 67%), pillows (4/23; 17%), and light switches (3/21; 14%). Infectious SARS-CoV-2 was also cultured from one nightstand sample. The authors discussed that the presence of infectious virus from only one of 23 RT-qPCR-positive samples, taken together with multiple studies showing no recovery of infectious virus from samples that were positive for SARS-CoV-2 RNA, supports that the risk of fomite transmission is low.

A further study has examined the prevalence of SARS-CoV-2 contamination of surfaces (RT-qPCR testing only) from 116 United States food plants that had already implemented measures to prevent symptomatic personnel from coming to work [252]. A total 278 of 22,643 (1.23%) environmental swabs tested positive by RT-qPCR, with frequently touched surfaces (doorknobs, computer devices, tabletops and sanitizers) being the most commonly contaminated. The study did not test infectivity and no conclusions were not made regarding fomite transmission, but the authors suggested that the study supported environmental monitoring for SARS-CoV-2 as a surrogate for identifying the presence of asymptomatic and presymptomatic personnel in workplaces.

Another Chinese study sampled seven cold storage facilities (<-18°C) and stored frozen foods imported from a range of countries in a department store where an outbreak had occurred, and food market surfaces (room temperature) that were potentially in contact with imported frozen foods [251]. A total of 24/6676 food packages and 2/5063 environmental surfaces tested positive by RT-qPCR. Only one of the positive samples was from a market (a prevalence of 1/10,034 market samples with the positive sample being from packaging). The other 25 positive samples were from cold storage facilities (prevalence 25/1705), with 23 of these being food packages.

Studies have also assessed the presence of SARS-CoV-2 RNA from supermarket surfaces. One study tested 300 swabs from 20 Italian supermarket surfaces (scales, shopping trolley handles, refrigerator and freezer handles, and keyboards) during a COVID-19 lockdown period [253]. A total of 13 (4.3%) samples tested positive for RNA, with trolley handles and scales being the most frequently contaminated sites (5%, 6/120 and 1/20 respectively). The presence of infectious virus was not tested. In another study conducted from food retail stores in Canada during their second COVID-19 wave, SARS-CoV-2 RNA was not detected from 957 swab samples from high touch surfaces (payment stations, deli counters, refrigerated food section and carts and baskets) [254]. Information was not available on how mask-wearing policies for consumers or sanitisation procedures differed between the communities and retailers in the two studies.

5.2.2. *Persistence in aerosols and distribution*

Van Doremalen *et al.* (2020) compared the stability of SARS-CoV and SARS-CoV-2 in aerosols (<5 µm, created and maintained by a nebuliser; 21-23°C and 65% RH) [230]. Median half-lives were 1.18 and 1.09 hours for SARS-CoV and SARS-CoV-2, respectively. Under these experimental conditions, the virus could remain infectious in aerosols for at least three hours (which was the length of time the experiment was conducted).

A study assessed the stability of SARS-CoV-2 (23°C and 53% RH) when maintained in aerosol format for up to 16 hours [255]. This study reported consistent levels of infectious SARS-CoV-2 over the 16 hour duration of aerosolisation. In addition, the SARS-CoV-2 virus particles from the 16 hour aerosol suspension maintained integrity when examined visually by scanning electron microscopy. However, the researchers cautioned that the results were based on limited data and repeated studies were needed for validation.

Although the level of stability of SARS-CoV-2 in aerosols differed between studies, both studies show that the virus remains infectious in aerosol format. However, the studies do not indicate how long aerosols remain airborne. One study employed laser light monitoring scattering to observe the fall time of small speech droplets, which was found to be from eight to 14 minutes [256]. Once airborne, speech-generated droplets rapidly dehydrate, thereby decreasing in diameter, which slows their fall. Therefore, droplets of any size do not remain airborne for long periods of time.

The rate of aerosol emission during speech has been correlated with loudness of vocalisation, for example, loud speech can emit thousands of respiratory drops per second [256-258]; accordingly, singing would also result in higher particle emissions than talking. Furthermore, certain people have been designated super-emitters, capable of releasing an order of magnitude higher number of particles than their peers [257]. These factors were implicated in a COVID-19 outbreak arising from a 2.5 hour choir practice involving a single index case and members sitting in close proximity (less than 2 metres apart). Of the 61 people that attended the practice, 53 cases were identified resulting in three hospitalisations and two deaths [259].

Air sampling for SARS-CoV-2 is achieved by pumping air through a filter, which traps the virus. In a study where researchers assessed the presence of SARS-CoV-2 in the air from symptomatic COVID-19 patients' isolation rooms using RT-qPCR, all samples tested negative [260]. Another study tested for the presence of SARS-CoV-2 RNA (using RT-qPCR) in air supply (upstream of airflow) and air discharge samples (downstream of airflow) from Wuhan intensive care and general COVID-19 hospital wards [245]. A total of 35% (14 /40) of intensive care air samples and 12.5% (2/16) of general ward air samples tested positive. Air outlet swab samples also tested positive (66.7% (8/12) in intensive care units and 8.3% (1/12) in general wards). Detection rates included 35.7% (5/14) near air outlets and 44.4% (8/18) in patients' rooms. At a site located against the airflow, which was four metres away from a patient's bed, virus was detected in 12.5 per cent (1/8) of samples. Based on this finding, the report suggested that the aerosol transmission distance of SARS-CoV-2 might be four metres.

A commentary was recently published regarding this study[89]. The authors of the commentary stated that:

"We should consider the results from this study with caution. The study tests for the presence of the virus on surfaces and in the air, but doesn't indicate if the virus was living and infectious. The authors didn't describe the nature of medical procedures undertaken in these wards, particularly if any might be likely to generate aerosols. The virus sample detected four metres away was described as a "weak positive". Both "intense positive" and "weak positive" samples were grouped together as positive samples in the results without defining what a "positive sample" was or explaining the distinction between the two outcomes. The study had a small sample size and importantly, researchers didn't use any statistical tests to determine the significance of their findings. So the results have limited utility in the real world."

The four metre distance reported by Guo *et al*. (2020) [245] is longer than the one-to-two metre rule of spatial separation guidelines recommended by regulatory authorities to prevent spread of the virus. The one-to-two metre rule of spatial separation assumes that the distance travelled by large respiratory droplets decreases with distance from an infected person, and these are less likely to travel further than 2 metres (as discussed in Section 4.2.1). Bahl *et al*. (2020) reviewed the evidence for horizontal distance travelled by droplets [261]. They concluded that the evidence for the one-to-two metre rule was not compelling and that eight of ten studies reviewed reported travel of droplets from two to eight metres. As discussed by the authors of the commentary:

"*Of the ten studies, five were conducted using human subjects. These studies looked at the dynamics of droplet transmission but were not specifically related to SARS-CoV-2-containing droplets. So we need more research to better understand transmission of SARS-CoV-2 in hospital settings. Health-care settings should adopt measures to prevent airborne transmission, such as using N95 respirators and gowns, if conducting any aerosol generating procedures*."

A further study of potential aerosol transmission within the environment of two additional hospitals in Wuhan has been reported [262]. One hospital was a tertiary facility designated for treatment of severe symptom COVID-19 patients, while the other was representative of the make-shift field hospitals which was renovated from indoor sports facilities or exhibition centres to quarantine and treat patients with mild symptoms. SARS-CoV-2 was quantified by RT-qPCR in three types of samples: all aerosol samples, size segregated aerosol samples, and aerosol deposition samples. The concentration of SARS-CoV-2 in aerosols detected in isolation wards and ventilated patient rooms was very low, but it was elevated in the patients' toilet areas. Levels of airborne SARS-CoV-2 in the majority of public areas were undetectable except in two areas prone to crowding, possibly due to infected carriers in the crowd. Some medical staff areas (e.g. protective equipment removal rooms) initially had high concentrations of viral RNA, but these levels were reduced to undetectable levels after implementation of rigorous sanitization procedures. Overall, in the positive samples, viral RNA copies were quantified as

[89] https://theconversation.com/can-coronavirus-spread-4-metres-136239; published 22 April 2020, accessed 14 April 2022

up to 113 genome copies per square metre per hour for deposition surfaces in intensive care units, and up to 42 genome copies per cubic metre for aerosol samples.

It is important to note that these studies concern healthcare settings where symptomatic cases are present.

5.2.3. *Effect of temperature and humidity on coronavirus infectivity*

Although climatic temperature appears to be associated with the prevalence of COVID-19 infections (for example, [263, 264]), the focus of this section is on inactivation and storage temperature and humidity effects on SARS-CoV-2 infectivity.

In general, the length of time SARS-CoV-2 and other coronaviruses remain infectious declines with increasing temperature. Abraham *et al.* (2020) reviewed existing literature on thermal inactivation of SARS-CoV-2 [265]. The necessary temperature and length of time required for thermal inactivation depended on the experimental setup (e.g. the strains used and culture conditions differed between studies), surface and the environment (e.g. relative humidity). However, the authors applied a conservative approach to provide the following recommendations for heat inactivation of SARS-CoV-2 from all surfaces and environments. To inactivate SARS-CoV-2, suspected contaminated objects should be heated for:

- 3 minutes at temperature above 75°C,
- 5 minutes for temperatures above 65°C, or
- 20 minutes for temperatures above 60°C.

It should be noted that recommendations are hotter than encountered in residential clothes dryers, clothes washing machines, and dish washers (typically below 57°C) and residential hot water (e.g. hot water limited to 49°C in the United States). However, under those circumstances, other factors, such the dilutional effect of the water and/or the presence of envelope-disrupting detergents, would reduce any infection risk.

Studies summarised in Table 3 show that warmer temperatures reduce SARS-CoV-2 infectivity at a faster rate. This effect was even observed when SARS-CoV-2 infectivity was measured over a 14 day storage period in virus transport media, which is designed to stabilise virus [136]. Five storage temperatures were used (4, 22, 37, 56 and 70°C), and a starting concentration of 6·8 $\log_{10}$ $TCID_{50}$/ml. Full inactivation (undetectable by the cell culture) of SARS-CoV-2 was reported after 5 min at 70°C, 30 min at 56°C, day 2 at 37°C and day 14 at 22°C. SARS-CoV-2 was highly stable at 4°C with only a ~0·7 log reduction of infectious titre by day 14.

Chan *et al.* (2020) compared the infectivity of SARS-CoV and SARS-CoV-2 on dried glass surfaces incubated at 4, 20-25, 33 and 37°C [234]. Loss of infectivity for both viruses was temperature-dependent, with both viruses maintaining infectivity at 4°C. For both viruses, there was a ~1 log reduction in infectious titres ($TCID_{50}$) after one week and a 2-3 log reduction after two weeks incubation at 4°C. In contrast, no infectious SARS-CoV-2 was detected after one week of incubation at 20-25°C or higher. A ~5-log reduction in infectious titres was observed following a one-week incubation of SARS-CoV at 20-25°C, and no infectious virus was detected

after two weeks at this temperature. No infectious virus was detected after one week at 33°C or higher. A similar temperature-dependent effect on survival dynamics were observed for SARS-CoV-2 incubated in solution, although SARS-CoV-2 infectivity was more stable in liquids than on dried surfaces. Inactivation rates of other coronaviruses have previously been shown to be lower in liquids compared with surfaces when incubated at the same temperatures [266, 267].

Kratzel *et al*. (2020) investigated infectivity of SARS-CoV-2 when dried onto a metal surface in the presence of 0.3% BSA and incubated at 4°C, room temperature (the actual temperature was not specified) and 30°C, at a humidity of 30-40% [235]. First, they observed more than 2 log reduction in infectious titres ($TCID_{50}$) following drying of the inoculated virus for one hour at room temperature, while infectivity of the dried virus remained stable over the following 4-8 hours. Surprisingly, the study did not find major differences in decay rates between the three incubation temperatures. Although the decay in infectivity of SARS-CoV-2 incubated at 4°C (median half-life of 12.9 hours) was slower than when incubated at room temperature (median half-life of 9.1 hours), the highest predicted half-life occurred at 30°C (17.9 hours). The findings contrast with studies by Chin *et al.* (2020) and Chan *et al.* (2020) discussed above, and the loss of infectivity at 4°C is also more rapid than described in those studies. Differences might be due to the different experimental conditions used between studies; e.g. solution versus dried application (although Chan *et al*. also tested a dried application), surface type, or the RH (which was not provided for the latter two studies).

Survival studies of SARS-CoV-2 on various surfaces and under different conditions to date have focussed on earlier SARS-CoV-2 variants, while emerging variants contain mutations in their spike protein which may influence their stability. A study compared the infectivity, RNA integrity and ACE2-binding capacity of an earlier variant of SARS-CoV-2 carrying the spike protein (S)-D614 allele with a more recent variant carrying the S-G614 mutation (present in the Delta variant [268]), following storage at refrigeration (4°C) and freezing (-20°C) [240]. Infectious titres (PFU/ml) of the S-D614 variant was almost undetectable after storage at 4°C for 30 days (~4-log reduction in PFU/ml), but reduced by only ~1-log following storage at -20°C. The S-G614 variant retained higher infectious titres following storage at 4°C, while titres were similar to S-D614 following -20°C storage. There was no significant reduction in infectivity of either variant following storage at -80°C for 2.5 months. The ACE2 binding ability and RNA integrity were similarly higher for the S-G614 variant than the S-D614 variant stored at 4°C.

Consistent with studies showing the stability of SARS-CoV-2 in dairy products (discussed in Section 5.1) and different variants in DMEM [240], freezing has very little impact on the infectivity of foodborne enteric viruses, with multiple outbreaks of hepatitis A and norovirus infections, for example, attributed to frozen foods [269, 270]. Indeed, freezing is used for the long-term storage of viruses in laboratories (although container material and storage media are also important for maintenance of virus infectivity). In addition, the infectious titre of HCoV-229E was also found to be stable to multiple rounds (25 cycles) of freezing and thawing [271], but to our knowledge no data are available to assess whether the same is true for SARS-CoV-2.

The studies summarised in Table 3 used different RH levels. The effect of RH is best evaluated through the study of Biryukov *et al*. (2020) [236]. In this study, SARS-CoV-2 was diluted 1:10 in

simulated saliva and wet droplets were deposited onto stainless steel, acrylonitrile butadiene styrene (ABS) plastic, or nitrile rubber glove coupons. The surfaces were chosen to represent common sources of fomite transmission (door knobs/handles and office electronics) and to address the risks associated with contaminated PPE. Infectivity was measured at different temperatures and RH combinations ranging from approximately 20 to 80% RH and 24 to 35°C (note that temperatures at or below 4°C were not tested). There was not a significant difference in half-life estimates between virus deposited on stainless steel, ABS plastic, or nitrile glove coupons under the same conditions. Across all surface types, the half-life of infectious virus decreased when either temperature increased or RH increased. For example, when the data was combined for all surface types at 24°C, the SARS-CoV-2 half-life ranged from 15 hours at 20% RH down to ~8 hours at 80% RH.

Results from Biryukov *et al*. (2020) are consistent with data from other coronaviruses, which have been shown to remain infectious for shorter periods at higher humidity than in drier environments [267, 272-276].

Guillier *et al.* (2020) modelled the impact of both temperature and RH on coronavirus persistence, using data on inactivation kinetics of coronaviruses in both solid and liquid fomites from a range of studies [277]. Some of the included studies were of SARS-CoV-2, but data from Biryukov *et al.* (2020) were not included. They found that RH had a non-monotonous, non-linear impact on coronavirus inactivation. Persistence was highest at 100% and low RH, compared with intermediate RH. As discussed in the previous section, infectivity also decreased with increasing temperature. A useful graphical representation of the modelled relationship between RH and temperature on coronavirus infectivity is provided in the publication. The authors also provide a spreadsheet for predicting virus inactivation for untested temperatures and RH, time points or any coronavirus strains belonging to Alphacoronavirus and Betacoronavirus (which includes SARS-CoV-2) genera[90]. It should be noted that Guillier *et al.* (2020) did not consider inactivation data on antimicrobial surfaces (e.g. copper or silver), or porous surfaces because of the difficulty determining whether any measured inactivation is associated with real loss of infectivity or difficulty in recovering viruses absorbed inside the porous material. Another predictive model of temperature-dependent effects on the inactivation of SARS-CoV-2 and other coronaviruses based on existing data has also been published [278].

5.2.4. *Inactivation treatments for coronaviruses*

Chemical treatments

A study evaluated the virucidal effects of common disinfectants against SARS-CoV-2 [136]. A 15 µl volume of SARS-CoV-2 culture (~7·8 $\log_{10}$ $TCID_{50}$ per ml) was added to 135 µl of various disinfectants at working concentration, and levels of infectious virus were assayed after incubation at 22°C for 5, 15 and 30 min. No infectious virus was detected after 5 min incubation

[90] https://github.com/lguillier/Persistence-Coronavirus; accessed 14 April 2022

in household bleach (active ingredient sodium hypochlorite; 1:49 and 1:99 dilution[91]), ethanol (70%), povidone-iodine (7.6%), chloroxylenol (0.05%), chlorhexidine (0.05%) or benzalkonium chloride (0.1%).

Aqueous povidone-iodine was further assessed for its SARS-CoV-2 inactivation efficacy as an oral antiseptic rinse prior to dental and surgical procedures [279]. The solutions tested contained povidone-iodine as the only active ingredient, at concentrations of 0.5%, 1%, and 1.5% (lower than the 7.6% solution used by Chin *et al.* (2020), above). The solutions of SARS-CoV-2 viral particles and povidone-iodine were mixed and incubated at 22°C for 15 or 30 seconds. Each solution was then neutralised and tested for infectivity using end point titration in Vero-76 cells. At both incubation periods, all concentrations of povidone-iodine completely inactivated SARS-CoV-2 viruses (final concentration below the limit of detection, equivalent to >3 log reduction in infectious virus ($TCID_{50}$) compared with the control solution). By comparison, a 70% ethanol formulation reduced the concentrations by 2.17 and >3.3 log $TCID_{50}$ after 15 and 30 seconds, respectively.

The United States Environmental Protection Agency (US EPA) has provided a list of disinfectants recommended for use against SARS-CoV-2[92]. The database lists active ingredients, the producer, guidelines for formulations and contact times, and whether the product qualifies for the "Emerging Viral Pathogen Claim" (which indicates that it has demonstrated efficacy against a harder-to-kill virus than the enveloped human coronavirus). Because coronaviruses are more susceptible to inactivation treatments than enveloped viruses, antiviral disinfectant treatments used in the food industry will also be effective against SARS-CoV-2. The US EPA states that genetic changes to the SARS-CoV-2 genome are not expected to impact the efficacy of disinfectants. The basic physical properties of viruses determine whether they can be killed by disinfectants, and the recent mutations to SARS-CoV-2 (such as are present in the Delta and Omicron variants) have not changed these physical features.

Hand sanitisers

Proper hand hygiene and sanitation has been recognised as critical to mitigate the transmission of SARS-CoV-2. The WHO has released guidance for general hand hygiene against a range of pathogens for the healthcare setting, which includes two recommended hand sanitiser formulations[93]. Formulation guidelines were later updated to include higher alcohol concentrations (measured by mass instead of volume percentage, see below) and lower glycerol concentrations (because glycerol was thought to reduce efficacy) [280].

The virucidal activity against SARS-CoV-2 of four WHO–recommended hand rub formulations (two original formulations and two modified formulations), and of their active ingredients, has

[91] The concentration of the sodium hypochlorite in household bleach was not given, but depending on the purpose, can range from 2-12%; concentrations in US bleach products are typically 6%. Assuming a 6% concentration, concentrations of sodium hypochlorite used in the study would be 0.12 and 0.06%. https://www.cdc.gov/vhf/ebola/clinicians/non-us-healthcare-settings/chlorine-use.html; accessed 14 April 2022
[92] https://www.epa.gov/pesticide-registration/list-n-disinfectants-use-against-sars-cov-2; accessed 14 April 2022
[93] https://apps.who.int/iris/bitstream/handle/10665/44102/9789241597906_eng.pdf; accessed 14 April 2022

also recently been assessed [281]. A suspension of SARS-CoV-2 was exposed for 30 seconds to the active ingredients or formulations, used at full strength or diluted, and infectivity was determined using cell culture. First, the active ingredients ethanol and 2-propanol (isopropyl alcohol), reduced viral titres to background levels in 30 seconds with reduction factors of between 4.8 and ≥5.9; a concentration of >30% (vol/vol) ethanol or 2-propanol was sufficient for complete viral inactivation. Formulations tested included: original formulation I (vol/vol: 80% ethanol, 1.45% glycerol, 0.125% hydrogen peroxide), original formulation II (vol/vol: 75% 2-propanol, 1.45% glycerol, 0.125% hydrogen peroxide), modified formulation I (wt/wt: 80% ethanol; vol/vol: 0.725% glycerol, and 0.125% hydrogen peroxide) and modified formulation II (wt/wt: 75% 2-propanol; vol/vol: 0.725% glycerol, and 0.125% hydrogen peroxide). All four formulations inactivated SARS-CoV-2 after 30 seconds, although it was noted that this may be a longer period than used in practice. The ethanol-based formulations were effective down to a dilution of >40%, and the 2-propanol-based formulations down to >30%.

The virucidal efficacy of a hand soap solution (1:49 dilution) was also assessed against SARS-CoV-2 [136]. Infectious virus was still detected after incubation at room temperature (22˚C) for 5 min (only 1/3 of the triplicate reactions was positive), but not after 15 min. Note that the hot water and physical agitation used in handwashing will increase the virucidal effect.

A recent non-peer reviewed preprint reported that despite the Alpha, Beta, Delta, and Omicron variants being slightly more resistant to ethanol than the Wuhan strain, all variants were still completely inactivated after exposure to 35% ethanol for 15 s on human skin [241]. Note that this ethanol concentration is considerably lower than the US CDC and WHO-recommended concentrations to be used in ethanol-based hand sanitisers, of at least 60% or 80% ethanol, respectively [280][94].

Ozone

Ozone reduces virus infectivity through lipid peroxidation and damage to the lipid envelope (for enveloped viruses) and to a lesser extent protein peroxidation and consequential protein shell damage (non-enveloped viruses) [282, 283]. Ozone is widely used as a disinfectant in water treatment (including wastewater) and food processing, and is used in either gaseous (for surface or air sterilisation) or aqueous form [283-287]. No information was found on the efficacy of ozone on SARS-CoV-2 or other coronaviruses. However, ozone treatment has been found to be effective against a range of other viruses, and is more effective against enveloped than non-enveloped viruses [282]. As such, ozone treatments that are effective against other more resilient viruses are also likely to be effective against SARS-CoV-2. However, ozone is toxic to humans, with strict restrictions around its use [283, 288].

[94] https://www.fda.gov/drugs/information-drug-class/qa-consumers-hand-sanitizers-and-covid-19; accessed 20 April 2022

Light-based sanitation with a focus on ultraviolet light

Considerable interest has been raised recently around the potential for ultraviolet-C (UV-C) light for the decontamination of SARS-CoV-2 from surfaces, hospital equipment, N95 respirators and other PPE [289-291][95,96]. The germicidal effectiveness of UV radiation is in the 180-320 nm range, with a peak at 265 nm. At this range, protein and nucleic acids adsorption and damage occurs [292]. However, this is also harmful to human skin, so any germicidal treatment should not be used to sterilise human skin, and must be carried out in areas where no one is present at the time of disinfection [293].

One study tested the effect of simulated sunlight (280-400 nm, which encompasses UV-A and UV-B) on the infectivity of the virus in experimentally generated aerosols [293]. Different light intensities, humidities and dilution media (simulated saliva or culture medium) were also tested. At 20°C, both simulated sunlight levels tested rapidly inactivated the SARS-CoV-2 in aerosols in both suspension matrixes, with half-lives of less than 6 minutes and 90% inactivation of the virus in less than 20 minutes. When tested under the same conditions in the dark, the half-lives were 55 minutes (in culture medium) or 86 minutes (in simulated saliva), which are comparable with the 1.1 hours reported by van Doremalen *et al.* (2020) in darkness in 65% humidity. In this study, any effects of humidity on SARS-CoV-2 infectivity were minor relative to the effect of the sunlight.

Weaver *et al.* [291] investigated the potential for using biosafety cabinets for sterilising N95 respirators and face shields using the UV-C function. One difficulty they discovered is that these cabinets do not deliver consistent UV levels throughout the internal space, and each cabinet performs differently. Elevating PPE closer to the UV light shortened the calculated time required for sterilisation. For example, under the conditions investigated, they conservatively estimated the time to sterilise N95 respirators for SARS-CoV-2 was one hour per side when in an elevated position, but over four hours when placed on the bottom of the biosafety cabinet. Effective decontamination of face shields likely requires a much lower UV-C dose, and may be achieved by placing the face shields at the bottom of the Biosafety Cabinet for 20 minutes per side. The calculations were based on a target dose of 1 J/cm^2, which is considerably higher than previously reported inactivation doses (1.32–3.20 mJ/cm^2).

The effectiveness of UV-C light to quickly decontaminate high-use plastic airport security bins for SARS-CoV-2 has been assessed [294]. The study inoculated bins at different sites with 10^6 PFU of Phi6 (an enveloped RNA bacteriophage used as a surrogate for coronaviruses) suspended in simulated mucus. Two standard low-pressure mercury UV-C (254 nm wavelength) lamps each providing 426 µW/cm^2 were placed 1 inch above the top of the bin and operated for 10, 20, or 30 seconds delivering a fluence of 8,520, 17,040, and 25,560 µW/cm^2 respectively. The 30 second treatment resulted in a reduction of infective Phi6 PFU titres of >3-log at all bin inoculation sites, which met with the pre-established criteria for decontamination used in the study.

[95] https://www.bbc.com/future/article/20200327-can-you-kill-coronavirus-with-uv-light; accessed 14 April 2022
[96] https://www.sciencedaily.com/releases/2020/04/200414173251.htm; accessed 14 April 2022

A wide range of UV-C germicidal irradiation (UVGI) facilities and equipment are available, such as UVG1 Rooms, lamps, and biosafety cabinets. The time taken to decontaminate a particular surface or product for SARS-CoV-2 will depend on the light source wavelength, degree of emission and distance from the surface requiring decontamination. Based on the light source employed, such devices can be calibrated via radiometry to deliver a measured amount of ultraviolet radiation energy per unit surface area (Joules per square centimetre) for a time period deemed sufficient for decontamination.

Hadi *et al.* (2020) have reviewed the inactivation of SARS-CoV-2 and other single-stranded RNA viruses in different matrixes (air, liquid, and solid) using light-based (UV, blue, and red lights) sanitisation methods [295]. They concluded that the rate of inactivation of ssRNA viruses in liquid was higher than in air, whereas inactivation on solid surfaces varied with the type of surface. In addition, the efficacy of light-based inactivation was reduced by the presence of absorptive materials.

Gamma irradiation

Gamma irradiation has been proposed as a means of inactivating SARS-CoV-2, particularly for PPE. A study of the irradiation doses required to inactivate a target dose of 6 $\log_{10}$ $TCID_{50}$/ml of various viruses, including SARS-CoV has been published [296]. It found that a comparatively low dose was required to inactivate SARS-CoV (1 Mrad) compared with other types of virus (up to 5 Mrad).

A study of the effect of Cobalt-60 gamma irradiation on N95 masks used these irradiation doses that had been shown to inactivate viruses, including SARS-CoV [297]. The ability of the masks to filter 0.3 µm particles was found to be significantly reduced by this treatment.

pH

Coronaviruses are sensitive to low and high pH levels, although the data on SARS-CoV-2 are sparse to date. A study has reported that SARS-CoV-2 remained infectious following incubation for 60 min at 22°C in solutions that covered a range of pH values from pH 3 to 10 [136]. pH values higher or lower than this range, incubation for longer time periods and at a physiologically relevant temperature were not reported. The pH of gastric acid is 1.5 to 3.5 in the human stomach lumen.

Washing produce

It has been suggested that washing fruit and vegetables with soap and water in the home should be conducted as a protection against COVID-19. A commentary from various US food safety scientists recommends against this idea, on the basis of adverse effects from consuming soap residues.[97] The US CDC offers the following advice[98]:

[97] https://www.livescience.com/do-not-wash-fruits-vegetables-with-soap.html; accessed 14 April 2022
[98] https://www.cdc.gov/coronavirus/2019-ncov/daily-life-coping/food-and-COVID-19.html; accessed 14 April 2022

- *“Do NOT wash produce with soap, bleach, sanitizer, alcohol, disinfectant or any other chemical.*
- *Gently rinse fresh fruits and vegetables under cold, running tap water.*
- *Scrub uncut firm produce (e.g., potatoes, cucumbers, melons) with a clean brush, even if you don’t plan to eat the peel.*
- *Salt, pepper, vinegar, lemon juice, and lime juice have not been shown to be effective at removing germs on produce.”*

6. WHAT IS INTERNATIONAL BEST PRACTICE FOR MITIGATION OPTIONS TO REDUCE TRANSFER OF COVID-19 FROM WORKERS TO FOOD PRODUCTS, INCLUDING RISK MANAGEMENT STRATEGIES WHEN A WORKER IS IDENTIFIED AS BEING INFECTED WITH SARS-COV-2?

Key findings:

- Based on available evidence, the best practice for reducing the risk of contamination of food products or packaging continues to be managing the risk of SARS-CoV-2 infection amongst workers. This includes workers getting fully vaccinated, as well as informing their employer, self-isolating, seeking medical advice and getting a COVID-19 test if they have any symptoms of COVID-19 and/or respiratory illness. Employers can recommend and facilitate vaccination, and promote and support good personal hygiene practices for all workers. Because vaccination does not completely prevent infection, particularly with the Omicron variant, and vaccinated people might still have asymptomatic infection, this underscores the importance of adherence to the use of PPE and good hygiene practices.
- Since the last report update in October 2021, New Zealand has moved from a COVID-19 elimination strategy to the current situation where Omicron variant transmission is widespread in the community. Rapid antigen tests (RATs) have overtaken RT-qPCR as the main testing method for people with COVID-19 symptoms, household contacts, and these tests form a key component of ensuring critical workers can remain working even if they are a close contact of a confirmed case. Workplace testing should not be an alternative to the fundamental controls of distancing, hygiene and ventilation.

6.1. How should the current protocols be strengthened based on the importance of aerosol transmission and increased risk associated with the Omicron variant (e.g. options for more rigorous worker testing, such as saliva testing)?

On 26 January 2022, the New Zealand Government announced the COVID-19 Protection Framework (traffic light system). This is a three phase plan to slow down and limit the spread of an outbreak of the Omicron variant, including measures to ensure there are sufficient workers available to support critical supply chains. At the time of this report, New Zealand is in Omicron Phase 3, in which there are thousands of new cases occurring every day. Management approaches centre around most people self-managing the disease at home, while health and social services focus on families and communities that have the highest needs.

MPI have developed enhancements to the guidance to mitigate the risk of transmission of the Delta and Omicron variants of the SARS-CoV-2 virus, and any emerging variants, within primary industry premises and other businesses. Links to specific guidance can be found below:

- COVID-19 Protection Framework (updated 23 April 2022)[99]
- COVID-19 Protection Framework guidance for the primary sector (updated 13 April 2022) [100]
- COVID-19 Protection Framework guidance for food service, food retail & food manufacturing businesses (updated 22 February 2022)[101]
- Guidance for critical workers in the primary industries[102]

Pertinent to this report, "*MPI considers the following procedures and practices to be critical to ensuring the risk to staff and the business is minimised:*

- *Full vaccination of all staff, contractors, and visitors. For the Pfizer vaccine, maximum protection occurs 7 days after a second dose, with at least three weeks between dose 1 and 2. Vaccination is taken into account when determining whether people need to stand down from work, so encouraging workers to be fully vaccinated and have their booster shots will significantly reduce the risk of your business needing to close.*
- *No financial disincentives for staff to stay at home when unwell, test, and get vaccinated, where appropriate.*
- *Health screens (including regular temperature checks, where required) for staff and visitors, with documented records including proof of vaccination status through My Vaccine Pass.*
- *Accurate record keeping of staff who are onsite (may be swipe card records), as well as any visitors and contractors. Ensure phone numbers and email addresses are recorded.*
- *Strengthened ability to trace the movements and interactions of staff within the premises, with these systems tested regularly.*
- *Optimising ventilation systems to ensure effective operation, and circulation of fresh air from outside (this is a MOH priority). The higher transmissibility of the Delta variant, combined with the virus's ability to travel at least eight metres in the air, is thought to be due to the increased viral load of infected persons.*
- *Use of masks by all staff at all times when close contact with other staff and visitors cannot be avoided or managed by other means. This includes production and ancillary staff. The use of face masks is taken into account when determining whether or not people need to stand down from work. Therefore, encouraging workers to consistently and correctly wear good quality, well fitting face masks when close work is unavoidable, will significantly reduce the risk of your business needing to close due to a significant number of staff required to isolate at home.*
- *Maximising the distance between staff and reducing the density of staff in work groups as much as possible.*
- *Strengthened workplace groups (previously known as "bubbles"), being particularly mindful of how staff travel to and from work, how staff entry to premises is controlled, and how they*

[99] https://www.mpi.govt.nz/covid-19/covid-19-protection-framework/; accessed 21 April 2022
[100] https://www.mpi.govt.nz/dmsdocument/48766-COVID-19-Protection-Framework-Guidance-for-the-primary-sector; accessed 21 April 2022
[101] https://www.mpi.govt.nz/dmsdocument/49126-Guidance-for-Food-Service-Food-Retail-Food-Manufacturing-Businesses; accessed 21 April 2022
[102] https://www.mpi.govt.nz/covid-19/critical-workers/; accessed 22 April 2022

congregate during break times. The fewer people interacting in close contact range and high-risk indoor areas, the fewer people will need to be stood down in the event a staff member tests positive for COVID-19."

The NZ Ministry of Health offers general advice around personal protective equipment for workers, that was updated on 13 December 2021, and is currently being reviewed in light of the Omicron outbreak[103].

General advice is also available from various authorities, for example, the Food Safety Authority of Ireland (updated 28 May 2021),[104] and the United States Occupational Safety and Health Administration (OSHA; updated on 13 August 2021)[105]. The advice is focussed on preventing person-to-person transmission within the workplace since there is currently no evidence to support foodborne transmission of SARS-CoV-2.

Testing of workers in the workplace

Saliva testing is being implemented for selected high-risk workplaces that are regularly tested, such as border workers and health care workers[106]. This test involves detection by RT-qPCR.

As discussed in Section 3.4, now that transmission of the Omicron variant is widespread in the community, RATs are currently New Zealand's primary testing tool for people with COVID-19 symptoms or household contacts[107]. Testing with RATs also forms part of the Close Contact Exemption Scheme designed to help keep New Zealand going during the Omicron outbreak, whereby critical businesses and organisations can keep their critical workers working if they become a household contact of someone with COVID-19[108]. Businesses outside of the critical services groups are also using RATs as part of managing the health and safety of their workers in their response to COVID-19.

Ventilation

Food handlers are particularly at risk of aerosol transmission events if they work in chilled hygienic environments which are highly conducive to virus transmission events (super-spreading events) given the cold temperature and reduced ventilation employed to keep the temperature down.

The US Environmental Protection Agency has provided COVID-19 resources including material on ventilation and air cleaning[109,110]. When used properly, air cleaners and filters can help

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[103] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-information-specific-audiences/covid-19-personal-protective-equipment-central-supply; accessed 22 April 2022
[104] https://www.fsai.ie/faq/coronavirus.html; accessed 22 April 2022
[105] https://www.osha.gov/coronavirus/safework; accessed 22 April 2022
[106] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-health-advice-public/assessment-and-testing-covid-19/covid-19-saliva-testing; accessed 22 April 2022
[107] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-health-advice-public/assessment-and-testing-covid-19/rapid-antigen-testing-rat#regulatory; accessed 22 April 2022
[108] https://www.business.govt.nz/covid-19/close-contact-exemption-scheme#e-29078; accessed 14 April 2022
[109] https://www.epa.gov/coronavirus/indoor-air-and-coronavirus-covid-19; accessed 21 April 2022
[110] https://www.epa.gov/coronavirus/air-cleaners-hvac-filters-and-coronavirus-covid-19; accessed 21 April 2022

reduce airborne contaminants including viruses in a building or a small space but air cleaning or filtration is not enough to protect people from COVID-19.

Bipolar ionization (also called needlepoint bipolar ionization) is also discussed. This is a technology that can be used in ventilation systems or portable air cleaners to generate positively and negatively charged particles. Provided manufacturers have data to demonstrate efficacy, manufacturers of these types of devices may market this technology to help remove viruses, including SARS-2-CoV-2, from the air, or to facilitate surface disinfection of surfaces within a treated area. This is an emerging technology, and little research is available that evaluates it outside of lab conditions.

A report from the UK on workplace safety related to COVID-19 also discusses ventilation[111]. It comments that "*most buildings with mechanical ventilation recirculate a portion of the indoor air. The extent to which the recirculated air is free of infectious aerosols depends on the particle-size dependent efficiency of the filtration on the recirculated air. Most buildings use filters with a low particle capture efficiency for the size range of interest for infectious disease transmission, such as a minimum efficiency reporting value (MERV) 8 filter. Higher efficiency filters, such as MERV 13 filters, can capture approximately 80% of particles in the 1-10 micron size range, thereby increasing the overall volume of virus-free air delivered to a space, even if outdoor air ventilation rates are low. In buildings without mechanical ventilation systems, opening windows can increase outdoor air ventilation rates. Portable air cleaners with HEPA filters, when sized correctly for the room, can also be used as a supplemental control strategy.*"

A blog from the University of Otago advocates for better guidance on ventilation in workplaces[112].

6.2. Is there any suggestion that a thorough clean down is required of processing/production areas in which a sick worker with COVID-19 has been in?

The New Zealand Ministry of Health has provided guidance on this question (last updated 14 March 2022)[113] . Specifically,

"*Clean surfaces after there has been a confirmed case of COVID-19 indoors within the last 24 hours.*

Wait about an hour before you clean and disinfect the areas that a person was using or was in and may have touched, ie their workspace

- *Wear a face covering.*
- *Open windows and doors (where possible) to improve air flow/ventilation.*

[111] https://static1.squarespace.com/static/5ef3652ab722df11fcb2ba5d/t/60a3d6713c9af62b4c2037ff/1621350002802/Safe+Work%2C+Safe+School%2C+Safe+Travel+%28Feb+2021%29.pdf; accessed 21 April 2022

[112] https://blogs.otago.ac.nz/pubhealthexpert/throwing-open-the-windows-the-need-for-ventilation-improvements-as-part-of-covid-19-outbreak-control-in-aotearoa/; accessed 21 April 2022

[113] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-health-advice-public/covid-19-general-cleaning-and-disinfection-advice; accessed 21 April 2022

- *If it has been more than 24 hours since the confirmed COVID-19 case: Routine cleaning is adequate, disinfection not required (unless your cleaning policy requires).*
- *If it has been more than 3 days since the confirmed COVID-19 case: No additional cleaning (aside from routine cleaning) is needed in the areas that the sick person used*

Clean and disinfect with household/supermarket products to reduce the risk of infection through touching surfaces.

Clean and disinfect high touched surfaces such as door handles, light switches, computers and tabletops which have a higher risk of being contaminated and require more frequent cleaning."

They also provide guidance on cleaning methods and recommend "*in general, routine cleaning performed effectively with detergent (not disinfectant) at least once per day substantially reduces viral levels on surfaces. Surfaces that are touched more frequently throughout the day such as door handles, light switches, computers and tabletops should be cleaned more frequently to further reduce the relatively low transmission risk from surfaces*."

Other useful international sources of information on this topic can be found at the following links for the US [114,115] and Ireland[116].

6.3. Should self-isolation of co-workers in contact with the primary case be implemented?

As a result of the Omicron variant transmission currently being widespread in the community, New Zealand regulations around isolation requirements for close work contacts have changed to ensure that critical workers can remain working despite potentially being a close contact and to ensure that critical supply chains keep running.

Current guidance from the Ministry of Health for the definition and requirements for close contacts would also apply to co-workers:[117]

"You are a Close Contact in the following situations:

- *If you have been close (within 1.5 metres) to someone who has COVID-19 for more than 15 minutes, and they were not wearing a face mask or not wearing it properly.*
- *If you have had direct contact with a person who has COVID-19. For example, kissing, or if the person coughed or sneezed on you.*
- *If you spent time in an indoor space with someone who has COVID-19 for more than 1 hour and at least one of the following.*
- *They were singing, shouting, smoking, vaping, exercising, or dancing.*
- *They were not wearing a face mask or it was not on properly.*

[114] https://static1.squarespace.com/static/5e7d1107dac60a6b3e3f098d/t/5e8664c27e5db072ad336918/1585865924826/FBIA+COVID19%2BCase+Recommended+Protocols_2April20+Version+4.pdf; accessed 21 April 2022
[115] https://www.cdc.gov/coronavirus/2019-ncov/community/disinfecting-building-facility.html; accessed 21 April 2022
[116] https://www.daera-ni.gov.uk/sites/default/files/publications/daera/NIFDA%20Best%20Practice%20-%20Covid-19%20v3%20final_0.pdf; accessed 21 April 2022
[117] https://covid19.govt.nz/testing-and-tracing/contact-tracing/close-contacts/; accessed 22 April 2022

- *It was poorly ventilated.*
- *It was smaller than 100m^2 (about 3 double garages)"*

"You do not need to self-isolate if you are a Close Contact. Monitor yourself for symptoms, and if you develop any, get a test." Any confirmed cases are then required to isolate for seven days after their symptoms first occurred or they received their positive test result, whichever ends sooner[118]. Note that household contacts, deemed as the highest risk contacts, are still required to isolate, unless part of the critical worker scheme.

Managing disease in the workplace

General advice for managing infectious disease risk in any workplace would also apply, to avoid infecting co-workers or contaminating product. This includes getting vaccinated, informing the employer, seeking medical advice, self-isolating and getting tested for COVID-19 if the worker has any symptoms of respiratory illness, or has travelled to affected regions. Creating an atmosphere where staff feel supported in taking these actions would be an important function for employers. Guidance (produced in August 2021) on such measures has been published by the FAO.[119]

Examples of general advice for workplace safety for infectious diseases:

- Ministry of Health: https://www.health.govt.nz/your-health/healthy-living/environmental-health/infectious-disease-prevention-and-control/workplace-infectious-disease-prevention; accessed 21 April 2022
- WHO: https://www.who.int/docs/default-source/coronaviruse/getting-workplace-ready-for-covid-19.pdf; accessed 21 April 2022
- WHO: https://www.who.int/publications/i/item/covid-19-and-food-safety-guidance-for-food-businesses; accessed 21 April 2022
- CDC: https://www.cdc.gov/coronavirus/2019-ncov/community/workplaces-businesses/; accessed 21 April 2022

6.4. What is the best practice for managing situations around potential product recalls if a worker on a production line becomes infected?

The US FDA view is as follows:[120]

"The U.S. food supply remains safe for both people and animals.

- *There is no evidence of food or food packaging being associated with transmission of COVID-19 regardless of the status of the worker in a plant.*

[118] https://www.business.govt.nz/covid-19/close-contact-exemption-scheme/; accessed 22 April 2022
[119] https://www.fao.org/3/cb6030en/cb6030en.pdf; accessed 21 April 2022
[120] https://www.fda.gov/food/food-safety-during-emergencies/food-safety-and-coronavirus-disease-2019-covid-19; accessed 21 April 2022

- *FDA does not anticipate that food products will need to be recalled or be withdrawn from the market should a person that works on a farm or in a food facility test positive for COVID-19."*

"U.S. exporters of FDA-regulated food products are responsible for following U.S. laws and regulations and following the requirements of the countries to which they export. Recently, some countries have begun to request commitments to provide information that food is free of the COVID-19 virus and/or has been produced under conditions that prevent contamination by the COVID-19 virus. At this time, there is no evidence of transmission of the COVID-19 virus, a respiratory virus, through food or food packaging, and the FDA does not anticipate that food products would need to be recalled or be withdrawn from the market because of COVID-19. FDA food safety requirements are robust and ensure that food produced for both domestic consumption and export is safe. The FDA is also communicating its understanding of the science related to COVID-19 transmission and food safety to foreign governments."

Although this advice was produced early in the pandemic, it is in keeping with advice from the ICMSF (3 September 2020).[121] FSANZ has a similar opinion (September, 2021):[122]

"Transmission from food packaging

Food packaging hasn't presented any specific risk of transmission. It's not yet confirmed how long the virus survives or remains detectable on surfaces. Studies suggest it may be a few hours or up to several weeks. This depends on the type of surface, temperature and humidity of the environment.

There remains no known cases of anyone contracting COVID-19 from food or food packaging. We are aware that the COVID-19 virus and traces of its genetic material have been detected in China on imported food products and packaging. The WHO has recommended further investigation of frozen food and packaging as a potential source of transmission. Two ICMSF members and co-authors reviewed the scientific literature on food safety and its linkage to SARS-CoV-2, and concluded that the overall risk of acquiring COVID-19 from contaminated food or food packaging is very low.

We will continue to monitor and assess evidence in relation to the potential transmission of COVID-19 from food or food packaging and consider its implications for our current advice.

If you are concerned, surfaces can be sanitised with common household disinfectants such as alcohol-based sanitiser or bleach."

Similar advice was also provided by Food Safety Authority of Ireland[123], as follows:

[121] https://www.icmsf.org/wp-content/uploads/2020/09/ICMSF2020-Letterhead-COVID-19-opinion-final-03-Sept-2020.BF_.pdf; accessed 21 April 2022
[122] https://www.foodstandards.gov.au/consumer/safety/Pages/Can-COVID-19-be-transmitted-by-food-or-food-packaging.aspx; accessed 21 April 2022
[123] https://www.fsai.ie/faq/coronavirus.html; last reviewed by Food Safety Authority of Ireland 28 May 2021; accessed 21 April 2022

"Do I need to recall food products if a food worker was potentially shedding the virus while working?

There is currently no evidence to indicate transmission of COVID-19 through food or food packaging."

6.5. What is the value and international guidance on food and environmental testing for SARS-CoV-2?

Food and environmental testing for SARS-CoV-2 is not recommended by ICMSF[121] or the Food and Agriculture Organization of the United Nations [298]. *"Whilst microbiological environmental sampling has a role in verifying sanitation protocols, the testing for SARS-CoV-2 in food processing facilities or on food packaging is costly, time consuming and does not aid in risk-based decision-making processes for consumer protection and is therefore not recommended."*

The US FDA guidance on this issue is:[124]

"If a worker in my food processing facility has tested positive for COVID-19, should I test the environment for the SARS-CoV-2 virus?

Currently there is no evidence of food or food packaging being associated with transmission of COVID-19. Therefore, we do not believe there is a need to conduct environmental testing in food settings for the virus that causes COVID 19 for the purpose of food safety. Cleaning and sanitizing the surfaces is a better use of resources than testing to see if the virus is present.

Facilities are required to use personnel practices that protect against contamination of food, food contact surfaces and packaging and to maintain clean and sanitized facilities and food contact surfaces. Although it is possible that the infected worker may have touched surfaces in your facility, FDA-regulated food manufacturers are required to follow Current Good Manufacturing Practices (CGMPs). Maintaining CGMPs in the facility should minimize the potential for surface contamination and eliminate contamination when it occurs. With the detection of the coronavirus in asymptomatic people and studies showing survival of coronavirus on surfaces for short periods of time, as an extra precaution, food facilities may want to consider a more frequent cleaning and sanitation schedule for high human contact surfaces."

More detailed information from the US CDC and OSHA regarding food industry-recommended protocols when an employee/visitor/customer tests positive for COVID-19 is also available[125]. Specifically, the recommendations cover:

[124] https://www.fda.gov/food/food-safety-during-emergencies/food-safety-and-coronavirus-disease-2019-covid-19; accessed 21 April 2022
[125] https://static1.squarespace.com/static/5e7d1107dac60a6b3e3f098d/t/5e8664c27e5db072ad33691815858659248 26/FBIA+COVID19%2BCase+Recommended+Protocols_2April20+Version+4.pdf; Issued 2 April 2020; accessed 21 April 2022

a) Steps to be taken when an employee tests positive for COVID-19 or has symptoms associated with COVID-19,

b) Steps to be taken when an employee/visitor/customer is exposed (in close contact) with an individual who is positive for COVID-19,

c) Cleaning and disinfection guidelines,

d) Disposition of food.

6.6. Now that COVID-19 vaccination is available, what are the implications for the risk management options for the food industry, particularly with the risk of breakthrough infections?

The NZ Ministry of Health vaccine information for COVID-19 is described in a dedicated webpage[126].

There are four different types of COVID-19 vaccine technologies that have been developed or are in development:[127]

- Protein-based, involving purified or recombinant proteinaceous antigens to elicit an immune response, e.g. the spike protein from SARS-CoV-2.
- Nucleic acid-based, involving a genetically engineered plasmid or messenger RNA containing the sequence for the disease-specific antigen, e.g. the SARS-CoV-2 spike protein gene.
- Viral vector-based, involving chemically weakened viruses to carry the genetic region for the disease-specific antigen, e.g. the SARS-CoV-2 spike protein gene, into human cells.
- Inactivated virus-based, involving chemically inactivated virus (e.g. SARS-CoV-2) or virus subunits grown under controlled conditions.

From the Ministry of Health website:[128]

*"**What we know about Omicron and vaccination (in this case with the Pfizer vaccine)***

- *a person is significantly **less likely to be severely sick, hospitalised or die** from Omicron if vaccinated, especially following the third (booster) dose*

[126] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-vaccines; accessed 21 April 2022
[127] https://www.gavi.org/vaccineswork/there-are-four-types-covid-19-vaccines-heres-how-they-work#:~:text=The%20four%20main%20types%20of,acid%20(RNA%20and%20DNA).; accessed 21 April 2022
[128] https://www.health.govt.nz/covid-19-novel-coronavirus/covid-19-health-advice-public/about-covid-19/covid-19-about-omicron-variant; accessed 21 April 2022

- *Real life evidence highlights in those countries with high vaccination rates (~95%) that this does provide **some population immunity** on top of individual immunity*
- *While vaccination provides less protection against contracting and transmitting the Omicron variant compared with earlier variants, **it still provides some protection, especially after the third (booster) dose**.*

Health advice, based on the evidence we have, is that the Omicron variant can still be contracted and transmitted by vaccinated people. Other key public health measures should continue to be deployed to reduce the spread of the virus. These include:

- *Vaccination (increasing booster rates to the highest possible level)*
- *Staying home when sick*
- *Mask use in indoor settings*
- *Improving ventilation*
- *Physical distancing*
- *Basic hygiene practices.*

High rates of vaccination remain critical to prevent severe disease and death, especially in vulnerable people. In addition, it affords some individual protection against infection and transmission of the virus and broad population protection with high vaccination uptake.

In addition, there is still the potential for new variants of the virus that are both more transmissible and more virulent and vaccination (with the current Pfizer or another vaccine that proves to be more effective against a new variant), will continue to play a central role in reducing the risk of transmission and of severe illness and death as the pandemic continues to evolve."

Will being vaccinated make a person test positive for COVID-19 infection?

It is not known whether clinical RT-qPCR tests which target the spike protein gene will return false RT-qPCR-positive results for a short period following vaccination due to amplification of this gene construct in the viral vector or nucleic acid-based vaccines. However, it is expected that if this occurs, it will be a very weak positive result, and not return a RT-qPCR-positive result for other gene targets not included in the vaccine construct. There will be a history of recent vaccination to inform interpretation of results. It is also considered unlikely that the vaccine would travel from the muscle to the nasopharyngeal mucosa in sufficient levels to be detected by the RT-qPCR (Dr Erasmus Smit, ESR, pers. comm.).

An Australian webpage has provided additional information:[129]

[129] https://theconversation.com/will-the-covid-vaccine-make-me-test-positive-for-the-coronavirus-5-questions-about-vaccines-and-covid-testing-answered-155958; accessed 21 April 2022

- ***Will the COVID vaccine make me test positive?***

No, a COVID vaccine will not affect the results of a diagnostic COVID test.

The current gold-standard diagnostic test is known as nucleic acid PCR testing. This looks for the mRNA (genetic material) of SARS-CoV-2, the virus that causes COVID-19. This is a marker of current infection…

Yes, the Pfizer vaccine contains mRNA. But the mRNA it uses is only a small part of the entire viral RNA. It also cannot make copies of itself, which would be needed for it to be in sufficient quantity to be detected. So it cannot be detected by a PCR test.

The AstraZeneca vaccine also only contains part of the DNA but is inserted in an adenovirus carrier that cannot replicate so cannot give you infection or a positive PCR test.

- ***How about antibody testing?***

While PCR testing is used to look for current infection, antibody testing — also known as serology testing — picks up past infections.

Laboratories look to see if your immune system has raised antibodies against the coronavirus, a sign your body has been exposed to it. As it takes time for antibodies to develop, testing positive with an antibody test may indicate you were infected weeks or months ago.

But your body also produces antibodies as a response to vaccination. That's the way it can recognise SARS-CoV-2, the next time it meets it, to protect you from severe COVID.

So as COVID vaccines are rolled out, and people develop a vaccine-induced antibody response, it may become difficult to differentiate between someone who has had COVID in the past and someone who was vaccinated a month ago. But this will depend on the serology test used.

The good news is that antibody testing is not nearly as common as PCR testing. And it's only ordered under limited and rare circumstances.

For instance, when someone tests positive with PCR, but they are a false positive due to the characteristics of the test, or have fragments of virus lingering in the respiratory tract from an old infection, public health experts might request an antibody test to see whether that person was infected in the past. They might also order an antibody test during contact tracing of cases with an unknown source of infection."

Other vaccine related information

Employment New Zealand has put together information regarding the legal situation about vaccination in the workplace.[130]

The US Centers for Disease Control website contains the following information for vaccinated people; note that the information has not been updated to include the Omicron variant:[131]

- *"Available evidence suggests the currently approved or authorized COVID-19 vaccines are highly effective against hospitalization and death for a variety of strains, including Alpha (B.1.1.7), Beta (B.1.351), Gamma (P.1), and Delta (B.1.617.2); data suggest lower effectiveness against confirmed infection and symptomatic disease caused by the Beta, Gamma, and Delta variants compared with the ancestral strain and Alpha variant. Ongoing monitoring of vaccine effectiveness against variants is needed.*
- *The risk for SARS-CoV-2 infection in fully vaccinated people cannot be completely eliminated as long as there is continued community transmission of the virus. Early data suggest infections in fully vaccinated persons are more commonly observed with the Delta variant than with other SARS-CoV-2 variants. However, data show fully vaccinated persons are less likely than unvaccinated persons to acquire SARS-CoV-2, and infections with the Delta variant in fully vaccinated persons are associated with less severe clinical outcomes. Infections with the Delta variant in vaccinated persons potentially have reduced transmissibility than infections in unvaccinated persons, although additional studies are needed.*

It is important to note that vaccination does not completely prevent infection; some people will still become infected. As stated above, even if you do become infected, the risk of severe health outcomes is reduced. Evidence is now appearing that vaccination reduces transmission; for example a study of vaccinated health workers in Scotland showed significantly reduced transmission within their households [299]."

[130] https://www.employment.govt.nz/leave-and-holidays/other-types-of-leave/coronavirus-workplace/covid-19-vaccination-and-employment/; accessed 21 April 2022
[131] https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/fully-vaccinated-people.html; accessed 21 April 2022

7. APPENDIX 1: LITERATURE SEARCHES

Table 4. Literature search terms and results for the current report. Searches from previous reports are not included.

Database	Search terms	Search date	Reference results	Retained references
Pubmed	(COVID-19 OR SARS-CoV-2) & (foodborne); publication date 2021 onward	05-04-2022	67	6
	(COVID-19 OR SARS-CoV-2) & (freezing OR frozen OR refrigeration); publication date 2021 onward	05-04-2022	328	11
	(COVID-19 OR SARS-CoV-2) & (omicron OR B.1.1.529) & (food)	05-04-2022	38	8
	(COVID-19 OR SARS-CoV-2) AND (omicron OR B.1.1.529) & (surface OR disinfectant OR fomite)	05-04-2022	37	5
	(omicron OR B.1.1.529) & (pathogenicity OR transmission OR transmissibility OR infectivity); publication date 2021 onward	05-04-2022	789	15
	(omicron OR B.1.1.529) & (freezing OR refrigeration OR temperature OR cold chain); publication date 2021 onward	05-04-2022	9	0
	(COVID-19 OR SARS-CoV-2) & (salmon OR vegetable OR fruit OR fish OR meat); publication date 2022	05-04-2022	219	7
	(COVID-19 OR SARS-CoV-2) & (sheep)	05-04-2022	43	2
	(COVID-19 OR SARS-CoV-2) & (livestock); publication date 2021 onward	05-04-2022	190	5
Web of Science	(COVID-19 OR SARS-CoV-2) & (foodborne); publication date Oct 2021 onward	21-04-2022	23	0
	(COVID-19 OR SARS-CoV-2) & (cold chain); publication date Oct 2021 onward	21-04-2022	57	1
	(omicron variant OR B.1.617.2) & (food); publication date Oct 2021 onward	21-04-2022	42	0
	(omicron OR B.1.617.2) & (surface OR fomite); publication date Oct 2021 onward	21-04-2022	27	0

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