Porous surfaces: stability and recovery of coronaviruses

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The role of indirect contact in the transmission of SARS-CoV-2 is not clear. SARS-CoV-2 persists on dry surfaces for hours to days; published studies have largely focused on hard surfaces with less research being conducted on different porous surfaces, such as textiles. Understanding the potential risks of indirect transmission of COVID-19 is useful for settings where there is close contact with textiles, including healthcare, manufacturing and retail environments. This article aims to review current research on porous surfaces in relation to their potential as fomites of coronaviruses compared to non-porous surfaces. Current methodologies for assessing the stability and recovery of coronaviruses from surfaces are also explored. Coronaviruses are often less stable on porous surfaces than non-porous surfaces, for example, SARS-CoV-2 persists for 0.5 h–5 days on paper and 3–21 days on plastic; however, stability is dependent on the type of surface. In particular, the surface properties of textiles differ widely depending on their construction, leading to variation in the stability of coronaviruses, with longer persistence on more hydrophobic materials such as polyester (1–3 days) compared to highly absorbent cotton (2 h–4 days). These findings should be considered where there is close contact with potentially contaminated textiles.

1. Introduction

Coronavirus disease 2019 (COVID-19) is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), an enveloped positive-strand RNA virus [1]. SARS-CoV-2 is mainly transmitted by respiratory droplets and aerosols [2], yet the role of indirect transmission of COVID-19 via contaminated surfaces (fomites) is not clear. Indirect transmission of COVID-19 is considered possible due to the detection of SARS-CoV-2 RNA in the environment, particularly in healthcare settings with COVID-19 patients [3–5]; however, a recent study did not detect SARS-CoV-2 RNA on surfaces in both community and healthcare settings [6]. Crucially, infectious SARS-CoV-2 has been isolated on objects in the near-patient environment such as bedsheets, bedrails and flooring [7,8]; although other studies have failed to isolate infectious virus from RNA-positive environmental samples [4,9,10]. Laboratory experiments have also demonstrated the persistence of infectious SARS-CoV-2 on surfaces for several days, with stability depending on the surface type, supporting the potential for indirect COVID-19 transmission [11–17]. There is currently a lack of direct evidence for fomite transmission due to difficulties in excluding droplet and aerosol transmission from asymptomatic individuals [14]. For indirect transmission to occur, a sufficient quantity of infectious SARS-CoV-2 must be deposited onto the fomite and subsequently transferred onto the mucous membranes of a susceptible individual, meaning that efficiency of transfer can be affected by a number of external factors [14]. The infectious dose of SARS-CoV-2 is currently unknown, making it difficult to infer a clinically relevant level of surface contamination. In animal model studies, COVID-19 infection occurs after inoculation with relatively high doses of SARS-CoV-2; for example, 1 in 6 ferrets showed signs of infection after intranasal administration of $5 \times 10^2$
plaque-forming units (PFU), and all ferrets showed signs of infection after intranasal administration of \(5 \times 10^5 \text{–} 5 \times 10^6\) PFU [18]. These doses likely do not reflect the infectious dose of SARS-CoV-2 in humans; as SARS-CoV-2 is not adapted to ferrets a higher dose may be required to establish infection. Analysis of COVID-19 superspreading events in Austria suggested that on average \(10^5\) SARS-CoV-2 virions were required to cause infection, although lower titres caused infection in some instances [19] and mathematical modelling estimates the infectious dose to be 100 virions [20]. The risk of transmission by fomites was considered to be lower than droplet or aerosol transmission by quantitative microbial risk assessment studies, but still possible [14–16], with one study estimating the risk of COVID-19 infection from touching a contaminated surface in the community to range from 2 in 10,000,000 to 4 in 10,000, depending on the COVID-19 prevalence rate [15]. This provides a rationale for further research into the role of fomites in the transmission of SARS-CoV-2. The majority of published studies have focused largely on hard non-porous objects and surfaces, such as plastic and stainless steel, with less research being conducted on different types of porous surfaces including textiles. This may have implications for infection control practices in different settings where there is close contact with porous surfaces, such as healthcare (e.g. bed linens), textile/clothing and shoe manufacturing and retailers.

The aim of this article is to outline the differences between the stability of coronaviruses on porous compared to non-porous surfaces and evaluate porous surfaces as potential fomites of coronaviruses, with a particular emphasis on textiles. The current methodologies for the assessment of stability and recovery of coronaviruses of surfaces will also be explored.

2. Methodology

Published articles relating to the stability of virus particles on surfaces were obtained via literature searches using PubMed, Google Scholar and Web of Science databases. Additional articles were identified from citations in relevant manuscripts.

3. Methods for investigating the stability of coronaviruses on surfaces

3.1. Surrogates for severe acute respiratory syndrome coronavirus 2

Coronaviruses are characterized by a positive-strand RNA genome surrounded by a protein capsid and a lipid envelope studded with spike proteins [1,21,22]. Coronaviruses produce four structural proteins and 16 non-structural proteins. The structural proteins share 43% identity between coronaviruses, compared to 53% identity between non-structural proteins [1]. The overall structural similarities between coronaviruses suggest that the environmental stability could be comparable between species [23]; however, there does not appear to be any direct comparisons between SARS-CoV-2 and potential surrogates in the published literature.

SARS-CoV-2 is currently considered a biosafety level 3 (BSL-3) pathogen [24–26]. Surrogate viruses for SARS-CoV-2 approved for use at lower BSLs enable research on the environmental stability of coronaviruses to be conducted in a wider range of laboratories, with the results used to infer the response of SARS-CoV-2. Human coronaviruses (HCoVs) 229E, OC43, NL63 and HKU1 are BSL-2 pathogens responsible for 10–30% of upper respiratory tract infections worldwide [27]. HCoV HKU1 and OC43 are more closely related to SARS-CoV-2, sharing the same genus (Betacoronavirus), whereas HCoVs 229E and NL63 are in the Alphacoronavirus genus [22]. The stability of SARS-CoV and HCoV-29E on polystyrene was comparable, where SARS-CoV persisted for 6 days and HCoV-229E for 3 days [28]. HCoV-OC43 was detectable on a PVC plastic surface for 48 h and had a similar rate of decay to SARS-CoV-2 as described in the published literature [29]. Murine hepatitis virus (MHV) and transmissible gastroenteritis virus (TGEV) have been used as surrogates for SARS-CoV [30], and porcine respiratory coronavirus (PRCV) was used as a surrogate for SARS-CoV-2 in investigating the decontamination of surgical masks and respirators [31]. The bacteriophage Phi6 has also been employed as a SARS-CoV-2 surrogate; it was postulated to provide a general indication of the persistence of SARS-CoV-2 due to the similar size and presence of a lipid envelope and spike proteins; however, the model does not appear to have been validated [32]. There is limited research on the structural drivers of environmental stability in coronaviruses, which aids in understanding their use as SARS-CoV-2 surrogates. For example, accessory proteins vary between species [21], and there are significant differences in the spike protein between species [22]; it is not clear how such differences in structure or post-translational modifications may affect the stability of coronaviruses. A number of factors impact the stability of other enveloped viruses, including envelope lipid packing [33–35], specific envelope proteins [36], and post-translational modifications [37,38]. Overall, further validation studies for SARS-CoV-2 surrogates are required [39]; although no direct comparisons have been made, based on previous studies across the literature the stability of closely related coronaviruses is likely within the same order of magnitude suggesting they may provide an estimate for its environmental persistence.

3.2. Quantification of coronaviruses from environmental samples

The most common method for the detection of SARS-CoV-2 in the environment and in clinical samples is quantitative reverse transcription-polymerase chain reaction (RT-qPCR) [3,40–42]. RT-qPCR detects the presence of viral nucleic acid and does not distinguish between infectious and non-infectious virions, i.e. those that do not cause disease. Indeed, SARS-CoV-2 RNA remained stable at 8–9 log_{10} genome copies ml^{-1} on cotton over 3 days, while infectivity reduced from 7.88 log_{10} 50% tissue culture infectious dose (TCID_{50}) ml^{-1} to less than 1 log_{10} TCID_{50} ml^{-1} within 4 h [17]. Detecting the presence of viral nucleic acids within the environment does not indicate the potential risk for disease transmission; in order to understand this, the quantification of infectious virus is instead more appropriate.

Cell culture-based techniques, including plaque assays and the TCID_{50} method, are considered the ‘gold standard’ method for the detection of infectious virus [43]. A disadvantage of such assays is the reduced sensitivity compared to RT-qPCR. Environmental samples typically have low levels of SARS-CoV-2 contamination and therefore infectious virus
may go undetected. Infectious SARS-CoV-2 could not be cultured from *in vitro* samples with Ct values above 29.27, equivalent to 4.125 PFU, while all PCR-positive environmental samples from acute healthcare settings had Ct values above 30 and no infectious virus was detected [10]. Further limitations include reduced throughput compared to RT-qPCR, where several days of incubation are required to culture infectious virus, potential variation based on the cell lines used, and the risk of false positives or reduced sensitivity where toxic compounds are present [44]. Nonetheless, infectivity assays provide a broader understanding of the potential risk for indirect disease transmission compared to nucleic acid-based methods due to the specific detection of infectious virus.

To overcome the limitations of infectivity assays, modified RT-qPCR assays have been developed for specific quantification of infectious virions, for example, by pretreatment with intercalating dyes. Intercalating dyes pass through damaged viral protein capsids (corresponding to inactivated virions), where they bind to nucleic acid and inhibit amplification, but cannot pass through intact capsids (infectious virions), allowing amplification to continue [44,45]. Inactivation methods that do not cause capsid damage are not accounted for (e.g. UV light) which can limit its application [45]. There are limited studies on the use of intercalating dyes coupled with RT-qPCR against coronaviruses and as such these methodologies are not well established [46]. The intercalating dye propidium monoazide coupled with RT-qPCR was recently used to measure the infectivity of bovine coronavirus as a surrogate for SARS-CoV-2 in domestic dishwashing machines; comparisons of infectivity to cell culture-based methods were not made [43] and therefore further investigation of this method against coronaviruses is warranted.

### 3.3. Methods for recovering coronaviruses from environmental surfaces

The efficient recovery of coronaviruses from surfaces is important for accurately determining their stability within the environment. Recovery methodologies employed vary within the currently published literature. Surface swabbing [9,13,29,42] is particularly useful in field studies, such as in healthcare environments [42] due to the non-destructive nature of sampling, or where de-sizing of surfaces is not possible. There can be significant variation in the swabbing method employed which can affect the recovery efficiency within and between studies, including swabbing pressure/angle, surface sample size, recovery media and viral elution method [47–49]. The choice of swab material is also of importance; recovery of mengovirus from glass, plastic and wood was greatest using small foam swabs (17–28% recovery) followed by cotton swabs (15–166%) and large foam swabs (11–84%), with the lowest recovery from nylon flocked swabs (3–70%) [50]. Differences in recovery efficiencies between swab materials are dependent on both a material’s properties and its ability to release virions into the recovery media [50]. For example, as a hydrophilic surface, cotton exhibits rapid absorption of the inoculum, allowing viral particles to be completely dispersed across the surface and providing a greater surface area for viral attachment [51]. Although polyester (hydrophobic surface) allows the inoculum to be absorbed, the rate of absorption and subsequent dispersion can be much slower when compared to cotton. Moreover, the drying process of microfibre cloths (e.g. polyester/polyester-amide blends) can change net surface charge, which could impact viral attachment and detachment from surfaces [52]. Dimensions of morphological features (e.g. pore size or fibre density) can also affect the level of absorption [50]. The recovery of microorganisms from porous or rough surfaces can be significantly lower than smooth, non-porous surfaces [48], which may be attributed to a lack of contact of the swab surface with microorganisms within pores in the surface [53]. Indeed, the percentage recovery of mengovirus from wood (3–17%) was lower than glass (56–289%) and plastic (18–93%) with all swab types tested [50].

The most commonly employed method for the recovery of coronaviruses from porous surfaces appears to be washing or immersion of contaminated coupons in a diluent [11,17,28,31,54–59]. Such methods may be more suited for the recovery of virus particles from rough or porous surfaces compared to swabbing due to penetration of the diluent into pores. There are limited studies directly comparing the recovery of coronaviruses from porous surfaces using these techniques, although conclusions can be drawn from bacterial studies; the recoveries of *Staphylococcus aureus* and *Klebsiella pneumoniae* from textiles were 2–3 log10 colony-forming units (CFU) ml⁻¹ higher by shaking in saline with polysorbate 80 compared to swabbing [53]. It has been argued that swabbing may more closely resemble the level of contact and transfer from surfaces to humans compared to elution; that said, the elution methods provide an estimate of a worst-case scenario to understand the risk of fomite transmission [17]. A disadvantage of the elution method is that it is destructive and therefore often unsuitable for sampling in the field. Variation in agitation methodology may affect the efficiency of microbial recovery; for example, the recovery of SARS-CoV-2 RNA from swabs was significantly (p ≤ 0.05) greater by vortexing for 30 s compared to swirling the swab in diluent for 10 s or soaking in diluent for 1 h [60]. Conversely, there were no significant differences in recovery of HCoV-OC43 from cotton by vortexing, paddle blending or shaking by hand, with 93.6–98.6% recovery of the 5 log10 TCID50 inoculum [61].

Further sources of variation include the recovery media employed [51]; Dulbecco’s modified Eagle medium (DMEM) cell culture media and phosphate-buffered saline recovered 92.7–93.6% of HCoV-OC43 (5 log10 TCID50 inoculum) from cotton compared to 79.2% recovery in maximum recovery diluent [61]. Cell culture media such as DMEM are commonly used for coronaviruses [17,62]. Further eluents include bovine serum albumin with HEPES [63] and Eagle’s balanced salt solution with peptone [64]. Recovery efficiency can be impacted by a number of factors including the addition of proteins where, for instance, the recovery of influenza A virus from N95 respirators was significantly reduced (p ≤ 0.05) by the addition of nutrient broth, peptone or tryptone to viral transport media (VTM) [65]. Further factors include pH, salinity and ionic strength; for example, pH of eluents has been known to impact the net charge of viral particles [66]. Rönnqvist et al. [52] obtained higher recovery efficiencies (p ≤ 0.05) of coronavirus from microfibre swabs using an alkaline glycine buffer (pH 9.5; 88.7%) than eluting with PBS (pH 7.2; 79.6%).

The inclusion of surfactants such as polysorbate 80 increase the recovery of viruses from surfaces [67,68]. Surfactants decrease the surface tension of solutions which increases the wetting of the sample surface, reduces hydrophobic interactions between adsorbed viruses and the surface, and increases the solubility of organic matter including proteins.
and microorganisms [65,69,70]. Investigations of different surfactant types demonstrated a fivefold greater recovery of influenza A virus from N95 respirators using VTM supplemented with 0.1% (w/v) sodium dodecyl sulfate (SDS, anionic surfactant) compared to VTM alone, while the non-ionic surfactants nondiet P-40, Triton X-100 and polysorbate 20 (0.1% v/v) increased recovery by two- to threefold compared to VTM [65]. Such behaviour could be explained by ionic binding being stronger than non-ionic binding, hence with anionic surfactants able to influence both ionic and non-ionic adsorption (as opposed to non-ionic surfactants only influencing non-ionic adsorption), this could result in greater virus recovery when using anionic surfactants.

The elution volume is also an important factor to ensure both sufficient agitation and sensitivity of the assay. Eluates are commonly directly titrated on susceptible cell lines for quantification. The concentration of infectious virus within eluates may increase the limit of detection; this may be achieved by flocculation, ultracentrifugation or filtration of eluates [71,72]. While these methods are commonly used to detect coronavirus in wastewaters [71,72], they are not commonly used in coronavirus environmental stability studies because smaller volumes are used.

4. Stability of coronaviruses on porous versus non-porous surfaces

There are a number of published studies investigating the stability of SARS-CoV-2 and other coronaviruses on surfaces (table 1). The titre of coronaviruses on surfaces decreases over time, indicating that the potential risk of indirect transmission decreases over time despite the detection of infectious virus for several days. Studies on the stability of coronaviruses typically employ high viral titres for the inoculum (5–8 log10 TCID50 ml−1; table 1), and it has been debated that these titres are likely greater than real-world conditions considering low levels of RNA detected in SARS-CoV-2 environmental samples (typical Ct values ≥30) [7,9,10]. An advantage of using high titres is that it allows for reductions in infectivity to be calculated and provide a ‘worst-case scenario’ of the ability of coronaviruses to persist on surfaces [17,61].

In assessing the stability of SARS-CoV-2 on different surface types, it is of vital importance to understand and evaluate surface interaction and adhesion mechanisms; for example, it was reported that adsorption onto organic particles protects HCoV-229E from inactivation in water [79]. Axiomatically, these mechanisms may vary in relation to surface properties and morphology, as per the recovery of viruses from surfaces discussed above, as well as environmental conditions, and the structure of the surface proteins and envelope of the virus itself [66,80]. However, while there is still conjecture on the specific mechanism of adhesion, it is likely that a combination of factors is involved, which include the hydrophobicity/hydrophilicity of the interacting systems (virus and surface), electrostatics and quantum dynamical effects, e.g. van der Waals forces [81]. The complexity of interactions at the virus–surface interface, stemming from their physico-chemical properties, is significant. For example, the magnitude and polarity of the charges carried by viral particles, in conjunction with the electrostatic properties of the surface in question, can govern virus adhesion. Moreover, the electrostatic interactions can vary with pH, surface charge concentration of the virus and the isoelectric properties of surface proteins [82].

Recent modelling of the adhesion of enveloped and non-enveloped viruses on a variety of archetype fomites (silica, nylon, stainless steel and polypropylene) has shown that under conditions when a virus and the fomite have surface charge of the same polarity, adsorption is stronger at a higher ionic strength, where the repulsive electrostatic interactions are screened out [83]. Whereas, if the polarity of a virus and surface are opposite, cleaning solutions with a high ionic strength can be used to screen out attractive electrostatic interactions. It is further argued that the efficiency of virus attachment to fomites is correlated with interfacial free energy, where anti-adhesion surfaces should have a high positive value of the interfacial free energy of its interaction with a virus (where high positive values indicate hydrophilicity). Therefore, for a virus with known surface tension parameters, it may be possible to select surfaces with as high an interfacial free energy as is practical to reduce virus adhesion, and hence aid recovery [83].

Given the above, and while further definitive studies are required to determine adherence mechanisms, the current literature suggests that coronaviruses are inactivated more rapidly on porous materials (i.e. materials containing pores/cavities [84]) than non-porous materials (without pores), which could have implications for infection control protocols relating to different surfaces. The stability of coronaviruses on a range of porous and non-porous surfaces is outlined in table 1. Chin et al. [11] compared the quantity of infectious SARS-CoV-2 over time on printing paper, tissue paper, treated wood and cloth (porous materials) to banknotes, glass, plastic and stainless steel (non-porous materials) (table 1). Significant reductions in infectious SARS-CoV-2 (7.8 log10 TCID50 ml−1 inoculum) were observed after 30 min on the porous materials (1.82–3.29 log10 TCID50 ml−1 before reaching an undetectable titre after 3 h–2 days. On the smooth non-porous surfaces, SARS-CoV-2 was reduced by 0.77–2.76 log10 TCID50 ml−1 within 24 h before reaching undetectable levels (less than or equal to 100 TCID50 ml−1) after 2–7 days [11]. Similarly, Kasloff et al. [17] reported lower stability of SARS-CoV-2 (7.9 log10 TCID50 ml−1 inoculum) on porous cotton (8 h; table 1) compared to non-porous surfaces (chemical resistant gloves, nitrile gloves, plastic and stainless steel), where infectious virus was detected for 4–21 days. Infectious SARS-CoV and SARS-CoV-2 (3.7 log10 TCID50 ml−1 initial titre) were also detected for longer on plastic (72 h) and stainless steel (48–72 h) than cardboard (8–24 h; table 1) [13]. A similar pattern was observed by Liu et al. [74], where the infectivity of SARS-CoV-2 decreased from 6 log10 TCID50 ml−1 to 3 to 4 log10 TCID50 ml−1 within 1 h on cotton, paper and wood, before reducing below the detection limit within 4–5 days (table 1), whereas infectious SARS-CoV-2 decreased steadily over the course of 7 days on plastic, stainless steel, glass, ceramics and latex gloves [74].

The lower stability of coronaviruses on porous surfaces is thought to be associated with more rapid viral desiccation. Porous surfaces absorb water, thereby reducing the size of moisture droplets compared to non-porous surfaces where, after the majority of the droplet evaporates, a thin film of moisture can remain on the surface for several days; as a result, evaporation and drying occur more rapidly on the porous surfaces (typically within hours) leading to viral
Table 1. Comparison of coronavirus stability on porous and non-porous surfaces and textiles.

| surface                          | coronavirus          | initial titre (Log$_{10}$ TCID$\text{50}$ ml$^{-1}$) | stability$^a$ | reference |
|----------------------------------|-----------------------|------------------------------------------------------|--------------|-----------|
| porous surfaces                  |                       |                                                      |              |           |
| cardboard                        | SARS-CoV              | 3.7                                                  | 8 h          | [13]      |
|                                 | SARS-CoV-2            | 3.7                                                  | 1 d          |           |
| paper                            | SARS-CoV              | 6.0                                                  | 1 d          | [73]      |
|                                 | SARS-CoV-2            | 7.8                                                  | 0.5 h        | [11]      |
|                                 |                       |                                                      | 5 d          | [74]      |
| paper (filter)                   | SARS-CoV              | 6.0                                                  | 5 d          | [56]      |
| paper (press)                    | SARS-CoV              | 6.0                                                  | 4 d          | [56]      |
| paper (tissue)                   | SARS-CoV-2            | 7.8                                                  | 0.5 h        | [11]      |
| polymer banknote                 | SARS-CoV-2            | 5.3                                                  | 3 d          | [75]      |
| skin                             | SARS-CoV-2            | 4.5                                                  | ≥14 d (4°C)  | [76]      |
|                                 |                       |                                                      | 4 h (22°C)   |           |
|                                 |                       |                                                      | 4 h (37°C)   |           |
| wood                             | SARS-CoV              | 6.0                                                  | 4 d          | [56]      |
|                                 | SARS-CoV-2            | 7.8                                                  | 1 d          | [11]      |
| textiles$^b$                      |                       |                                                      |              |           |
| banknotes (25% linen/75% cotton) | SARS-CoV-2            | 4.5                                                  | 96 h (4°C)   | [76]      |
|                                 |                       |                                                      | 8 h (22°C)   |           |
|                                 |                       |                                                      | 4 h (37°C)   |           |
| cloth                            | SARS-CoV              | 6.0                                                  | 5 d          | [56]      |
|                                 | SARS-CoV-2            | 7.8                                                  | 1 d          | [11]      |
| cotton                           | HCoV-229E             | 5.0                                                  | 2 h          | [61]      |
|                                 | HCoV-OC43             | 5.0                                                  | 24 h         | [61]      |
|                                 | SARS-CoV-2            | 7.9                                                  | 24 h         | [17]      |
|                                 |                       |                                                      | 14 d         | [62]      |
|                                 |                       |                                                      | 4 d          | [74]      |
|                                 |                       |                                                      | 6.0          | <30 min   | [77]      |
|                                 |                       |                                                      | 5.3          | 3 d       | [75]      |
| cotton gauze                     | HCoV-229E             | 5.7                                                  | 6 h          | [55]      |
|                                 | HCoV-OC43             | 5.7                                                  | <1 h         |           |
| cotton gown                      | SARS-CoV              | 6.0                                                  | 1 d          | [73]      |
| disposable gown                  | SARS-CoV              | 6.0                                                  | 2 d          | [73]      |
|                                 | SARS-CoV-2            | 5.3                                                  | 6 d          | [75]      |
| faux fur                         | SARS-CoV-2            | 6.0                                                  | <1 d         | [77]      |
| faux leather                     | SARS-CoV-2            | 6.0                                                  | <1 d         | [77]      |
| leather (corrected-grain finished)| HCoV-OC43            | 6.6                                                  | 24 h         | [78]      |
| leather (full-grain calf)        | HCoV-OC43             | 6.6                                                  | 48 h         | [78]      |
| leather (nubuck)                 | HCoV-OC43             | 6.6                                                  | 0 h          | [78]      |
| leather (patent)                 | HCoV-OC43             | 6.6                                                  | 6 h          | [78]      |
| mink pelt                        | SARS-CoV-2            | 6.0                                                  | ≥10 d        | [77]      |
|                                 |                       |                                                      | <1 d (skin side) |           |
| polycotton                       | SARS-CoV-2            | 4.5                                                  | 96 h (4°C)   | [76]      |
|                                 |                       |                                                      | 4 h (22°C)   |           |
|                                 |                       |                                                      | <4 h (37°C)  |           |
|                                 | HCoV-229E             | 5.0                                                  | 2 h          | [61]      |
|                                 | HCoV-OC43             | 5.0                                                  | 6 h          |           |

(Continued.)
Recent theoretical studies have postulated that while diffusion-limited evaporation dominates mass loss from a bulk droplet (and subsequently a thin liquid film) on non-porous surfaces, capillary imbibition dominates the same process on porous materials [85]. The droplet spreads due to capillary action between the contact line and fibres present on the porous surface, resulting in a modified effective-wetted area due to the voids of porous materials, which leads to enhanced disjoining pressure within the film, thereby accelerating film evaporation [85].

### Table 1. (Continued.)

| Surface          | Coronavirus | Initial titre (Log_{10} TCID_{50} ml^{-1}) | Stability \(^a\) | Reference |
|------------------|-------------|---------------------------------------------|------------------|-----------|
| Polyester        | HCoV-229E   | 5.0                                         | 24 h             | [61]      |
|                  | HCoV-OC43   | 5.0                                         | ≥72 h            |           |
|                  | SARS-CoV-2  | 6.0                                         | <1 d             |           |
|                  |             | 5.3                                         | <1 d             |           |
| Respirator mask  | SARS-CoV-2  | 7.9                                         | 21 d             | [17]      |
| Surgical mask    | SARS-CoV-2  | 7.8                                         | 7 d (outer layer)|           |
|                  |             | 7.8                                         | 4 d (inner layer)|           |
|                  |             | 6.0                                         | 7 d              |           |
|                  |             | 5.3                                         | 6 d              |           |
| Tyvek®           | SARS-CoV-2  | 7.9                                         | 14 d             | [17]      |
|                  |             | 5.3                                         | 6 d              | [75]      |
| Non-porous surfaces |            |                                             |                  |           |
| Aluminium        | HCoV-229E   | 5.7                                         | 6 h              | [55]      |
|                  | HCoV-OC43   | 5.7                                         | 2 h              |           |
| Banknote         | SARS-CoV-2  | 7.8                                         | 2 d              | [11]      |
|                  |             | 7.7                                         | 28 d             | [62]      |
| Ceramic          | SARS-CoV-2  | 6.0                                         | 7 d              | [74]      |
| Chemical resistant gloves | SARS-CoV-2 | 7.9                                         | 4 d              | [17]      |
| Copper           | SARS-CoV    | 5.0                                         | 8 h              | [13]      |
|                  | SARS-CoV-2  | 5.0                                         | 4 h              |           |
| Glass            | SARS-CoV    | 6.0                                         | 4 d              | [56]      |
|                  | SARS-CoV-2  | 7.7                                         | 28 d             | [62]      |
|                  |             | 6.0                                         | 7 d              | [74]      |
| Latex gloves     | HCoV-229E   | 5.7                                         | 3 h              | [55]      |
|                  | HCoV-OC43   | 5.7                                         | <1 h             |           |
|                  | SARS-CoV-2  | 6.0                                         | 7 d              | [74]      |
| Metal            | SARS-CoV    | 6.0                                         | 5 d              | [56]      |
| Mosaic           | SARS-CoV    | 6.0                                         | 3 d              | [56]      |
| Nitrile gloves   | SARS-CoV-2  | 7.9                                         | 7 d              | [17]      |
| Plastic          | SARS-CoV    | 6.0                                         | 4 d              | [56]      |
|                  |             | 5.0                                         | 3 d              | [13]      |
|                  | SARS-CoV-2  | 7.9                                         | 21 d             | [17]      |
|                  |             | 7.8                                         | 4 d              | [11]      |
|                  |             | 7.7                                         | 28 d             | [62]      |
|                  |             | 5.0                                         | 3 d              | [13]      |
| Stainless steel  | SARS-CoV    | 5.0                                         | 2 d              | [13]      |
|                  | SARS-CoV-2  | 7.9                                         | 14 d             | [17]      |
|                  |             | 7.8                                         | 4 d              | [11]      |
|                  |             | 7.7                                         | 28 d             | [62]      |
|                  |             | 5.0                                         | 3 d              | [13]      |
| Vinyl            | SARS-CoV-2  | 7.7                                         | 28 d             | [62]      |

\(^a\)Stability was measured as the last time point where infectious virus was detectable.

\(^b\)The degree of porosity varies between textiles.
The absorption of droplets within hydrophilic materials also spreads virions over a larger surface area which prevents aggregation [75]. Desiccation may lead to the viral lipid envelope undergoing phase changes and oxidation, and Maillard reactions may occur within proteins, rendering the virus non-infectious. Changes in pH and salt concentration occurring as water droplets evaporate also contribute to viral inactivation [32,88,89]. This is reflected in previously reported inactivation kinetics of coronaviruses, with a slower initial reduction in viral titre during evaporation followed by a more rapid decline as solutes become more concentrated; this is exemplified by SARS-CoV-2 ($5 \log_{10} \text{TCID}_{50} \text{ ml}^{-1}$) remaining stable on poly styrene for 4 h during the evaporation phase, followed by a decline in viral titre, with around 1 $\log_{10}$ remaining at 24 h [90]. Given the above, environmental conditions play a significant role in the stability of coronaviruses on surfaces, including relative humidity (RH), temperature, deposition buffer, deposition volume and initial viral titre as outlined below. Such conditions are therefore a likely source of variation under real-life conditions and between laboratory studies and may result in the discrepancies in stability of coronaviruses on the same materials described in table 1.

SARS-CoV-2 ($4.5 \log_{10} \text{PFU}$) stability on skin, polycotton clothing and banknotes (linen/cotton blend) was inversely correlated with temperature, with half-lives ranging 15.9–46.8 h at 4°C, 1.0–3.5 h at 22°C and 0.2–0.6 h at 37°C [76] (table 1), which may arise from viral protein denaturation at higher temperatures [79]. Light conditions can also significantly alter stability of coronaviruses; SARS-CoV-2 ($3 \log_{10} \text{TCID}_{50} \text{ ml}^{-1}$ inoculum) was reduced by 1 $\log_{10}$ within 6.8 min of exposure to simulated summer sunlight conditions (1.6 W m$^{-2}$ UVB) on stainless steel compared to 14.3 min under simulated winter sunlight conditions (0.3 W m$^{-2}$ UVB), with no significant reduction in infectious viral titre over 60 min under darkness [91]. Simulated sunlight was not tested on porous surfaces, and therefore the impact of absorption into a porous matrix on SARS-CoV-2 susceptibility to light was not determined.

Coronaviruses exhibit an inverse correlation [86] or ‘U-shaped’ relationship with RH [30,88]; for example, the half-life of SARS-CoV-2 on stainless steel decreased from 15.33 h at 20% RH to 8.33 h at 80% RH [92], while TGEV and MHV (4–5 $\log_{10}$ initial titre) were inactivated more rapidly on stainless steel at 50% RH (3–5 days) than 20 and 80% RH (11–28 days) [30]. Water molecules in the liquid phase could condense from the vapour phase on various surfaces (e.g. between virus particles and solid substrates) and create liquid bridges with a curvature, which is related to the RH as expressed in the Kelvin equation [93]. In conditions of high humidity, greater water networks around the virus could result in facilitating interactions with the proteins and the lipid bilayer that promote degradation [62]. Solute crystals also form at low RH, which may reduce the rate of reactions that cause viral inactivation [90]. The pattern of stability of Phi6 at different salt concentrations varied depending on RH, with lower viability in salt-containing media at 20% RH (1 and 35 $g \text{l}^{-1}$), whereas at 80% RH, viability was lower in media without salt [88].

The deposition media significantly influence the stability of SARS-CoV-2 [94]. The half-life of SARS-CoV-2 ($5 \log_{10} \text{TCID}_{50} \text{ ml}^{-1}$) on polypropylene at 21°C and 40% RH was 3.1 days in nasal mucus and sputum compared to 6.8 days in culture media [95]. Conversely, the stability of Phi6 on glass over 14 h was greater in saliva (approx. 1.5 $\log_{10}$ PFU ml$^{-1}$ reduction; 6 $\log_{10}$ PFU ml$^{-1}$ inoculum) compared to water and SM buffer (3–4 $\log_{10}$ reductions) [32]. There may therefore be significant differences between the persistence of coronaviruses under real-life conditions, where the virus is suspended in saliva or sputum, compared to in vitro where culture media or buffer is often employed. Saliva is a complex mixture compared to culture media, with components such as proteins, surfactants and salts potentially affecting the stability of viruses [32,96,97]. Proteins may have a protective effect on the stability of enveloped viruses by reducing surface tension within liquid droplets, preventing viruses from reaching the air–water interface where inactivation occurs [88]. Bovine serum albumin increased the persistence of SARS-CoV-2 ($6 \log_{10} \text{TCID}_{50} \text{ ml}^{-1}$) from 44 h to greater than 100 h on glass, and less than 4 h to greater than 100 h on aluminium [98]. The pH of the deposition buffer also influenced stability of Phi6, with a complete reduction of infectious virus at pH 4, a 2 $\log_{10}$ reduction at pH 7 and 3 $\log_{10}$ reduction at pH 10 [88].

The deposition volume influences the length of the evaporation phase of moisture on a surface; this may in turn affect viral persistence [89]. A relatively large volume (50 µl) was used by Morris et al. [90], where SARS-CoV-2 was detected for 24 h and exhibited an exponential decay pattern. By contrast, Chin et al. [11] employed a 5 µl deposition volume and reported short half-lives of 0.3–1.6 h up to 6 h post-inoculation, followed by longer half-lives of 4.8 to 14.7 h. The 5 µl droplet may have evaporated within minutes, leading to the stability during the evaporation period not being resolved; this is more in line with real-world conditions, where respiratory droplets are less than 10 µl [90]. Conversely, Biryukov et al. [92] concluded that there was no significant difference (p > 0.05) in the stability of SARS-CoV-2 on stainless steel between deposition volumes (1, 5 or 50 µl); however, there is limited research on porous surfaces. Biphasic decay patterns may be caused by a heterogeneous population or the aggregation of viruses, which increases stability; this could lead to initial reductions of free virions followed by a slower rate of decay of aggregated virus [99]. Changes in salt concentration and pH encourage viral aggregate formation due to reduced electrostatic repulsion between viral surface proteins [75,88,100]. Aggregation is highly dependent on (i) the type of virus, hence why the isolectric points of viruses vary pH can mediate aggregation; (ii) the type of salts in solution (cation, anion, monovalent, divalent); and (iii) the overarching role that electrostatic and hydrophobic forces play in aggregate formation [99].

Further differences in methodology that could affect the findings include the viral titre applied to the surface, which varies between studies (table 1). Paton et al. [75] reported no significant difference (p > 0.05) in SARS-CoV-2 decay on stainless steel between high (5.6 $\log_{10}$ Pfu) and low (3.6 $\log_{10}$ PFU) inoculum suggesting that inactivation is not associated with the viral load. Conversely, SARS-CoV-2 was detectable on paper for 30 min at 7.8 $\log_{10}$ initial titre, with a 2.58 $\log_{10}$ decline over this time period [11], compared to approximately 3.5 $\log_{10}$ reduction over 5 days at 6.0 $\log_{10}$ initial titre [74]. SARS-CoV was also detectable on a disposable gown for 1 h with a 4 $\log_{10}$ TCID$_{50}$ ml$^{-1}$ inoculum, 24 h with a 5 $\log_{10}$ TCID$_{50}$ ml$^{-1}$ inoculum and 48 h with a 6 $\log_{10}$ TCID$_{50}$ ml$^{-1}$ inoculum [73] which may be associated with the infectious virus approaching the limit of detection faster using lower inocula; this may account for some discrepancies observed in the published literature.
5. Stability of coronaviruses on textiles

Textile manufacturing and retail are significant industries worldwide, with an estimated 6.4 million tonnes of clothing consumed per year in Europe alone [101]. Research into the stability of SARS-CoV-2 on textiles determines the potential risks of indirect transmission of COVID-19 where there is close contact with textiles. This includes textile manufacturing and retail [77] and healthcare settings. In healthcare settings, patients, healthcare workers and laundry workers may come into contact with contaminated linen, and in countries such as the UK, Ireland and the USA, healthcare workers wash their uniforms domestically [61].

One study reported the detection of infectious SARS-CoV-2 on bed sheets in the room of a COVID-19 patient [7] suggesting that SARS-CoV-2 can persist on textiles in the environment. Published research also suggests that infectious coronaviruses can be recovered from textiles for hours to days post-inoculation (table 1), although their recovery is often lower than from non-porous surfaces as discussed above. The structure of textiles differs significantly based on the type of fibre and construction method. Textiles can be comprised of natural or manufactured fibres, and often blends of multiple fibres are used; and they may be woven, knitted or non-woven. Such factors affect the overall properties of the textile [102] including the porosity, moisture absorbency, surface charge and roughness. In turn, these properties affect the ability of textiles to support the viability, adherence and transfer of microorganisms [51,103–105].

The majority of published studies on the persistence of coronaviruses on textiles have focused on cotton, and there have been few examples of published studies directly comparing the stability of coronaviruses on different textile types (table 1). On cotton, the reported length of persistence ranges from less than 30 min to 14 days; however, the majority of studies demonstrate a rapid drop in infectious viral titre, followed by persistence of lower titres for several days (table 1). For example, Liu et al. [74] reported that infectious SARS-CoV-2 decreased by around 3 log_{10} TCID_{50} ml^{-1}, from an initial titre of 6 log_{10} TCID_{50} ml^{-1}, within 1 h of inoculation and a complete reduction in infectious SARS-CoV-2 was achieved by 4 days post-inoculation. Similarly, Riddell et al. [62] recovered only 2.63 log_{10} TCID_{50} ml^{-1} SARS-CoV-2 of a 7.53 log_{10} TCID_{50} ml^{-1} inoculum from cotton immediately after inoculation and a complete reduction in the detectable virus was reported between 7 and 14 days. In both aforementioned studies, the low recovery of infectious virus immediately after inoculation could be due to failure to recover virus based on absorption of the inoculum into the textile rather than inactivation; Liu et al. [74] stated that infectious virus was recovered by addition of 500 µl VTM without any mention of agitation method, while Riddell et al. [62] employed repeated pipetting of the sample in two volumes of culture media (115 µl) rather than more forceful agitation methods. Alternatively these findings may be a result of capillary imbibition dominating absorption as discussed above. Virtanen et al. [77] reported a significantly lower stability of SARS-CoV-2 on cotton, with infectious virus detected for less than 30 min; however, swabbing was used as the recovery method and therefore absorbed virus may not have been detected. SARS-CoV was reportedly less stable on a cotton gown, with complete inactivation of 4 log_{10} TCID_{50} ml^{-1} virus 5 min after inoculation, while a 6 log_{10} TCID_{50} ml^{-1} inoculum was inactivated within 24 h [73]. HCoVs OC43 and 229E were reduced by 5.7 log_{10} TCID_{50} ml^{-1} within 1 and 12 h, respectively, on cotton gauze [55].

Coronaviruses often persist for longer periods of time on synthetic textiles compared to cotton (table 1). It has been postulated that many differences between most natural and synthetic fibres can be explained by the fact that the latter have no active chemical or charged moieties which reduces absorption [69], in turn reducing desiccation and inactivation as discussed above. Indeed, cotton is an absorbent natural fibre with a moisture regain of 8.5% compared to the synthetic hydrophobic fibre polyester which possesses a moisture regain of 0.4%. HCoV-OC43 (5 log_{10} TCID_{50} sample^{-1} inoculum) was less stable on cotton than woven polyester; infectious virus was detectable for 72 h post-inoculation (1.96 log_{10} TCID_{50} sample^{-1}) on woven polyester, while there was a more rapid decline in infectious viral titre on cotton, with 1.70 log_{10} TCID_{50} sample^{-1} recovered after 24 h and no detectable infectious virus remaining after 48 h [61]. SARS-CoV-2 (6 log_{10} TCID_{50} ml^{-1}) was detected on polyester for 1 day after inoculation whereas no infectious virus was detected on cotton immediately after inoculation [77]. In accordance, SARS-CoV was infectious for 1 day on a cotton gown compared to 2 days on a disposable (non-porous) gown at a 6 log_{10} inoculum, and at a 5 log_{10} inoculum, the stabilities were 1 h and 24 h, respectively [73]. The stability of coronaviruses on synthetic/hydrophobic porous surfaces is often more comparable to non-porous surfaces than absorbent porous textiles. For example, Chin et al. [11] detected infectious SARS-CoV-2 (2.47–2.79 log_{10} TCID_{50} ml^{-1} of a 7.8 log_{10} TCID_{50} ml^{-1} inoculum) up to 4 days on the inner layer and 7 days on the outer layer of surgical masks, which are comprised of non-woven polypropylene, a hydrophobic synthetic fibre [106]. This was in line with observations for non-porous materials (banknotes, glass, plastic and stainless steel), where infectious virus was detected for 2–7 days, compared to 1 day persistence on cloth [11]. In a similar manner, SARS-CoV-2 (7.9 log_{10} TCID_{50} ml^{-1} inoculum) declined by 1 log_{10}TCID_{50} ml^{-1} within 2 days on N95 and N100 respirator masks (porous; synthetic, non-woven material [87]), then remained stable for 4 days before steadily declining in titre over the course of 21 days [17]. SARS-CoV-2 was also detected at low titres for up to 14 days on Tyvek [17], a porous, non-woven synthetic (polyethylene) hydrophobic material [107]. By contrast, there was a rapid decline in viability of SARS-CoV-2 on cotton and a complete reduction in 24 h [17].

A systematic review suggested that enteric viruses persist for extended periods on more absorbent materials such as wool compared to cotton. It was hypothesized that greater adsorption of the virus onto absorbent materials provides protection from desiccation compared to unbound virus [51]. There does not appear to be a comparison of wool and cotton against coronaviruses in the published literature, which may behave differently from non-enveloped enteric viruses, due to enveloped viruses being more susceptible to desiccation than non-enveloped viruses. Indeed, the quantity of infectious HCoV-OC43 recovered between intact and homogenized (destroyed) cotton, polycotton and polyester textile samples was not significantly different, suggesting that the reduction in infectious virus over time was not the result of attachment of HCoV-OC43 onto the textile [61].

While the majority of studies report longer persistence of infectious coronaviruses on synthetic textiles, Paton et al. [75]
concluded that SARS-CoV-2 (5.3 log$_{10}$ PFU) was less stable on a woven polyester sports shirt compared to a woven cotton t-shirt, with 1 log reduction in less than 2.5 h compared to 33.94 h, respectively, and complete reductions by less than 1 day versus 5 days. It was noted that although polyester is hydrophobic, the fibres were finely spun and the material absorbed liquid, which may have trapped the virions within the weave of the textile. This is in contrast with other hydrophobic materials where droplets remain at the surface in a way that limits inactivation. Alternatively, chemicals used in the manufacture of the textile could have contributed to inactivation [75]. Owen et al. [61] also suggested that chemical residues on polycotton produced a cytotoxic effect upon the cell lines employed for quantification of HCoV-OC43, reducing the limit of detection rather than an inactivation of the virus. HCoV-OC43 was only detectable for 6 h (2.93 log$_{10}$ TCID$_{50}$ sample$^{-1}$) on a polyester/cotton blended textile compared to 24 h on cotton; however, the rate of decline was similar to cotton, with infectious viral titres reducing from 5.05 to 5.22 log$_{10}$ TCID$_{50}$ sample$^{-1}$ at 0 h to 2.57–2.93 log$_{10}$ TCID$_{50}$ sample$^{-1}$ 6 h post-inoculation [61]. A similar pattern was observed for HCoV-229E (5 log$_{10}$ TCID$_{50}$ sample$^{-1}$ inoculum), with detection of infectious virus up to 24 h on polyester (2.43 log$_{10}$ TCID$_{50}$ sample$^{-1}$) and 2 h on both cotton (1.83 log$_{10}$ TCID$_{50}$ sample$^{-1}$) and polyester/cotton blend (2.97 log$_{10}$ TCID$_{50}$ sample$^{-1}$) [61]. These findings highlight the importance of the construction and finishing process of textiles on the stability of coronaviruses.

Pelts and skins are another form of clothing material that has been less well studied than constructed textiles. Virtanen et al. [77] compared the stability of SARS-CoV-2 on mink fur pelt to a range of synthetic textiles. Infectious SARS-CoV-2 (6 log$_{10}$ PFU ml$^{-1}$ inoculum) was detected for up to 10 days on a mink fur pelt, compared to less than one day on the skin side of the mink fur pelt, faux fur and faux leather, although the viral titre over time was not reported. These findings could be related to lower absorbency of the mink fur or the presence of biological substances (such as oils or waxes) or structural properties of the fur that provide a protective effect against inactivation or absorption, warranting further investigation [77]. Shivkumar et al. [78] reported that the stability of HCoV-OC43 (6.6 log$_{10}$ TCID$_{50}$ ml$^{-1}$) on leather depended on the finish, with persistence for 48 h on full-grain calf leather, 24 h on corrected-grain finished leather and 6 h on patent leather, while no infectious virus (less than or equal to 2.2 log$_{10}$ TCID$_{50}$ ml$^{-1}$) was recovered from nubuck leather immediately after inoculation. Nubuck leather is strongly absorbent compared to other leather types and is not commonly treated with a finish, which was attributed to the sharp decline in infectious viral titre immediately after inoculation. Conversely, patent and finished leathers are coated in wax, protein, polymer or resin which reduces their porosity [78]. Structural differences between the remaining leathers were not investigated, which may provide further insight into the inactivation of HCoV-OC43. Overall, investigations of the stability of coronaviruses between different textiles (table 1) suggest that there may be a greater risk of indirect transmission from less absorbent materials, which may behave more similarly to non-porous surfaces.

There is limited evidence demonstrating the transfer of coronaviruses to other surfaces which is necessary for textiles to behave as fomites. HCoV-OC43 did not transfer from cotton or polycotton to PVC or textile samples immediately after inoculation; however, 2.28–2.38 log$_{10}$ TCID$_{50}$ sample$^{-1}$ infectious virus transferred from polyester (5 log$_{10}$ TCID$_{50}$ sample$^{-1}$ inoculum) to PVC and polyester immediately after inoculation, and 1.64–1.67 log$_{10}$ TCID$_{50}$ sample$^{-1}$ transferred 72 h after inoculation [61]. These results suggest that polyester and similar materials could be a greater risk for onward transmission of coronaviruses to humans, whereas the risk of cotton and polycotton is limited. Considering that the infectious dose of HCoV-229E is reportedly 13 virions and SARS-CoV-2 is approximately 100–1000 virions [19,20], this suggests that a relevant quantity could transfer if contaminated with relatively high viral titres such as the 5 log$_{10}$ TCID$_{50}$ inoculum used by Owen et al. [61]. Onward transfer to human mucous membranes is required for infection to occur, and there does not appear to be any published studies on the transfer of coronaviruses to and from skin [14]. Greater viral transfer from polyester compared to cotton was hypothesized to arise from the lower absorbency (0.4% versus 8.5% moisture regain [108]) and surface roughness of polyester compared to cotton and polycotton. Although surface roughness and absorbency were not quantified [61], similar work reported surface mean deviations of 2.5 µm for polyester, 2.7 µm for cotton and 3.1 µm for polycotton [104]. HCoV-OC43 (6.6 log$_{10}$ TCID$_{50}$ ml$^{-1}$) transferred from patent, full-grain calf and corrected-grain finished leathers onto stainless steel and cardboard 0 and 2 h post-inoculation, with a higher (p > 0.05) level of transfer onto stainless steel (4.5–5.5 log$_{10}$ TCID$_{50}$ ml$^{-1}$) than cardboard (less than or equal to 3.2–4.5 log$_{10}$ TCID$_{50}$ ml$^{-1}$), which could be associated with surface roughness. There was no transfer of HCoV-OC43 from nubuck leather to cardboard, whereas 4.5 log$_{10}$ TCID$_{50}$ ml$^{-1}$ transferred onto stainless steel that was weighted on top of the inoculated nubuck leather sample [78]. This suggests that the absorption of the viral inoculum limits the availability of virus at the surface for transfer, while pressure plays a role in transfer from such surfaces. The risk of fomite transmission is therefore likely lower from highly absorbent materials than less porous surfaces. It was demonstrated that HCoV-OC43 was rendered undetectable on cotton after washing with cold water and detergent, suggesting that the risk of infection is limited to handling textiles prior to laundering [61]. These findings highlight the need to further investigate the potential for transfer of coronaviruses between textiles and other surfaces to understand the risk of transmission in real-world settings and develop infection control protocols.

6. Conclusion

The role of indirect contact in the transmission of COVID-19 is not fully understood. Understanding the persistence and transfer of SARS-CoV-2 and surrogate coronaviruses on surfaces can be useful for developing infection control protocols for SARS-CoV-2, especially in considering worst-case scenarios. Experimental conditions may significantly affect the stability and recovery of coronaviruses from surfaces, making comparisons between studies difficult, although the literature suggests that stability on porous surfaces is highly dependent on the material. In general, longer persistence is observed on less absorbent or hydrophobic porous surfaces, particularly hydrophobic synthetic items such as surgical
masks, compared to hydrophilic natural fibres like cotton. While the mechanism of inactivation of coronaviruses on these surfaces is incompletely understood, it is hypothesized that moisture absorption by hydrophilic materials increases viral desiccation and structural changes associated with droplet absorption/evaporation. The adsorption of coronaviruses to surfaces may play a role in their stability. While the adsorption mechanism is a current subject of study, the physico-chemical properties, and the nature and magnitude of the electrostatic charge of the virus and fomite surface, can lead to variations in adsorption. This is highly dependent on the surface type and environmental conditions. The risk of transmission of coronavirus should be considered in environments where there is close contact with potentially contaminated textiles, for example, in healthcare settings (e.g. surgical masks), manufacturing and the domestic environment. Further research is required on the adsorption of coronaviruses to surfaces and their onward transfer, which is essential for providing evidence that surfaces are involved in indirect transmission of COVID-19.

Data accessibility. This article has no additional data.

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