Chapter

Environmental Persistence of SARS-CoV-2 and Disinfection of Work Surfaces in View of Pandemic Outbreak of COVID-19

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Abstract

Coronavirus disease 2019 (COVID-19) is primarily a respiratory illness, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The pandemic outbreak of SARS-CoV-2 across the world has been responsible for high morbidity and mortality, which emphasizes the role of the environment on virus persistence and propagation to the human population. Since environmental factors may play important roles in viral outbreaks, and the severity of the resulting diseases, it is essential to take into account the role of the environment in the COVID-19 pandemic. The SARS-CoV-2 may survive outside the human body from a few hours to a few days, depending upon environmental conditions, probably due to the relatively fragile envelope of the virus. The shedding and persistence of SARS-CoV-2 in the environment on animate and inanimate objects contributes to the risk of indirect transmission of the virus to healthy individuals, emphasizing the importance of various disinfectants in reducing the viral load on environmental surface and subsequently control of SARS-CoV-2 in the human population.

Keywords: SARS-CoV-2, disinfection, inactivation, surfaces, nanotechnology

1. Introduction

The causative agent of coronavirus disease-19 (COVID-19), the Betacoronavirus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was for the first time isolated in Wuhan, China in December 2019, from a patient suffering from non-recognizable acute pneumonia [1]. Subsequently, COVID-19 and the causative virus have spread to different regions of the globe, with the greatest number of caseloads being observed in the industrialized countries. Betacoronaviruses belong to the family Coronaviridae, which are enveloped viruses with single-stranded RNA genomes with positive polarity. These viruses are responsible for a wide range of infections in humans, primarily of the upper respiratory tract, including pneumonia, bronchitis, bronchiolitis, etc. [2]. The primary route of transmission of SARS-CoV-2 is thought to be contact with oral-nasal droplets released from infected persons during coughing, sneezing, and talking [3]. The transmission of SARS-CoV-2 through food and water has not yet been well established. Studies on previous epidemics caused by Middle East respiratory syndrome coronavirus (MERS-CoV) and severe acute respiratory syndrome coronavirus (SARS-CoV) have identified no cases of viral transmission

through food. Similarly, no cases of transmission of SARS-CoV-2 infections via food have been identified [4]. Therefore, SARS-CoV-2 is not recognized as a foodborne virus and the risk of transmission of COVID-19 through contaminated food is considered to be very low [4]. On the other hand, studies have demonstrated the presence of viral genetic material in the blood and anal swabs from human patients [5]. The fact that diarrhea is a symptom of COVID-19 raises concerns about possible transmission of SARS-CoV-2 via the fecal-oral route. Destite this, it is not yet clear that the fecal-oral route represents a significant transmission modality for this virus [6].

Fortunately, the lipid envelope of this virus renders it susceptible to a wide variety of disinfectants. As such, this virus is expected to be more susceptible to inactivation by microbicides in comparison to non-enveloped viruses with a similar route of transmission, such as norovirus, adenovirus, hepatitis A virus, etc. [7, 8]. Several physical agents, such as sunlight, high temperature, UV radiation, and gamma radiation, etc. also act as effective agents to inactivate the virus [9]. SARS-CoV-2 exhibits temperature sensitivity and can be inactivated within 5 minutes at 70°C [9]. Healthcare areas contain several types of high-touch environmental surfaces, including furniture, tables, chairs, and toilets, along with medical instruments, including stethoscopes, wheelchairs, incubators, etc. [10]. These environmental surfaces are vulnerable to contamination with SARS-CoV-2 shed from patients [11, 12].

Previous studies have confirmed that SARS-CoV-2 transmission is linked with close contact of infected and healthy individuals within a closed setting, such as exists in healthcare facilities and residential institutions, etc. [11]. The same considerations apply to settings outside of the healthcare arena, including temples, churches, mosques, local markets, and business centers, etc. [13].

Transmission of SARS-CoV-2 from infected to healthy individuals may be disrupted through disinfection of contaminated high-touch environmental surfaces. The survivability (persistence of infectivity) of SARS-CoV-2 informs the need for surface disinfection at an appropriate frequency. However, in areas where resources for regular disinfection and cleaning are limited, the guideline should be mandated for avoiding frequent touching of the face along with frequent hand washing to reduce the risk of SARS-CoV-2 transmission associated with surface contamination and transfer of virus from hands to susceptible mucous membranes of the eye, nose, and mouth.

2. SARS-CoV-2 persistence in the environment and risk of transmission to humans

The study of the persistence of SARS-CoV-2 in the environment is necessary, as this informs the need for and frequency of disinfection of those surfaces. This virus shows environmental persistence for a few hours to a few days. Several studies are now available to provide viral persistence data for various environmental surfaces, both porous and non-porous. Many of these studies also documented the virus persistence half-life or decay rate information on different surfaces and materials [9, 14–22]. This information allows one to estimate the amount of time necessary for the virus to decay to titers beneath an estimated human minimal infectious dose. As might be expected, the amount of time required depends, in part, on the initial contamination titer for the surface, the type of surface, and the temperature and relative humidity.

2.1 Environmental and surface persistence of SARS-CoV-2

Previous research work related to the environmental persistence of coronavirus species was conducted on human coronavirus strain HCoV-229E [23]. This virus

was found to survive for 2 hours to 9 days on various surfaces including metal, glass, and plastic. Moreover, the study also confirmed the temperature sensitivity of coronaviruses. Environmental temperatures in the range of 30–40°C were found to reduce the persistence of transmissible gastroenteritis virus (TGEV), Middle East respiratory syndrome coronavirus (MERS-CoV), and mouse hepatitis virus (MHV) [23]. At environmental temperatures above 40°C the virus is inactivated within hours to minutes [24]. However, based on the lack of experimental data available on the minimal human infectious doses of the human coronaviruses, it is difficult to say for how long the viruses may survive on different inanimate surfaces at levels actually capable of infecting a human host.

Subsequently, several studies have been conducted on environmental persistence of SARS-CoV-2 specifically (**Table 1**). The data on the survival of SARS-CoV-2 on different surfaces have revealed that viral persistence on prototypic high-touch environmental surfaces (HITES) mainly depends upon four factors: the type of surface (porosity), presence of organic matrix on the surface, temperature/humidity, and time [9, 15–22, 25, 27]. The survival data analyses for SARS-CoV-2 demonstrate that the virus remains infectious for longer durations on hard non-porous surfaces, such as stainless steel and plastic, in comparison with cardboard or wood [15]. The presence of organic matrix during drying of SARS-CoV-2 on surfaces may lead to an increase in half-life of the virus [16, 17, 21]. However, in one of the studies it was demonstrated that SARS-CoV-2 exhibited a shorter half-life on a surface in the presence of human mucus and sputum in comparison to when dried in presence of matrix of culture medium [18]. In the absence of an organic load, the half-life of SARS-CoV-2 on plastic, glass, and aluminum surfaces was demonstrated as 35 hours, 7 hours, and 0.33 hours, respectively at 19–21°C and 45–55% relative humidity (RH) [17]. Similarly, the persistence half-life on stainless steel, wood, in a matrix of 10% suspension of human feces or human urine was demonstrated as 23 hours, 21 hours, 2.6 hours, and 16 hours, respectively at 25–27°C and 35% relative humidity [20]. In another study the persistence of SARS-CoV-2 in human sputum and mucus was found to be very close to that on porous surfaces, with half-lives of 1.9 and 3.5 hours, respectively [18]. These half-life values demonstrate that the SARS-CoV-2 may remain infectious for few days on HITES following a contamination event, if hygiene interventions are not implemented.

In one of the studies, infectious SARS-CoV-2 was detected at up to 10 days on mink fur, 5 days on plastic, 1 day on faux fur, and less than a day on various materials including faux leather, cotton, and polyester [22]. Further study revealed that UV light failed to inactivate the virus on pelts, probably due to mechanical protection by the fur. However, heat treatment at 60°C for 1 h was found sufficient to inactivate the virus on all the mentioned surfaces [22].

Other researchers have also evaluated the environmental persistence of the SARS-CoV-2 on different surfaces. In one such study, it was demonstrated that SARS-CoV-2 remained infectious for up to 1 day on wood and cloth, 2 days on a glass surface, 4 days on stainless steel and plastic surfaces, and up to 7 days on facemasks [9]. Similarly, in another study, it was found that SARS-CoV-2 remained infectious for up to 4 hours on a copper metal surface, 24 hours on a cardboard surface, and 72 hours on objects made of plastic and stainless-steel materials [25].

SARS-CoV-2 infectivity has been found to persist over a wide range of ambient temperatures and pH values, but the virus was found to be susceptible to temperatures above 40°C [24] and standard disinfection procedures (**Table 1**) [15]. The environmental survivability of the virus depends on various factors, such as types of material, surfaces, temperature, and humidity. For instance, it has been shown that SARS-CoV-2 may remain viable for up to 4 hours on a copper surface, and up to 72 hours on a stainless steel or plastic surface (**Table 1**) [25]. Similarly, this virus

S. n.	Surface material	Relative Humidity (%)	Temperature (°C)	Persistence (Minute/ Hour/Day)	Complete inactivation (Hour/Day)	Reference
Porous surfaces						
1	Surgical mask (inner layer)	65	22	4 days	7 days	[9]
2	Surgical mask (outer layer)	65	22	7 d	—	[9]
3	Tissue paper	65	22	30 minutes	3 hours	[9]
4	Cloth	65	22	1 day	2 days	[9]
5	Cotton	35–40	20	1 hour	4 hours	[16]
6	Nitrile Gloves	35–40	20	7 days	7 days	[16]
7	Chemical gloves	35–40	20	4 day	4 days	[16]
8	N95 mask	35–40	20	14 days	21 days	[16]
9	N100 mask	35–40	20	14 days	21 days	[16]
10	Tyvek	35–40	20	14 days	21 days	[16]
11	Wood	65	22	1 day	2 days	[5]
12	Paper	65	22	30 minutes	3 hours	[9]
Non-porous surfaces						
13	Cardboard	65	21–23	1 day	2 days	[25]
14	Copper	65	21–23	4 hours	8 hours	[25]
15	Polypropylene Plastic	65	21–23	3 days	4 days	[25]
16	Banknote paper	65	22	2 days	4 days	[9]
17	Plastics (face shield)	35–40	20	21 days	21 days	[16]
18	Stainless steel	35–40	20	14 days	21 days	[16]
19	Stainless steel	65	21–23	3 days	4 days	[25]
20	Stainless steel	65	22	4 days	7 days	[9]
Liquid medium and Air sample						
21	Aerosol	65	21–23	3 hours	—	[25]
22	Aerosol	53	23	>16 hour	—	[26]
23	Virus transport medium	—	4	14 days	—	[9]
24	Virus transport medium	—	22	—	14 days	[9]
25	Virus transport medium	—	37	—	2 days	[9]
26	Virus transport medium	—	70	—	5 minutes	[9]

Table 1.
Persistence of SARS-CoV-2 on different prototypic environmental surfaces.

may survive for up to 1 day on cloth and wood, 2 days on a glass surface, and up to 7 days on the outer surface of a regular medical mask along with a wide range of ambient temperature and pH values of 3–10 [9]. However, in another study it was

demonstrated that the stability of SARS-CoV (a related betacoronavirus) may rapidly decrease after exposure to low pH (pH < 3) and high temperature (>65°C) [28].

The surface viability of SARS-CoV-2 was demonstrated in one of the experiments using plaque assay followed by viral RNA extraction and detection [14]. The study showed that infectious viruses may persist for the longest duration on a surgical mask and stainless steel, with an overall reduction in infectivity of 99.9% by 122 and 114 hours, respectively. On polyester shirt and banknote, the infectivity of SARS-CoV-2 reduced to 99.9% within 2.5 hours and 75 hours, respectively. Further study revealed that SARS-CoV-2 is most stable on nonporous hydrophobic surfaces. The viral RNA was also found highly stable on surfaces, and only 1 $\log_{10}$ reduction in recovery was observed in three weeks [14]. However, in comparison to viral RNA, the infectivity of SARS-CoV-2 reduced more rapidly on surfaces. The level of infectivity SARS-CoV-2 may become undetectable within 2 days on environmental surfaces. This indicates that mere detection of viral RNA on surfaces does not prove the presence of infectious SARS-CoV-2 [14].

Studies have also been conducted to evaluate the survival time of coronaviruses in food matrices. It has been demonstrated that MERS-CoV may survive up to 72 hours in food at 40°C [29]. In a similar study, a lower persistence of human coronavirus 229E (HCoV-229E) was found in comparison to poliovirus 1 (PV-1) on lettuce stored at 40°C [27]. Further, the study revealed that HCoV-229E was not detected on lettuce samples after four days of storage at 40°C and no virus was identified after ten days of spiking of HCoV-229E on another fruit sample (strawberries) [27]. Recent evidence suggests that coronaviruses may remain stable at low temperatures on food and surfaces for an extended period. This suggest that, theoretically, SARS-CoV-2 transmission through foods or food packaging when stored under these conditions [30]. An experimental study under laboratory conditions revealed that SARS-CoV-2 remained highly stable at freezing (−10 to −80°C) and refrigerated (4°C) temperatures on poultry, meat, fish, and swine skin for 14–21 days [30]. Similarly, in another study SARS-CoV-2 was found stable on swine skin even after 14 days at 4°C [19]. These studies suggest that SARS-CoV-2 might remain infectious for a prolonged period in food stored at low temperature. In another study, SARS-CoV-2 was isolated from the swab samples of imported frozen cod outer package surfaces, which showed that the frozen food industry may transmit SARS-CoV-2 virus to other countries and regions [31]. Therefore, based upon available data, it can be hypothesized that contaminated cold-storage foods may pose a risk for SARS-CoV-2 transmission. Since coronaviruses are thermolabile and thus susceptible to traditional heat treatments of cooking (70°C), consumption of cooked foods should not pose risk of transmission of these viruses. Consumption of uncooked or frozen food should be avoided during a coronvirus outbreak to avoid possible transmission of virus.

2.2 SARS-CoV-2 survival on atmospheric particulate matter

Airborne particulate matter may also transmit the causative agent of COVID-19. In hospital wards, SARS-CoV-2 RNA has been recovered from air samples collected in greater amounts than recovered from outdoor premises [32]. The study suggests that air might be a route of virus transmission. The aerosol-generating mechanisms in healthcare facilities are a major cause of concern. For instance, researchers have demonstrated the possibility of airborne diffusion of the virus from aerosols and suspended particles in the air at hospitals in Wuhan (China) [33] and Omaha (USA) [34]. The initial study confirmed the persistence of 1 to 113 genomic copies/m^3 of SARS-CoV-2 in the air in Wuhan Hospital during gatherings of high numbers of people. With the reduction in the number of patients and adequate sanitization

and disinfection, viral RNA was not detected [33]. Similarly, at Nebraska Medical Center, Omaha (USA), 63.2% positivity for the presence of SARS-CoV-2 RNA was detected in analyzed air samples, with 2 to 9 genomic copies/L of virus [34].

The atmospheric pollutants and particulate matter (PM_{10} and $PM_{2.5}$) may also be linked with the spread of respiratory viral infections, because particulate matter may act as a carrier (vehicle) for viruses [35]. Researchers have confirmed the increased transmission of SARS-CoV-2 through PM_{10} in Italy [36]. Therefore, it is assumed that air pollution and particulate matter in the air may contribute to the spread of COVID-19. Periodic air monitoring may be needed to mitigate the risk of transmission of the virus in the most highly impacted environments.

2.3 Survival of coronavirus in water and wastewater effluents

The onset of respiratory infections on a large scale in the human population informs the need for detailed information concerning the survival of coronavirus in water and wastewater effluents. The persistence of several coronaviruses, such as feline infectious peritonitis virus (FIPV) and human coronavirus 229E (HCoV-229E), has been analyzed in tap water and wastewater samples [37]. Filtered tap water showed a lesser number of viruses [37]. Moreover, the study also revealed that coronavirus persistence in wastewater depended on temperature and levels of organic matter. To inactivate the coronaviruses in tap water at the level of 99.9% at 23°C, 10 days were required. Further study revealed that these viruses may survive up to 588 days in tap water at 4°C [37]. However, the time required to inactivate the coronaviruses in wastewater plant effluents up to 99.9% varied between 2.3 to 3.5 days at 23°C [37]. This study also revealed that the transmission risk of coronavirus through water is less in comparison to enteroviruses, such as poliovirus 1, due to the faster inactivation of coronaviruses in wastewater effluents at ambient temperature.

However, with the current inactivation and persistence estimates on surrogate viruses, it is difficult to predict the fate of SARS-CoV-2 in water and wastewater. Several researchers have initiated study of SARS-CoV-2 persistence in water and wastewater. In one of the studies, 90% reduction (T_{90}) in infectious SARS-CoV-2 in tap water and wastewater at room temperature was observed after 1.5 and 1.7 days, respectively [38]. However, in wastewater the T_{90} values for infectious SARS-CoV-2 were reported as 15 min and 2 min at 50°C and 70°C, respectively [38]. Researchers have identified SARS-CoV-2 RNA in river water. However, no infectivity detected in cultured cells was observed for the recovered SARS-CoV-2 [39]. As mentioned before, this emphasizes that the identification of viral RNA in the environment does not equate to presence of infectious virus. In another study, it was revealed that SARS-CoV-2 may survive up to 14 days under laboratory conditions at 4°C in a virus transport medium. SARS-CoV-2 was incubated in a virus transport medium at a final concentration ~ 6·8 $\log_{10}$ $TCID_{50}$ per mL at 4°C. After 14 days, there was only a 0·7 $\log_{10}$ reduction in infectious titer observed [9].

2.4 SARS-CoV-2 persistence in hospital and industrial wastewater

Apart from enteric viruses, certain species of coronaviruses may also remain present in wastewater [40]. However, the persistence of SARS-CoV-2 in wastewater and the potential for transmission through the fecal-oral route has yet to be confirmed. The studies have confirmed the inhibiting effect of wastewater on the persistence of coronaviruses [41]. In contrast to this, in one of the studies it was also demonstrated that coronavirus surrogates may survive for a longer duration in non-filtered primary effluents in comparison to filtered samples [37]. The longer

survival duration in non-filtered water is primarily attributed to the presence of organic sediments which may provide protection from chemical or biological inactivating agents present in water. In contrast, the available data on surrogate viruses for SARS-COV-2 suggest that the novel coronavirus may be less persistent in wastewater, primarily due to the presence of organic substances as well as inhibiting matrix autochthonous flora, including protozoa, which may contribute proteases and nucleases resulting in faster inactivation of the virus [42].

As a response to the SARS-CoV-2 pandemic and relatively high transmissibility of SARS-CoV-2, several countries have implemented the monitoring of wastewater streams to confirm the presence of the virus in the community, with special reference to asymptomatic individuals and the possibility of risk to contamination of wastewater and risk to solid waste treatment plant employees [43].

SARS-CoV-2 RNA has been detected in human feces [44] and in raw sewage and sludge [45, 46]. The levels correlate with the COVID-19 epidemiological curve and increased number of hospital admissions [46]. Again, the detection of viral RNA does not necessarily indicate the presence of infectious virus particles; rather it indicates the viral prevalence in community.

SARS-CoV-2 RNA was also detected in the wastewater at the Amsterdam Schiphol Airport (Netherlands) and the wastewater treatment plant in Kaatsheuvel (Netherlands) in 2020. This was a crucial finding, since the first case of COVID-19 was reported in February 2020 and viral genetic materials in wastewater samples were detected in March 2020 in Netherland [47]. In one of the studies, SARS-CoV was found to remain infectious at 20°C in wastewater for up to 2 days and viral genomic RNA was isolated for about 8 days [48]. It is not unexpected that SARS-CoV RNA can be detected in wastewater following disinfection protocols using chlorine [48].

Most of these reports are discussing the detection of viral RNA in hospital and sewage water, which does not necessarily confirm the presence of infectious virus. The real challenge is to identify and prevent the transmission of infectious SARS-CoV-2 particles in bioaerosols created during flushing of toilets. Several studies have reported the presence of high concentrations of SARS-CoV-2 in aerosols from patients' toilets and the neighboring environment in hospitals [11, 49, 50]. Thus, toilets may represent one of the most highly contaminated areas of the hospital and may play a potential role in COVID-19 transmission in hospitals. The above studies justify the requirement for adequate disinfection protocols in hospital premises when treating COVID-19 patients, with the aim of inactivating the virus and mitigating possible subsequent spread in hospital wastewater.

2.5 Viral persistence in sewage and biological solids

The possibility of transmission of SARS-CoV-2 from asymptomatic patients via the fecal-oral route is under study. Wastewater-based viral epidemiology and surveillance of sewage material may provide valuable information regarding the prevalence of SARS-CoV-2 in the human population, which may be used as an early warning system in disease forecasting. In biological waste materials and specimens, such as in human serum, plasma, feces, and sputum, SARS-CoV may survive up to 96 hours. However, in human urine, the virus survives for a lesser time, probably due to the presence of urea and adverse pH conditions [51]. Although in one of the experiments SARS-CoV-2 was cultured from feces of confirmed positive patients in the laboratory, still no cases of SARS-CoV-2 infections have been attributed to sewage transmission [52]. The stringency of biological waste treatment also contributes to inactivation of the virus, limiting the amount of infectious virus remaining in these waste streams [53].

Other biological waste materials, such as personal protective equipment (PPE) including masks, gloves, etc., may play roles in the individual-to-individual transmission of SARS-CoV-2. These biowaste materials should be properly segregated according to waste type, and should be subjected to disinfection modalities to minimize the risk of the spread of infection in the environment [54]. For recycling of PPE (gowns, medical gloves, masks and other face and eye shields) waste into value-added products, several advanced processes, such as aminolysis, glycolysis, pyrolysis, hydrogenation, hydrolysis, and gasification are now in practice at the industrial level [55].

Currently, there are only few robust studies that have been reported on reuse of PPE. Thus, the reuse of PPE may harm the healthcare worker via accidental contamination. Therefore, to avoid the possibility of accidental infection, the direct reuse of PPE (i.e., rendering contaminated PPE non-infectious) is not advisable even during acute shortages of PPE [56].

3. Cleaning and disinfection of surfaces for SARS-CoV-2 control

SARS-CoV-2 is transmitted primarily through respiratory droplets and close physical contact. Longer rangee airborne transmission may also occur in hospital areas, due to aerosol-generating medical procedures. Environmental surfaces may act as a source of virus spread in health care settings where certain health care procedures are performed [11, 57]. The virus may be spread via the indirect pathway involving touching of contaminated surfaces followed by touching of susceptible mucous membranes. Alternatively, virus may be re-aerosolized from contaminated surfaces including toilets [58], carpets [59], indoor air [60], fomites [61], etc. Therefore, environmental surfaces such as tables, chairs, light switches, electronic equipment, and toilets, along with medical equipment such as blood pressure cuffs, stethoscopes, etc. must be properly cleaned and disinfected to interrupt the possible transmission of SARS-CoV-2.

SARS-CoV-2 contains a lipid envelope which renders it more susceptible to common disinfectants than non-enveloped viruses, such as rotavirus, poliovirus, etc. [7]. Coronaviruses have been found to be susceptible to the same disinfectants and disinfecting conditions employed to control the risk of several other enveloped viruses. The common disinfection protocols using hydrogen peroxide, sodium hypochlorite, peracetic acid, and UV light that have been employed for the civil and industrial wastewater treatment and inanimate surface hygiene have been found suitable for control of SARS-CoV-2 (**Figure 1**).

SARS-CoV-2 was found to be effectively inactivated by 70% isopropanol, 70% ethanol, 0.1% H_2O_2 and 0.1% sodium laureth sulphate within 60 seconds of exposure on different surfaces, including stainless steel, glass, cardboard, polyvinyl chloride (PVC), polyethylene terephthalate (PET), and cotton fabric [62]. Ethanol and H_2O_2 can conveniently be used for disinfection against SARS-CoV-2 in healthcare settings. Moreover, this study also highlighted the importance of common household detergents (sodium laureth sulphate) and hand soap in rapid inactivation of SARS-CoV-2 [62]. Similarly, in another study, original WHO recommended hand rub formulations I and II [63] and modified formulation I (80% (w/w) ethanol, 0.725% (v/v) glycerol, and 0.125% (v/v) hydrogen peroxide) and formulation II (75% (w/w) 2-propanol, 0.725% (v/v) glycerol, and 0.125% (v/v) hydrogen peroxide) were found effective for reducing SARS-CoV-2 titers to background level within 30 s [64]. Moreover, it is also established that under laboratory conditions >30% (v/v) concentration of 2-propanol and ethanol may also efficiently inactivate SARS-CoV-2 in 30 s [64]. A limitation of alcohol-based disinfectants is the specified

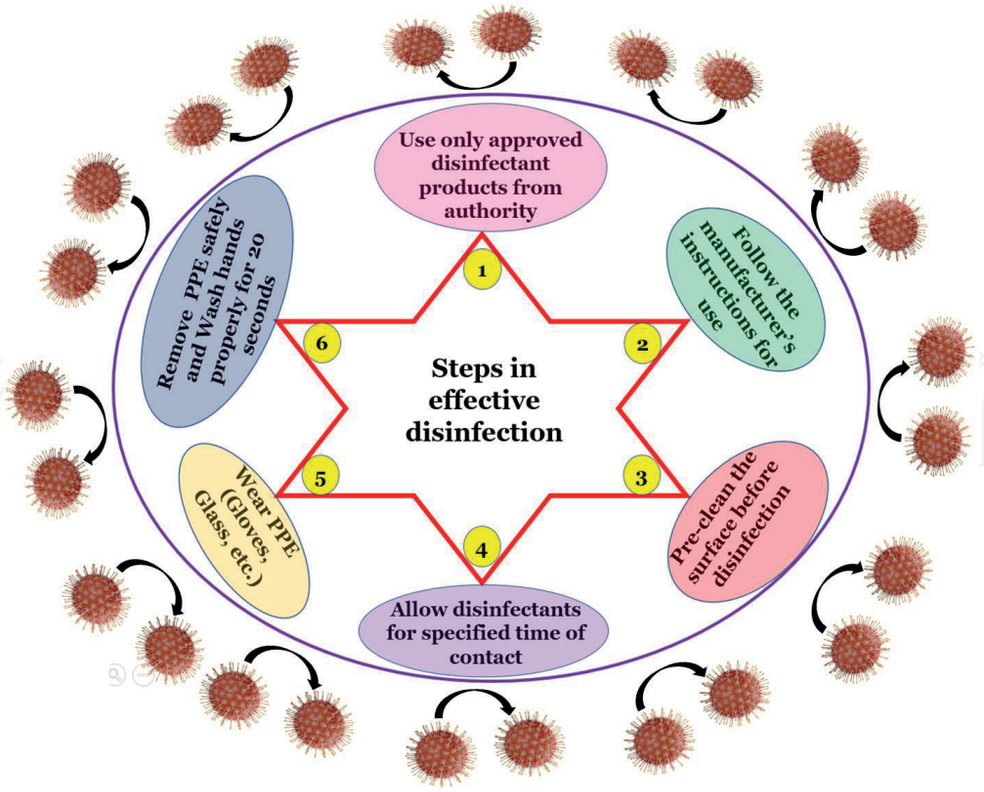

Figure 1.
Steps for application of safe and effective disinfectant against SARS-CoV-2.

inactivation time of exactly 30 s, which must be strictly followed for effective inactivation of virus. In another study, chemical disinfectants including citric acid, quaternary ammonium compounds (QAC), ethanol, and sodium hypochlorite at various concentrations were found effective against SARS-CoV-2 and another associated coronavirus on glass surface. Within a contact time of 0.5 to 10 minutes, these microbicides were able inactivate ≥3.0 to ≥ 6.0 $\log_{10}$ [15]. Furthermore, it is a fact that SARS-CoV and MERS-CoV are highly susceptible to disinfectant and detergent treatments, and reports also confirm the susceptibility of SARS-CoV-2 against these chemicals [29]. Therefore, the periodic cleaning and sanitization of HITES should be done to prevent the transmission of SARS-CoV-2. To minimize the adverse impacts of chemical disinfectants on the environment, organizations working in the field of COVID-19 control have recommended the use of microbicides with low environmental impact, such as hydrogen peroxide, phenolic compounds, and hydroalcoholic formulations for COVID-19 control [65].

3.1 Disinfectants for environmental surface cleaning

For surface and environmental disinfection, hypochlorite-based compounds such as powdered calcium hypochlorite and liquid sodium hypochlorite may be used. Upon dissolution in water, these compounds create an aqueous solution of hypochlorous acid (HOCl) as the active antimicrobial ingredient. The HOCl possesses broad spectrum antimicrobial activity against pathogens. A 0.1% (1000 ppm) concentration of hypochlorite is recommended to inactivate the majority of pathogens present in the healthcare areas [66]. However, for blood and bodily fluids, a concentration of 0.5% (5000 ppm) is recommended [67]. Hypochlorite should be freshly prepared before use, because it is rapidly inactivated in the presence of environmental organic material. For better efficacy, surfaces should be thoroughly cleaned with soap or detergent, using mechanical scrubbing

or friction, before application of hypochlorite. Hypochlorite should be applied at optimum concentration, because high concentrations of chlorine may lead to metallic corrosion and irritation of skin or mucous membranes. SARS-CoV-2 deposited on HITES can be easily inactivated using chlorine-based disinfectants, detergents, iodine-containing detergents, 70% alcohol, glutaraldehyde, hydrogen peroxide compounds, halogenated compounds, various cationic and anionic surfactants, etc. [68]. SARS-CoV-2 in sewage samples can be effectively inactivated using chlorine dioxide (20 mg/L) [69]. Recently, critical information exploration on predicted and measured virucidal efficacies of several antimicrobial agents against priority viral diseases of WHO, including SARS-CoV-2, have been reviewed by Ijaz et al. [70].

3.2 Spraying of chemical disinfectants and UV irradiation of surfaces in indoor spaces

In indoor areas, routine application of disinfectants by spraying or fogging (i.e., fumigation or misting) is usually not recommended for COVID-19 control because this strategy may not remove all the contaminants outside the spray zones (i.e., not contacted by the spray/fog) [71]. Moreover, fogging using formaldehyde, chlorine-based agents, and quaternary ammonium compounds may also result in risks to the eyes and irritation of the respiratory mucosa or skin [72, 73]. However, some countries have allowed the no-touch methods for applying specific chemical disinfectants, such as vaporized hydrogen peroxide (HPV) in vacated spaces in healthcare settings [74]. In one such experiment, HPV was demonstrated to inactivate >4 $\log_{10}$ of feline calicivirus, transmissible gastroenteritis virus, human adenovirus-1, etc. at lower percentages of active compound (1400 ppm) and lower potential toxicity on living cells [75]. Hydrogen peroxide and 2-phenyl phenol are usually employed for surface disinfection and food sanitation and act as valid alternatives to sodium hypochlorite.

Ultraviolet light irradiation devices have also been modified for use in healthcare settings. Exposure to sunlight or UV light drastically limits coronavirus survival, as is the case for many microorganisms [76]. The efficacy of UV irradiation devices is dependent on several factors, such as irradiation dose, lamp placement, the distance between surface and UV device, wavelength, exposure time, and duration of use, etc. [10] along with fluence of UVC (J/m^2, mJ/cm^2, etc.) which may take into account all other factors [77]. On the basis of review of the UVC inactivation literature, a consensus efficacy of 0.5 to 2 $\log_{10}$ inactivation of SARS-CoV-2 per mJ/cm^2 has been demonstrated. These results indicate that SARS-CoV-2 is quite susceptible to UVC inactivation [24].

In another experiment, more than 3 $\log_{10}$ inactivation of SARS-CoV-2 was detected with a UVC dose of 3.7 mJ/cm^2 on samples contaminated with comparable virus density to that found in COVID-19 patients. However, the complete inactivation of SARS-CoV-2 was observed with 16.9 mJ/cm^2 of UVC [78]. The UV irradiation devices developed for disinfection in health care settings usually are used during terminal surface sanitization i.e., sanitization of rooms after discharge of patient and in rooms unoccupied by the staff and patients. In one of the studies, deep ultraviolet light-emitting diode (DUV-LED) was used for inactivation of SARS-CoV-2 from a COVID-19 patient [79]. Such a study shows the importance of development of DUV-LED based devices to prevent virus contamination of the air and surfaces. However, when using the no-touch disinfection methods, such as fumigation or UV treatment, prior manual cleaning of surfaces is also essential [80]. However, during surface cleaning care should be taken to prevent the re-aerosolization of virus from the surface material, which could represent a potential source of infection. Moreover, for optimal effectiveness, these no-touch approaches should not be considered as replacements for surface cleaning. Rather, after

surface disinfection using appropriate virucidal agents, the no-touch approaches can be used to reach surfaces not reached by the surface cleaning methods.

Outdoor application of disinfectants, such as spraying or fumigation on streets and other public places, may not advisable since most of the action of many classes of disinfectant agents are adversely impacted the presence of organic dirt and debris on surfaces. The body surface spraying of individuals with chemical disinfectants in a cabinet, tunnel, or chamber is also not advisable [81]. The research data do not provide evidence of the reduced ability of an infected person, so treated, to spread the virus. Moreover, direct spraying of individuals with a chemical disinfectant, such as a chlorine-releasing agent, may result in irritation in the eye or skin, and may cause nausea, and vomiting, etc. [82, 83].

Healthcare and sanitation personnel involved in disinfection should be provided training in the use of personal protective equipment (PPE) especially in areas where COVID-19 patients are present [84]. Depending upon the disinfectant to be used, healthcare workers involved in the disinfection process should be equipped with a PPE kit including impermeable aprons, face masks, face shields, rubber gloves, and closed shoes [85]. Also, depending upon the disinfectant used, cleaning solutions should be prepared and used in ventilated areas and the mixing of two or more disinfectant solutions should be avoided, because the resultant mixture may be harmful to human health and to surfaces.

3.3 Disinfection in healthcare settings

For environmental cleaning and disinfection of clinical premises, specific international and local authority guidelines should be followed. Surfaces and items with high-touch possibilities, such as door handles, light switches, tables, bed rails, intravenous pumps, etc., should be given proper attention during disinfection. Healthcare workers may act as resource persons for disinfection and cleaning of hospital premises. They should be made aware of cleaning schedules and the risks associated with touching surfaces and equipment during patient care [86]. After a thorough cleaning of environmental surfaces with detergent, 70% alcohol, ≥0.5% hydrogen peroxide, or 0.1% (1000 ppm) to 0.5% (5000 ppm) of chlorine-releasing disinfectants, including sodium hypochlorite, sodium chlorite or chlorine dioxide, can be used for overall disinfection of hospital settings against SARS-CoV-2 [87]. During preparation and application of disinfectants, the use instructions and material safety data sheets supplied by the microbicide manufacturers should be strictly followed to avoid any impacts to humans and to equipment surfaces.

3.4 Disinfection in non-healthcare settings

The risk of fomite (indirect) transmission of SARS-CoV-2 may apply as well to settings outside of hospitals and other healthcare settings. To avoid the risk of any such transmission, it is important to reduce the possibility of contamination in possible high-touch surfaces in offices, homes, schools, gyms, etc. High-touch surfaces in these non-healthcare settings may be thoroughly cleaned with detergent to remove organic dirt and debris before chemical disinfection using sodium hypochlorite (0.1% or 1000 ppm) or alcohol (70–90%) [10].

4. Nanotechnology-based formulations for SARS-CoV-2 control

Although most of the chemical disinfectants are effective against SARS-CoV-2, they are often associated with several drawbacks, such as requirements for higher

concentrations for proper virucidal effect, reduced efficacy in the presence of organic substances, and possible risks associated with the environment and public health [88]. The nosocomial transmission through inappropriate PPE may contribute to infection and death of healthcare workers. To prevent nosocomial transmission, PPE can be treated with copper nanoparticles or copper oxides and salts [89]. Nanoparticle-coated non-woven tissues or cloths using metal-grafted graphene oxide (GO) have been found effective against surrogate viruses, including SARS-CoV, MERS-CoV, and Ebola virus [90]. The coating of silver nanoparticles on face masks made up of woven and nonwoven textiles showed efficacy of 99.99% against surrogate viruses for SARS-CoV-2 [91].

Several metallic nanomaterials, such as titanium dioxide, silver, copper, etc. have been proposed as alternatives to chemical-based disinfectants, due to their characteristic antiviral activities, and effectiveness at a much lower concentrations [92]. Nanomaterials act as a virucidal agents via promoting the surface oxidation by toxic ions, leading to inhibition of viral dissemination by inhibiting the binding or penetration of viral particles. The virus penetration to host cells is inhibited by the generation of reactive oxygen species, and photodynamic and photothermal capabilities which destroy the viral membranes [88].

Facial masks coated with silver nanocluster/silica composite showed viricidal effects against SARS-CoV-2 [93]. Similarly, titanium dioxide and silver ion-based nano-formulations can be used for surface disinfection [88]. The cellulose nanofiber-based breathable and disposable filter cartridge may filter particles, including viruses, even those less than 100 nanometers in size [94]. Because of their unique chemical and physical properties, along with a high surface area to volume ratio, some of the nanomaterials such as graphene nanomaterial can be used to adsorb and remove SARS-CoV-2 from surfaces [95]. Graphene-based nanomaterial has been used to make a reusable mask that may trap viruses and inactivate them with the help of an electrical charge [96]. Graphene in association with copper, silver, and titanium nanoparticles, may enhance the antiviral activity and durability of PPE material [90]. Similarly, quaternary ammonium salts, peptides, or polymer-based nanoparticles may promote the oxidation of viral envelopes and inhibit their replication [97]. However, nanomaterials should be used with caution to avoid any possible health hazards. The adverse effects of metallic nanomaterials on the environment and human health can be minimized by utilizing biodegradable nanomaterials, including polymeric lipid-based nanomaterials [98]. However, to the best of available literature, it is difficult to suggest the complete reliance on disinfectant efficacy of nanoparticle-coated PPE, especially against SARS-CoV-2. Hence, traditional chemical-based disinfectants are still primarily in use. However, nano-based formulations represent a promising field of research and will assist in control of current and similar viral outbreaks in the future [99].

5. Conclusion

SARS-CoV-2 may be transmitted through inhalation of virus present in the air farther than six feet away from the source of infection. Apart from airborne transmission, fecal shedding of the virus has been also been reported from some patients. However, the environmental viability of the virus from fecal shedding has been demonstrated at low levels. Moreover, several studies have demonstrated that the environmental survivability of SARS-CoV-2 in wastewater, surface water, sludge, and other biosolid waste material, is very low with temperatures greater than 20°C. Several reports have also demonstrated that the inactivation rate of coronavirus in waste water is higher than other enteric viruses. On inanimate

surfaces, SARS-CoV-2 may remain infectious from a few hours to up to a few days. Like most enveloped viruses, SARS-CoV-2 is susceptible to a variety of surface disinfection agents, including ethanol, quaternary ammonium compounds (QAC), sodium hypochlorite, chlorine compounds, etc. Moreover, nanomaterial-based disinfectants have also been investigated for ability to inactivate SARS-CoV-2. Proper public awareness and adequate compliance with recommendations from the public health agencies on appropriate use of personal protective equipment (PPE), adequate application of disinfectants in healthcare settings and public places and the home may reduce the number of infectious SARS-CoV-2 virions on environmental surfaces, which may mitigate the transmission of the virus and the risk of acquiring COVID-19. Moreover, national and international guidelines for infection prevention and control of COVID-19 should be followed strictly and such guidelines should be updated in a timely manner based on new information from the scientific literature.

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