




The role of disinfectants and sanitizers during COVID-19 pandemic: advantages and deleterious effects on humans and the environment

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Abstract

Disinfectants and sanitizers are essential preventive agents against the coronavirus disease 2019 (COVID-19) pandemic; however, the pandemic crisis was marred by undue hype, which led to the indiscriminate use of disinfectants and sanitizers. Despite demonstrating a beneficial role in the control and prevention of COVID-19, there are crucial concerns regarding the large-scale use of disinfectants and sanitizers, including the side effects on human and animal health along with harmful impacts exerted on the environment and ecological balance. This article discusses the roles of disinfectants and sanitizers in the control and prevention of the current pandemic and highlights updated disinfection techniques against severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). This article provides evidence of the deleterious effects of disinfectants and sanitizers exerted on humans, animals, and the environment as well as suggests mitigation strategies to reduce these effects. Additionally, potential technologies and approaches for the reduction of these effects and the development of safe, affordable, and effective disinfectants are discussed, particularly, eco-friendly technologies using nanotechnology and nanomedicine.

Keywords COVID-19 · SARS-CoV-2 · Disinfectants · Environment · Hazard · Prevention

Introduction

Intensive global research efforts have been engaged for the development of potential therapies and vaccines for coronavirus disease 2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Dhama et al. 2020a, b; WHO 2021), and the control of the COVID-19 pandemic remains the highest priority globally. Considering the current ineffectiveness of various strategies in the prevention of the spread of the virus, the lack of targeted treatments, and frequent increase in cases on a daily basis, disinfection is an important available measure to prevent COVID-19 spread and to combat SARS-CoV-2 directly.

Successful disinfection of SARS-CoV-2 is determined by the characteristics of the virus, properties of the disinfectants or sanitizers, and the environment where the virus is present or where disinfection is to be conducted. Disinfectants are chemical agents that are used to inactivate or destroy microorganisms, while sanitizers are available in the liquid, gel, or foam forms that are used to reduce the number of microorganisms present and to clean hands. SARS-CoV-2 is susceptible to disinfection (Rutala and Weber 2019; WHO 2020), exhibits stability at a broad range of pH values (pH 3–10) at room temperature (Chin et al. 2020), and is very much stable in a favorable environment (van Doremalen et al. 2020). SARS-CoV-2 persists for variable durations in different environments; for instance, it can reside on the outer layer of surgical masks for up to 7 days, and its presence on smooth surfaces (glass, plastic, banknotes, stainless steel) varies from 4 to 7 days (Chin et al. 2020). SARS-CoV-2 has not been detected on printing and tissue papers after 3 h, and treated wood and cloth show negative results for SARS-CoV-2 after 2 days (Chin et al. 2020). SARS-CoV-2 demonstrates increased stability on stainless steel and plastic as compared to copper and cardboard, and viable virus has been detected up to 72 h of

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application to such surfaces (van Doremalen et al. 2020). Furthermore, it has been detected in sewage and wastewater (Randazzo et al. 2020; Dhama et al. 2021).

SARS-CoV-2 is susceptible to a wide variety of disinfectants (Chin et al. 2020; United States Environmental Protection Agency (EPA), 2020). Lipid solvents, including ethanol (> 75%), formaldehyde (> 0.7%), isopropanol (> 70%), povidone-iodine (> 0.23%), sodium hypochlorite (> 0.21%), or hydrogen peroxide (H_2O_2 ; > 0.5%), can also be used to inactivate SARS-CoV-2 (Duarte and de Santana 2020). Considering viral presence, persistence, stability, viability, and environmental influence on viral persistence, the disinfection of environments, such as offices, healthcare settings, public transportation, markets, restaurants, and auditoriums, is necessary to prevent the transmission and infection waves of COVID-19.

However, strategies and techniques of cleaning, sanitization, disinfection, and other methods to contain the devastating effects of the pandemic should be subjected to modification development over time according to their deleterious consequences on the environment and human health (Mukherjee et al. 2021). Hence, the present article highlights the beneficial usages, effectiveness, modes of antiviral action, and deleterious consequences of different disinfectants, along with a brief note on sanitizers, while also discussing the mitigation strategies with updated disinfection approaches to counter their harmful effects during the COVID-19 pandemic.

Disinfectants and their antiviral mechanisms

Disinfectants are chemical agents that are specifically formulated to inactivate or destroy microorganisms and include various classes, such as detergents, acids, oxidizing agents, alcohols, alkalis, aldehydes, biguanides, halogens, phenols, and quaternary ammonium compounds (QACs) (FDA 2020a; Choi et al. 2021). Chemical disinfectants vary in their action mechanism, and the majority of disinfectants of a chemical nature target the outer lipid layer of coronaviruses (CoVs) and inactivate the viral particles (Choi et al. 2021). However, variations among the mechanisms of chemical disinfectants have been recorded. Detergents are a well-known category of chemical disinfectants that vary in their mechanism of action depending upon the class of disinfectant, the organism against which the disinfectant exhibits strong activity, the structure being affected, the surface or medium on which the disinfectant is applied, and the environment of application (Maris 1995; McDonnell and Russell 1999). Disinfectants may initiate three types of killing mechanisms that include cross-linking, coagulation, clumping, structural and functional disruption, and oxidation. These processes can occur through oxidation, hydrolysis, denaturation, or substitution (Ewart 2001). In case of viruses, they may affect the

lipid membrane, cytoplasmic membrane, energy metabolism, cytoplasm, nucleus, enzymes, or proteins (Maris 1995). Non-ionic (uncharged) detergents are preferred over anionic detergents as they are good emulsifiers and exhibit better penetration and dispersion, decreased surface tension, lesser foaming property, and do not undergo complexation with hard water and result in microbial accumulation in the residue (Ewart 2001; CFSPH 2008).

Alcohol causes damage to microorganisms by denaturing proteins, leading to membrane damage and cell lysis (Ewart 2001; CFSPH 2008; Al-Sayah 2020). Ethanol shows appreciable activity on both living and non-living surfaces and evaporates quickly without leaving residue (CFSPH 2008). Ethanol at > 75% concentration acts as a potent virucidal agent that inactivates all lipophilic viruses (herpes, influenza, and vaccinia) and several hydrophilic viruses (adenovirus, rhinovirus, enterovirus, and rotaviruses). At a concentration of > 70%, ethanol and isopropanol inactivate CoVs within 30 s (Kampf et al. 2020a). Isopropyl alcohol is extremely active against lipid viruses (CDC 2008). The primary mode of action is the coagulation and denaturation of proteins, apart from its lipid solvent properties.

Chlorine aids the oxidation of peptide links owing its electronegativity, and therefore, causes the oxidation of lipids and proteins and, in turn, inflicts damage on the membrane and cell wall of the microbes (McDonnell and Russell 1999). Moreover, hypochlorous acid is the most active compound, and it penetrates the cell layers even at a pH of 7. QACs damage the membrane permeability of microbes by irreversibly binding to phospholipids and proteins of the membrane (Gerba 2015). An alkaline pH (above 10.0) results in the disorganization of the peptidoglycan structure and leads to hydrolysis of the virus genome (Maris 1995). Phenolic compounds act specifically on the cell membrane and lead to the inactivation of the intracytoplasmic enzymes by forming unstable complexes (Sankar et al. 2016). Acids and alkalis mediate their antiviral action through H^+ and OH^- ions that inflict damage on the amino acid bond in nucleic acids, modify the cytoplasmic pH, precipitate proteins, and saponify the lipids (Russell 1983; Maris 1995). H_2O_2 catalyzes the oxidation and denaturation of proteins and lipids, causing membrane disorganization, resulting in swelling due to the saturation of H^+ ions (Russell 1983; Maris 1995; Al-Sayah 2020). Against SARS-CoV, H_2O_2 exhibits virucidal activity at a 1–3% concentration and inactivates the virus within 1 min; however, the gaseous form is more efficient (Herzog et al. 2012; Goyal et al. 2014). H_2O_2 -based non-touch disinfection techniques help reduce environmental contamination, particularly in hospital settings and intensive care units with infectious agents after routine cleaning (Huttner and Harbarth 2015; Blazejewski et al. 2015). Airborne H_2O_2 in the form of vapor and dry mist has been used as an environmental disinfectant and to control infection in clinical settings (Falagas et al.

2011). Aldehydes demonstrate activity against CoVs at concentrations of 0.5–3% and result in viral deactivation within 2 min (Al-Sayah 2020). Povidone–iodine at a concentration of 1% or less triggers SARS-CoV inactivation within seconds (Kariwa et al. 2006; Eggers et al. 2018).

If the lipid envelope, glycoproteins, attachment (spike) proteins, and virion genome of CoVs, which impart infectivity to the virus, undergo damage or disruption, then the aftermath of such an occurrence is virus inactivation or exertion of effects on its infectivity (Al-Sayah 2020). Disinfectants have been evaluated and recommended against SARS-CoV-2 (Noorimotlagh et al. 2020). Among these, ethanol at a concentration > 70% and 2-propanol at a concentration of 70–100% have shown virucidal activity, while others have demonstrated either less effectivity or complete ineffectivity, with several agents posing a threat to human health and the environment (Kampf et al. 2020a; Lai et al. 2020; Noorimotlagh et al. 2020; Schrank et al. 2020).

Necessity of disinfection during the COVID-19 pandemic

A recent study predicted that a considerable proportion of the global population would eventually be infected by SARS-CoV-2 (Giasecke 2020). The only available method of containing this pandemic is to prevent further transmission and to confer protection to individuals against exposure to the virus. Implementation of strict lockdowns, rampant testing, contact tracing, quarantine, isolation, and treatment approaches have decelerated the virus spread to a certain extent, and now it is imperative to adopt effective disinfection procedures to ensure the safety of populations after the lifting of lockdown and resumption of on-site work. Considering the persistence of SARS-CoV-2 on surfaces and the potential risk of infection through fomites, disinfection of the work environment is a priority before the resumption of regular working environments (ECDC 2020; van Doremalen et al. 2020). As SARS-CoV-2 survives in the environment with persistence ranging from hours (3 h in the air, 4 h on copper, and 24 h on cardboard) to days (2 to 3 days on both stainless steel and plastic), the disinfection of workplaces is imperative, especially where public visits or assemblies of crowds are inevitable (ECDC 2020; van Doremalen et al. 2020). Similarly, SARS-CoV-2 can persist for days on non-porous surfaces under 22°C and 65% relative humidity (Chin et al. 2020). Moreover, it has also been detected on desktops, printers, keyboards, doorknobs, gloves, and eye shields (ECDC 2020). A comparative study of SARS-CoV-1 and SARS-CoV-2 showed that the viability of the two CoVs is similar; however, SARS-CoV-2 spread is characterized by rapid dissemination and infection of more people (Gates 2020).

Although most SARS-CoV-2 transmissions occur in community settings, healthcare settings are also vulnerable to the establishment and spread of infections. In this context, hospitals engaged in treating patients with COVID-19 must be equipped with the most appropriate disinfection techniques and materials for the disinfection of healthcare personnel, hospital rooms, and medical equipment to avoid nosocomial transmission. The guidelines for the application of disinfectants in healthcare and non-healthcare settings issued by various agencies must be followed while using disinfectants in different environments (ECDC 2020; US EPA 2020).

Disinfection is a prerequisite for the control of infectious disease outbreaks, with SARS-CoV-2 containment being of utmost importance. It is vital to reduce the potential for virus contamination. Disinfection may also lessen the burden on other measures of pandemic control. Commonly, sodium hypochlorite, ethanol, and H₂O₂ have been used and found to be more effective compared to benzalkonium chloride (BAC), chlorhexidine digluconate, povidoneiodine, and diluted ethyl alcohol, especially with reference to their application in hand hygiene, protective equipment sanitization, and in environmental disinfection (León Molina and Abad-Corpa 2021). Rowan and Laffey (2020) proposed the disinfection of personal protective equipment (PPE) for their reuse and the utilization of vaporized H₂O₂ for the sterilization of filtering facepiece respirators and UV irradiation. Increased extent of liquid disinfection (Actichlor+) is being adopted in the USA and Ireland. This will help prevent a shortage of PPE. The European Centre for Disease Prevention and Control (ECDC) has suggested different cleaning options for different settings, which are described in Table 1 (ECDC 2020).

Moreover, several chemical disinfectants with high toxicity are being used for the decontamination of the surfaces of several environmental settings, such as clinical and surgical practices and water bodies, which is imperative to ensure well-being and safety. However, the development of new decontamination strategies, which neither leave residues nor induce toxicity, is vital. The following section emphasizes the updated and modified disinfection approaches to contain the overwhelming effects of the COVID-19 pandemic.

An overview of the important disinfectants and their antiviral mechanisms and the need for disinfection during the COVID-19 pandemic is illustrated in Fig. 1.

Updated disinfection approaches against SARS-CoV-2

Commonly used disinfectants against COVID-19 include detergents/soaps, alcohols, and chlorine. Chlorine is recommended as a disinfectant for indoor facilities (Yang et al. 2020). In healthcare settings, equipment, including imaging devices (e.g., endoscopes), scanners, bedding, and contact

Table 1 Cleaning options for different settings

Setting	General settings	Non-healthcare setting	Healthcare setting
Toilets	• 0.1% sodium hypochlorite or Virucidal disinfectant	• 0.1% sodium hypochlorite or Virucidal disinfectant	• 0.1% sodium hypochlorite or Virucidal disinfectant
Surface	• Neutral detergent	• Virucidal and Neutral detergent • 0.05% sodium hypochlorite or Disinfectant or 70% ethanol	• Virucidal and Neutral detergent • 0.05% sodium hypochlorite or Disinfectant or 70% ethanol
Textiles	-	• Hot-water cycle (90°C) and Regular laundry detergent • Alternative: lower temperature cycle + bleach or other laundry products	• Hot-water cycle (90°C) and Regular laundry detergent • Alternative: lower temperature cycle + bleach or other laundry products
PPE for cleaning staff	• Gloves • Uniform	• Gloves • Surgical mask • Uniform and plastic apron	• Gloves • Surgical mask • Disposable long-sleeved water-resistant gown • FFP2 or 3 when cleaning facilities where AGP have been performed
Cleaning equipment	• Non-disposable cleaned at the end of cleaning session or • Single-use disposable	• Non-disposable disinfected with: Virucidal disinfectant or 0.1% sodium hypochlorite • Single-use disposable	• Non-disposable disinfected with: Virucidal disinfectant or 0.1% sodium hypochlorite • Single-use disposable
Waste management	• Unsorted garbage	• In a separate bag in the unsorted garbage	• Infectious clinical waste category B (UN3291)

instruments, must be disinfected using appropriate disinfectants (Prochazka Zá Rate et al. 2020; Wan et al. 2020). To perform disinfection of the floor, environment, and table surfaces, application of 2 g/L of chlorine-containing disinfectant is recommended at least four times daily for at least 30 min, while application of UV irradiation and spraying techniques using 500 mg/L of chlorine-containing disinfectant for at least 30 min are the methods of choice for the disinfection of air (Barcelo 2020). Additionally, personal items, such as mobile phones, keys, credit cards, and writing pens, may be subjected to sanitization using 75% ethanol to ensure their disinfection (Yang et al. 2020). Virusend (TX-10) is a unique disinfectant that has already exhibited efficient activity against several microbial agents, including viruses. Virusend (TX-10) application was found to inactivate SARS-CoV-2 in an in vitro study based on surface and solution inactivation assays. This novel disinfectant rapidly decreased the SARS-CoV-2 viral titer by 4log₁₀ PFU/mL within a contact period of 1 min (Anderson et al. 2020).

The use of plasma-activated water is another alternative to conventional disinfectants that can efficiently be used to inactivate bacteria and bacteriophages via induction of direct damage to the biological macromolecules. Plasma-activated water can be used to inhibit SARS-CoV-2 pseudovirus infection via inactivation of the S protein (Guo et al. 2020). The alcohol-based hand sanitizers (ABHSs) that are commonly used on skin are not suitable for use on PPE. Therefore, new compounds or products should be developed that can be used to

effectively disinfect PPE without causing detrimental effects to the surrounding skin tissue. Clyraguard copper iodine complex is a product that has exhibited potential efficacy in the decontamination of non-critical PPE (Mantlo et al. 2020).

As various environmental factors are considered to determine the transmission of SARS-CoV-2, disinfection of surfaces in work environments with diluted sodium hypochlorite (0.1%) is recommended (Eslami and Jalili 2020; Seymour et al. 2020). CoVs present on inanimate objects or surfaces may be inactivated by conducting treatment with biocidal agents, such as 0.5% H₂O₂, 62%–71% ethanol, and 0.1% sodium hypochlorite, for at least 1 min (Kampf et al. 2020a). Presently, the disinfection of fabrics and carpets used in hospitals is nearly neglected, though such materials are highly prone to contamination by aerosols and dust. Standard procedures for the disinfection of surface coverings and linens include laundering, cleaning with water, and vacuuming, which, in many cases, are inadequate to remove infectious load (Malik et al. 2006a). The carpets of shopping malls where a COVID-19-positive patient may have visited are disinfected by spraying 1% NaOCl, and the disinfection time is 30 min for spraying of disinfectants, as recommended by the WHO and the Central Pollution Control Board in India. Chlorine has been applied as a disinfectant to contain SARS-CoV-2 in indoor and outdoor spaces in China (China Ministry of Ecology and Environment 2020). Thermal methods involving temperatures of at least 50°C for conducting 30-min Uv radiation (100-μwcm⁻² power) with a contact time of 15 to 20 min

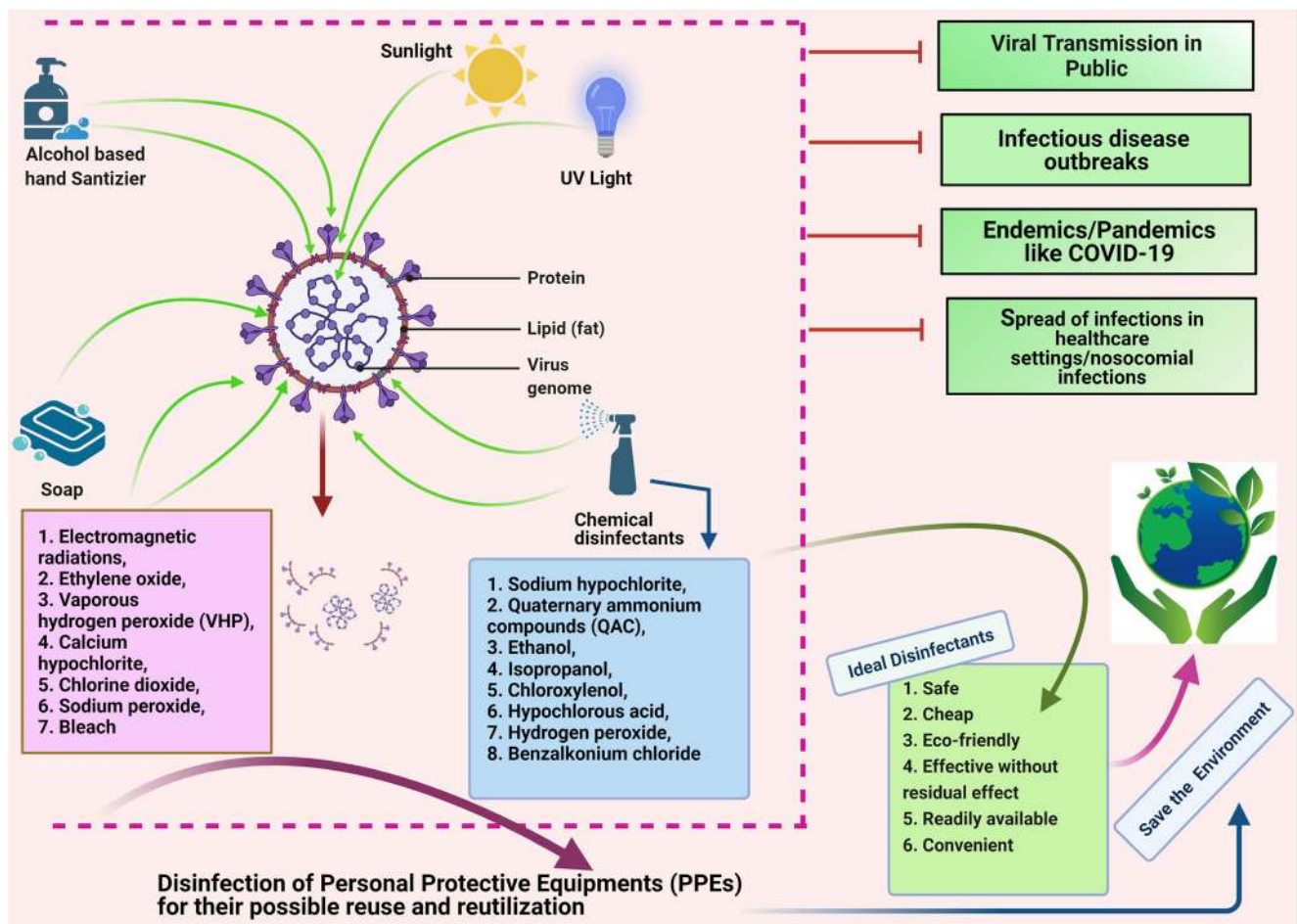


Fig. 1 Disinfectants and their antiviral mechanisms (such as targeting lipid layer and spike proteins) and the need of disinfection during COVID-19 pandemic. The figure was created with [BioRender.com](https://www.biorender.com)

and H_2O_2 vapor are being used for the disinfection of masks, especially N95 masks (Card et al. 2020; Seymour et al. 2020). Moreover, one study with the inclusion of original data based on 10 studies indicated that thermal disinfection at 80°C for 1 min, 65°C for 15 min, and 60°C for 30 min was highly effective in reducing CoV infectivity by at least 4 \log_{10} (Kampf et al. 2020b). In this context, thermal aggregation of the membrane protein along with complete denaturation of nucleocapsid protein (55°C for 10 min) of SARS-CoV is suggested as a probable explanation of infectivity reduction (Wang et al. 2004; Lee et al. 2005).

The US Environmental Protection Agency (EPA) has published a list of effective disinfectants for use against SARS-CoV-2, including sodium hypochlorite, QAC, ethanol, isopropanol, hypochlorous acid, chloroxylenol, H_2O_2 , BAC, and chlorine-based chemicals (US EPA 2020). Common disinfectants against SARS-CoV-2 are listed in Table 2. BAC and related disinfectants are ubiquitously used and have been recommended by the FDA for use in soaps, hospital sanitation kits, and cleaning wipes; however, knowledge of their efficacy against SARS-CoV-2 is crucial, and thus, they must be

evaluated. In addition to alcohols and ABHSs, QACs, such as BAC, have been evaluated against CoVs but have shown less activity; thus, similar to other disinfectants, including sodium hypochlorite, peroxides, aldehydes (formaldehyde and glutardialdehyde), and didecyldimethylammonium chloride, the above-mentioned agents should be subjected to proper analysis to avoid their improper application as disinfectants against SARS-CoV-2 (Kampf et al. 2020a; Lai et al. 2020; Schrank et al. 2020). The CDC issued a warning regarding the use of products containing BAC for the prevention of COVID-19 (Schrank et al. 2020). Additionally, CoVs undergo destruction within 15 min of exposure to ultraviolet C (UVC) light (Darnell et al. 2004). The beta-CoVs, including SARS-CoV and Middle East respiratory syndrome (MERS) CoV, are effectively inactivated by germicidal ultraviolet (UV) irradiation; however, its efficacy for inactivating SARS-CoV-2 warrants further investigation (Leung and Ko 2020). Germicidal UV lamps for household disinfection should be used with extreme caution because their improper use can cause epidermal photo-toxicity and photo-keratitis (Leung and Ko 2020). UV radiation is more dangerous and

Table 2 Disinfectants, their use, merits, and demerits against viruses especially SARS-CoV-2

Disinfectant	Use	Strength/ concentration	Application sites and condition	Merits and demerits	Associated health and environmental hazards	Reference
Ethanol (Ethyl alcohol)	Living and non-living surfaces	70–95%	Skin (80%) Non-living surfaces (70–95%) Food (70%)	Effective against SARS-CoV-2, convenience in application, cheap, and affordable. Dehydration, dryness, smell, not suitable as aerosol, poisoning in children.	Can cause confusion, vomiting and drowsiness, and in severe cases, respiratory arrest and death. Concerns of antimicrobial resistance. Chance of other viral diseases. Lactic acidosis, ketoacidosis, nausea, cardiac arrhythmia, acute liver injury, myoglobinuria, hypokalemia, hypomagnesemia, hypocalcemia, hypophosphatemia, cardiac arrest, and death.	Kampf et al. 2020a; Kumar et al. 2020; Mahmood et al. 2020
Hydrogen peroxide	Living and non-living surfaces	0.125–35%	Skin (0.125%), mouth wash (3%) Non-living surfaces (35%) Food (35%)	Comparatively effective, convenient, and affordable. Mild gastrointestinal and mucosal irritation, vomiting, skin irritation.	Air embolism Death in rare cases	Kumar et al. 2020; Mahmood et al. 2020; Moon and Chun 2006
Isopropanol (isopropyl alcohol)	Living and non-living surfaces	60–90%	Skin (75%) Non-living surfaces (60–90%) Food (70%)	Effectiveness, ease of applicability, cheap, and affordable. Toxicity, dryness of skin, not suitable as aerosol.	Central nervous system and respiratory depression, skin and mucous membrane irritation, death, ketosis, osmolar gap ketonemia, rhabdomyolysis, myoglobinuria, acute renal failure	Kratzel et al. 2020; Kumar et al. 2020; Mahmood et al. 2020; Zaman et al. 2002
Nanoparticles	Non-living surfaces	Copper-based nanobiocides, silver-based nanobiocides		Effective antiviral actions (silver-based nanobiocides—99.99% effective), suitable for disinfecting air and surfaces, effective in reinforcing PPEs such as facial respirators. Costly, rarely available, issues of dose standardization, adverse effects of heavy metals.	Can be applied on PPEs like masks, goggles, food packages, but are costly and not available everywhere, risks of toxicity and irritation. Environmental side effects.	Balagna et al. 2020; Talebian et al. 2020; Lingayya et al. 2020
Povidone-iodine	Living and non-living surfaces	0.3–10%	Skin (5–10%)	Effective, can be used as nasal sprays, demerits of irritation, staining.	Local swelling, irritation, itching, and rash. With overuse, povidone-iodine can have corrosive effects.	Kumar et al. 2020; Lingayya et al. 2020
Quaternary ammonium compounds	Non-living surfaces	200 ppm or more	Food and non-food surfaces (≥ 200 ppm)	Quite effective virucidal, can be used in combination, low human toxicity, skin and material tolerability, no odor, not applied on living surfaces, do not damage clothing and	Ineffective in presence of organic matter on surfaces, irritation, toxicity, environmental side effects	Kumar et al. 2020; Lingayya et al. 2020

Table 2 (continued)

Disinfectant	Use	Strength/ concentration	Application sites and condition	Merits and demerits	Associated health and environmental hazards	Reference
UV radiation	Non-living things, air	200–280 nm	Fomites, air	carpets unlike oxidizing agents. Effective virucidal action, does not affect textile or fabric quality, nonpolluting, radiation hazards	Can damage human eyes and prolonged exposure can cause burns and skin cancer	Al-Gheethi et al. 2020; FDA 2020b; Kumar et al. 2020
Sodium hypochlorite	Non-living surfaces	100–200 ppm	Fomites	Effective for disinfecting surfaces, cheap and convenient. Toxic, irritating, and chlorine gas formation. Hazardous to aquatic life and environment.	Lower concentrations can cause mild irritation of the mucous membranes occurs, stimulation of the upper airways. Higher concentrations cause shortness of breath, nausea, chest pain, and coughing immediately	Yari et al. 2020; Kumar et al. 2020

may severely damage the eyes and skin; repeated exposure to such radiation can also cause skin cancer (ICNIRP 2004). The use of human disinfection chambers is an example of recent innovations developed in response to the COVID-19 pandemic (Wickramatillake and Kurukularatne 2020).

As the number of COVID-19 cases continues to increase worldwide, a considerable shortage of N95 respirators has emerged. Therefore, it is essential to note that N95 respirators can be reused after disinfection. In a recent study, N95 respirators were subjected to conditions of heat at temperatures $\leq 85^{\circ}\text{C}$ and relative humidity $\leq 100\%$, which resulted in the inactivation of the virus without affecting the filtration properties of the masks (Liao et al. 2020). Furthermore, the use of H_2O_2 and hot air is the most effective method for the industrial and home disinfection of face masks, respectively. In contrast, surgical masks and homemade or non-certified masks are slightly less and significantly less effective than PPE and face masks, respectively (Carlos Rubio-Romero et al. 2020). The disinfection of used masks is necessary for their safe reuse while there is an acute shortage; however, incorrect decontamination procedures can damage the filtering structure of the masks. Medical masks and N95 masks retain their blocking efficacy against over 99% of viruses in aerosols even after subjection to steam conditions in boiling water for 2 h, suggesting that they can be reused for several days with the application of steam decontamination between uses (Ma et al. 2020). Disinfection of the masks and PPE after use and prior disposal is imperative. Otherwise, they may become a source of environmental contamination of SARS-CoV-2. The disinfection of N95 respirators may be essential during pandemics, such as the present COVID-19 pandemic, to overcome the curtailment crisis. However, the decontamination method should not alter the efficiency of the filtration of the N95 respirators and surgical masks. The use of UV germicidal irradiation, microwave-generated steam, moist heat, and H_2O_2 vapor techniques should be strictly followed for the efficient containment of SARS-CoV-2.

Considering the transmission of COVID-19 in public transport vehicles, such as aircraft, ships, trains, subways, and buses, public transportation staff and passengers are advised to adopt strict preventive measures. All surfaces in public transport vehicles must be appropriately disinfected and sanitized. For this purpose, surfaces can be sprayed or wiped with chlorine-containing disinfectants (COVID-19 Emergency Response Key Places Protection and Disinfection Technology Team 2020a). A disinfectant should be used at an appropriate concentration and sufficient contact exposure time should be allowed with the surface to destroy the virus.

The precise timing, the location, and the mechanism of disinfection, the type of disinfectant to be used, and safety measures to be implemented for both public health and the environment must be determined (Iyiola et al. 2020; Nabi et al. 2020; Zhang et al. 2020). Determination of the minimum

amount of disinfectant necessary, appropriate exposure levels, and appropriate level of contact is essential for optimum action (Sarada et al. 2020). Avoidance of indiscriminate sprays, minimization of public movement, and the development of low-risk or nontoxic but effective disinfectants for future safe applications should be an international priority (Iyiola et al. 2020; Nabi et al. 2020; Zhang et al. 2020). Additionally, efforts should be engaged for the development of disinfection systems, such as UVC-based disinfection trolleys, UVC germicidal lamp-based fogging chambers, dry heat sterilization, and HOCl-based chemical disinfectants (Sarada et al. 2020).

Disinfection and its deleterious effects on humans and the environment

Improper and inappropriate use of disinfectants can result in the exertion of adverse effects. Excessive use of disinfectants poses a potential threat to living beings and ecosystems (Chen et al. 2021; Ghafoor et al. 2021) as they present with a myriad side effect (Yari et al. 2020). Disinfectants can affect both the applicant and the environment and may have future deleterious consequences (Yari et al. 2020). Chemical agents used as highly concentrated, aerosolized, or atomized disinfectants can easily be inhaled or absorbed into the skin. For example, aerosolized particles can penetrate alveoli upon inhalation. The increased frequency and duration of exposure to disinfectants (e.g., in disinfection chambers) can cause harmful effects on human and animal health. Disinfectants may cause reactions in the mucosal lining, resulting in irritation, inflammation, swelling, and ulceration of the upper and lower respiratory tract. A few chemicals are absorbed quickly through the mucosa of various organs and organ systems (e.g., the central nervous system and gastrointestinal tract) into the bloodstream. A recent case study reported the infliction of severe corrosive damage to gastric, esophageal, and small intestinal mucosa after the intentional oral ingestion of 10 mL of ethanol-containing hand disinfectant for 3 weeks, as the patient aimed to perform self-disinfection against COVID-19 owing to a fear of infection by the virus (Binder et al. 2020). Direct contact of the cornea and skin with aerosols may cause severe irritation and irreversible damage (Wickramatillake and Kurukularatne 2020). In addition to dryness of the skin, ABHSs can lead to infection and poisoning, particularly in children, who are believed to be susceptible and thus are subject to a major health risk (Ghafoor et al. 2021). Bleach (diluted sodium hypochlorite), one of the most commonly used disinfectants, can be directly absorbed by the skin, leading to allergic reactions. Additionally, various harmful effects, such as acute cardiopulmonary arrest, gastrointestinal ailments (e.g., nausea, vomiting, and diarrhea), and renal problems, have occurred in individuals after the accidental inhalation and ingestion of bleach (Peck et al. 2011). QAC and bleach

reportedly increase the risk of development of asthma, chronic obstructive pulmonary disease (COPD), infertility, and impaired brain development in children (Fair 2020). The potential impact of disinfectants on individuals with asthma remains to be investigated, especially in the case of disinfectants with strong odors. Such disinfectants can act as potential asthma triggers (Eldeirawi et al. 2020). Therefore, individuals with asthma should use safer disinfection alternatives. A recently published cohort study revealed that out of 55,000 health professionals who used QAC and bleach routinely, 663 developed COPD (European Lung Foundation 2017). A correlation between the concentration of sodium hypochlorite and microscopic/cellular alterations, including chromosomal aberrations, cell death (apoptotic and necrotic changes), and increased mitotic activity, has also been documented (Gul et al. 2009). Additionally, psychotic episodes associated with a fear of death from SARS-CoV-2 infection can result in the consumption of liquid disinfectants or inhalation of aerosol sprays containing chlorine in an effort to cleanse their body. This can result in the infliction of primary inhalational toxic lung injury, which can mimic the symptoms of clinical COVID-19 due to the development of acute respiratory distress syndrome (Willems et al. 2020).

Chemical compounds used as disinfectants are not only harmful to humans but also affect animals and aquatic ecosystems. Though the disinfection of wastewater originating from healthcare facilities, offices, public places, and other organizations, such as hotels and processing units, is essential for minimization of the likelihood of spreading infection and deleterious effects, application of these disinfectants can cause harm to both living organisms and the environment. Other disinfection practices, such as the washing of external floors, streets, and markets, also contribute to the discharge of disinfectants into sewage, rivers, and lakes (Subpiramaniyan 2021). Sodium hypochlorite is commonly used for the disinfection of hospital wastewater to prevent the spread of nosocomial infectious diseases. Therefore, such chemicals may gain entry into the sewage and cause pollution of drinking water resources (China Ministry of Ecology and Environment 2020). Furthermore, as both direct and indirect sewage effluents are discharged into rivers and lakes, aquatic ecosystems are at a risk of contamination with chemical disinfectants (Sedlak 2011; Subpiramaniyan 2021). Chlorine disinfectants threaten aquatic wildlife and plants as the agents catalyze the oxidation of their proteins and destruction of their cell walls (Sedlak 2011). Moreover, these chemicals may bind to other materials to form harmful compounds. For example, chlorine disinfectants undergo reactions with dissolved organic matter of surface water to produce disinfectant byproducts, such as haloacetic acids and trihalomethanes, which are highly toxic to aquatic flora and fauna (Sedlak

2011; Liu and Zhang 2014). Chlorine also undergoes reaction with organic matter in wastewater, thereby resulting in the generation of organic chlorine compounds that persist as environmental contaminants and may pose a considerable risk to aquatic ecosystems (Emmanuel et al. 2004). An effect of disinfectants may be exerted on microbial activity in wastewater treatment plants that may compromise the effective removal of pollutants (carbon, nitrose, and phosphorous). Extensive use of disinfectants against COVID-19 also poses potential risks to urban wildlife (Nabi et al. 2020). While humans can avoid the establishment of contact with disinfectants during the active disinfection of areas or localities, other organisms, including wild animals, are unable to do so, thus resulting in potential contact with corrosive or otherwise harmful substances (Nabi et al. 2020). The overuse of disinfectants has led to the death of animals, such as birds and weasels (You 2020). They exert toxicological effects on both terrestrial and aquatic animals (El-Nahhal and El-Nahhal 2020) and may have impacts on food and water sources (Zhang et al. 2020). Excessive use of disinfectants can lead to their enrichment, bioaccumulation, and biomagnification, resulting in toxicity, mutations, spread of antibiotic resistance genes, and the emergence of antibiotic-resistant bacteria (Chen et al. 2021).

The salient deleterious effects of disinfectants and sanitizers on humans and the environment during COVID-19 are depicted in Fig. 2.

Disinfectants may also affect material surfaces (Bonin et al. 2020). Their corrosive nature may lead to the corrosion of important metal surfaces. Though four out of five disinfectants pose little or no risk to metals, further studies are warranted for the evaluation of the impact of disinfectants on surfaces subject to frequent and continuous use of various types of disinfectants, as these agents may exert adverse effects (Bonin et al. 2020). The increased use of disinfectants in response to the COVID-19 pandemic may lead to the occurrence of a secondary disaster in aquatic ecosystems worldwide. Therefore, sewage originating from medical institutions should be treated as per the guidelines provided by concerned authorities. This implies that sewage originating from healthcare facilities should be treated separately before combination with other sewage. Additionally, to remove remaining virus particles from the sewage originating from healthcare facilities, chemical agents, such as dibromo-dimethyl hydantoin, chlorine dioxide, and other chlorine-containing disinfectants, can be used (COVID-19 Emergency Response Key Places Protection and Disinfection Technology Team 2020b). Analysis and re-evaluation of the current methods of sewage treatment are of utmost importance for preventing the transmission of COVID-19 via sewage; additionally, the substitution of conventional methods (chlorination and simple filtration) with advanced methods (centralized wastewater treatment, oxidation, filtration, and membrane technology) of sewage treatment is

necessary to prevent the dissemination of SARS-CoV-2 throughout the environment (Núñez-Delgado 2020).

Mitigation strategies to reduce the deleterious consequences of disinfectants in humans and the environment

Safe and eco-friendly disinfectants should be used, and post-disinfection measures should be undertaken to avoid the occurrence of health hazards. In this context, light, including sunlight (Ratnesar-Shumate et al. 2020), UV light (Seyer and Sanlidag 2020; Zhao et al. 2020), and color light (Enwemeka et al. 2020), may demonstrate prospects and potential applications in managing the COVID-19 pandemic. However, further studies relating to this matter are warranted (Derraik et al. 2020; Ratnesar-Shumate et al. 2020; Seyer and Sanlidag 2020). Simulated sunlight can reportedly inactivate SARS-CoV-2 particles dried on stainless steel and suspended in simulated saliva or culture media (Ratnesar-Shumate et al. 2020). Moreover, 90% of infectious virus is inactivated at every 6.8 and 14.3 min of exposure in simulated saliva and culture media, respectively (Ratnesar-Shumate et al. 2020). This indicates that sunlight may be useful as a natural disinfectant for non-porous outdoor materials contaminated with SARS-CoV-2 (Ratnesar-Shumate et al. 2020). Special air-disinfecting machines are also presently being proposed (Zhao et al. 2020).

Hitherto, studies have shown the activity of alcohol-based disinfectants and sanitizers against several viral infections (Malik et al. 2006b; Patnayak et al. 2008; Suman et al. 2020). The use of ethanol-based sanitizers is recommended for the prevention of the harmful effects of other chemical compounds on humans and animals. Direct spraying of bleach onto infected individuals or affected areas is discouraged. Disinfected surfaces must be subjected to drying and rinsing with water because disinfectants can persist for a long period on contaminated surfaces and may cause unintentional exposure to hazardous chemicals. Government agencies should, therefore, develop facilities for proper disinfectant drainage to minimize the harmful effects on aquatic flora and fauna. The use of eco-friendly technologies along with safe and effective disinfection methods is highly warranted, not only to combat the ongoing pandemic but also to protect the environment and living beings from hazardous chemicals.

Low-cost antibody-linked graphene sheets that function as environmental virus sensors have been synthesized; their application as coatings on face masks/PPEs represents a promising strategy to fight COVID-19 by minimizing the risk of transmission (Palmieri and Papi 2020). Moreover, magnetic nanomaterials or nanoparticles can be exploited as efficient alternatives for coating PPEs such as masks and eye-protecting glasses in order to produce reusable and

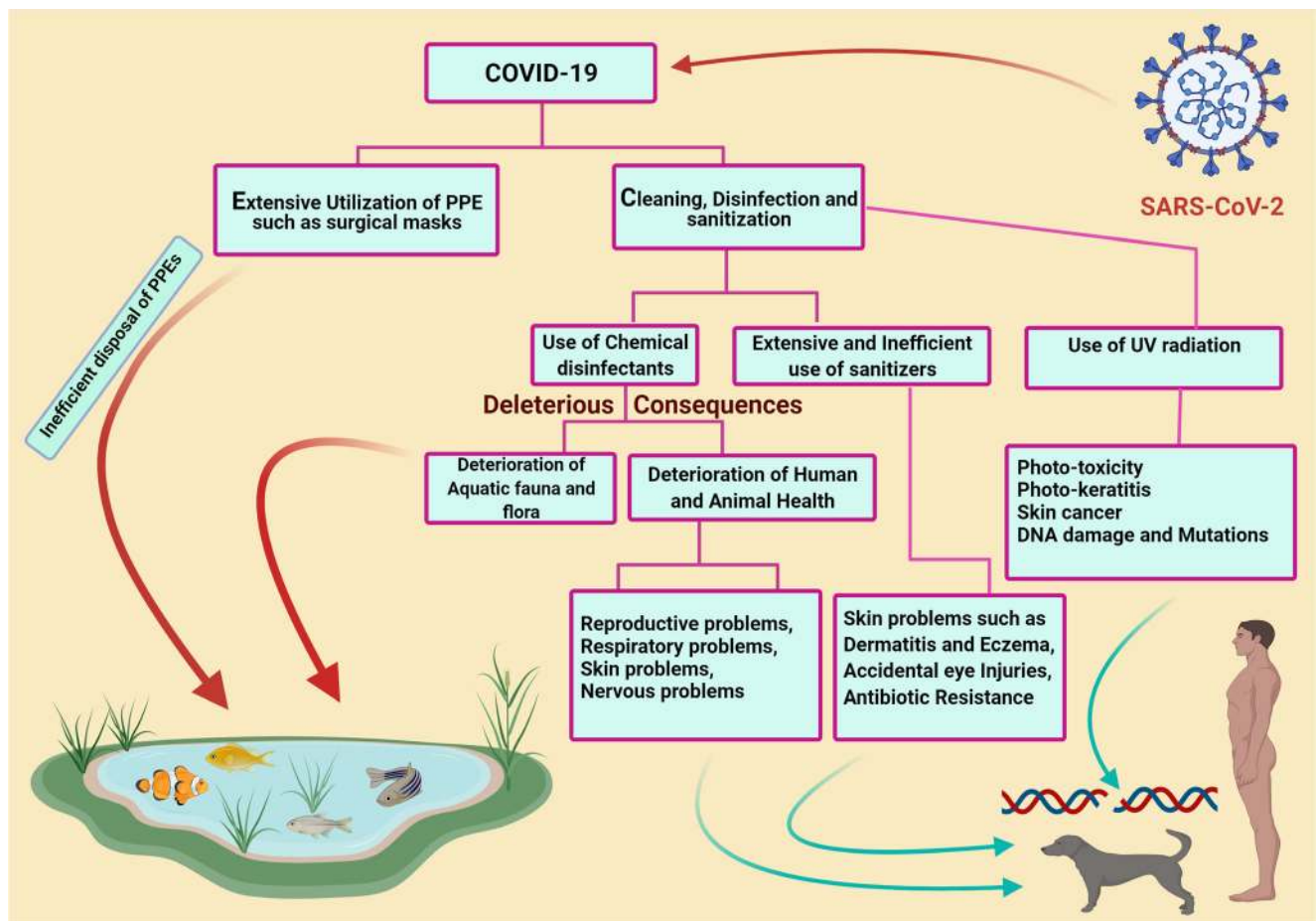


Fig. 2 Deleterious effects of disinfectants and sanitizers in human and environment during COVID-19. The figure was created with [BioRender.com](https://www.biorender.com)

environmentally friendly antiviral nanocoated PPEs (Tyagi et al. 2021). However, antiviral nanoparticles such as silver (Ag), copper (Cu), copper oxide (CuO), and zinc (Zn) have been incorporated on surfaces and PPE textiles, and can be a viable alternative to chemical disinfection processes (Valdez-Salas et al. 2021; Ruiz-Hitzky et al. 2020). In a recent study, the nanodisinfectant has been evaluated as a reliable technique for efficient disinfection, reusing, and even antimicrobial promotion of surgical masks for healthcare professionals (Valdez-Salas et al. 2021). In addition, modern nanotechnology and nanomedicine approaches have been harnessed to develop disinfection and treatment strategies to tackle increasing infection cases worldwide, especially challenges posed by pathogens of viral origin (Nikaeen et al. 2020). Recently, more sophisticated and modern strategies, such as the use of agriculture spraying drones and robotic machines, have been suggested to disinfect areas that pose a high risk of infection, such as stadiums and theaters, in a short timespan (Clay and Milk 2020; Khan et al. 2021). Various nanomaterials such as carbon nanotubes, graphene, or silver nanowires have been used to improve current physical disinfection methods (Kumar and Mohanty 2020; Palmieri and Papi 2020; Ruiz-Hitzky et al. 2020). Furthermore, nanomaterials have been

proposed as possible disinfection candidates since they do not exhibit antiviral activities for single use but rather exhibit their action over a prolonged period of time (Campos et al. 2020; Ruiz-Hitzky et al. 2020), and this property can be used to produce sustainable and environmentally friendly disinfectants.

Furthermore, a recent study proposed that the use of a variety of physical techniques such as photolithography and laser surface modification, in conjunction with ion beam-assisted deposition, can be used to evolve biomaterial surfaces or self-cleaning surfaces with suitable topographical features and controlled cell adhesion (Kumari and Chatterjee 2021). In this sense, the antiviral behavior of aluminum surfaces with appropriately aligned ridges has been studied against SARS-CoV-2, and it was found that the self-disinfecting surfaces with coated nanoparticles are substantially effective against SARS-CoV-2 (Hasan et al. 2020a; Hasan et al. 2020b). Hence, the self-cleaning surfaces with minor deleterious consequences are incredibly effective at mitigating viral transmission by contact. Their ability should be explored further in the future to reduce the usage of chemical disinfectants.

Moreover, disinfectants are biocidal products; therefore, they are regulated by the Biocidal Products Regulation

(BPR) (EU) in European Union countries and are appropriately evaluated before marketing (EPC 2020). However, considering the urgency of addressing the COVID-19 pandemic, a few agents may be provided for developing transitional measures without BPR for immediate use against SARS-CoV-2, such as 70–80% ethanol application for 1 min (Kampf et al. 2020a). Most biocidal products with virucidal activity regulated under BPR are effective against SARS-CoV-2. This includes disinfectants used in hand hygiene and skin disinfection, albeit they may demonstrate limited biocidal activity against viruses or less remarkable activity against enveloped viruses (ECDC 2020). Hence, proper assessment before application and monitoring during use is of utmost importance for human health and environmental safety.

Appropriate use of disinfectants as recommended by various agencies should be practiced to counter SARS-CoV-2. The WHO (2020) has provided recommendations for the appropriate utilization of suitable disinfectants and at specified intervals. Similarly, cleaning and disinfection as per community facilities guidelines of the CDC (CDC 2020a) and disinfection as per quarantine facility guidelines of the NCDC (2020) may be helpful. However, any disinfectant, regardless of its nature and properties, used for disinfection under a selective environment must meet local authority specifications and be used in an eco-friendly and efficient manner to prevent environmental contamination (WHO 2020).

Important mitigation strategies to reduce the deleterious consequences of disinfectants in humans and the environment during the COVID-19 pandemic are presented in Fig. 3.

Sanitizers during the COVID-19 pandemic

Sanitizer is an antimicrobial liquid, gel, or foam that is used to reduce the number of microorganisms present on a surface. Although alcohol-based hand rubs and washing with soap and water are effective against CoVs, due to ease of utilization, hand sanitizers have gained more popularity than other available options, including washing with soaps, chemical disinfection, exposure to sunlight, UV light, or heating. The increased frequency of sanitizer usage due to fear of developing COVID-19 has resulted in increased aerosol generation and, in certain cases, poses a potential hazard to exposed mucosal surfaces and skin. The adverse effects of alcohol used in hand sanitizers can be manifold and may lead to a condition called sanitizer aerosol-driven ocular surface disease owing to the increased sensitivity of eyes to the toxic effects of these sanitizers compared to that of skin (Ahn et al. 2010; Shetty et al. 2020). There has been a significant increase in the number of ocular injuries from 2020 to 2021 in the pediatric population due to inefficient use of ABHSs (Martin et al. 2021).

However, a few associated problems are caused by the market formulations of available hand sanitizers, and the

capacity of chemists has increased manifold during the COVID-19 pandemic with emphasis on the use of hand sanitizers (Opatz et al. 2020). The use of hand sanitizers as a result of the COVID-19 pandemic has increased the number of cases of hand dermatitis in more than 90% of healthcare workers (HCWs) and hand eczema in nearly 14% of these cases (Guertler et al. 2020). Not all market formulations are effective for use. A screening of all WHO-recommended hand rub formulations (alcohol-based hand rubs) showed high virucidal activity with complete inactivation of SARS-CoV-2 (Kratzel et al. 2020). In this context, the Centers for Disease Control and Prevention (CDC) also recommended adopting practices for good hand hygiene, which includes proper handwashing with warm water and soap for a minimum period of 20 s and the use of ABHSs as the most effective approach to reduce COVID-19 infection (CDC 2020b; Schrank et al. 2020).

Life-threatening clinical effects can be attributed to acute ethanol intoxication. A case study reported by Lim revealed that hand sanitizer application did not interfere with the course of treatment of infectious spondylitis or cause abnormal complications. However, during the current COVID-19 pandemic, it is expected that such intoxications will increase due to the increased use of hand sanitizers (Lim 2020).

Additionally, the toxicity and harmful effects of alcohol-based sanitizers on skin and their excessive use gradually lead to natural mutations in microbes and can contribute to the issue of antimicrobial resistance, which is already a significant threat to developing countries and continents, such as India, Pakistan, Africa, and Bangladesh (Mahmood et al. 2020).

To prevent the hazardous effects of ABHSs, the use of soap and water should be encouraged in susceptible individuals. The use of a face shield or protective goggles would be beneficial, wherein the frequent cleansing of hands is unavoidable. Moreover, the closure of eyes while pressing the nozzle of the sanitizer and maintenance of proper distance by ensuring that the sanitizer is below the eye level. Furthermore, keeping doors and windows open and avoiding sanitizer usage when air conditioning systems are activated may help reduce exposure to sanitizer droplets. Additionally, the most effective approach to confer protection to the eyes and mucosal surfaces from the harmful effects of sanitizers is by minimizing their use.

Steps to be followed while using disinfectants (National Pesticide Information Center 2020; COVID-19 Prevention: Enhanced Cleaning and Disinfection Protocols 2020):

- Before using disinfectant, follow the precautionary statements on the accompanying label to prevent chemical exposure to self and surrounding individuals. Use appropriate recommended doses at appropriate intervals. Disinfectants containing 2 g/L chlorine need to be sprayed four times daily on highly infected areas (such as floors,

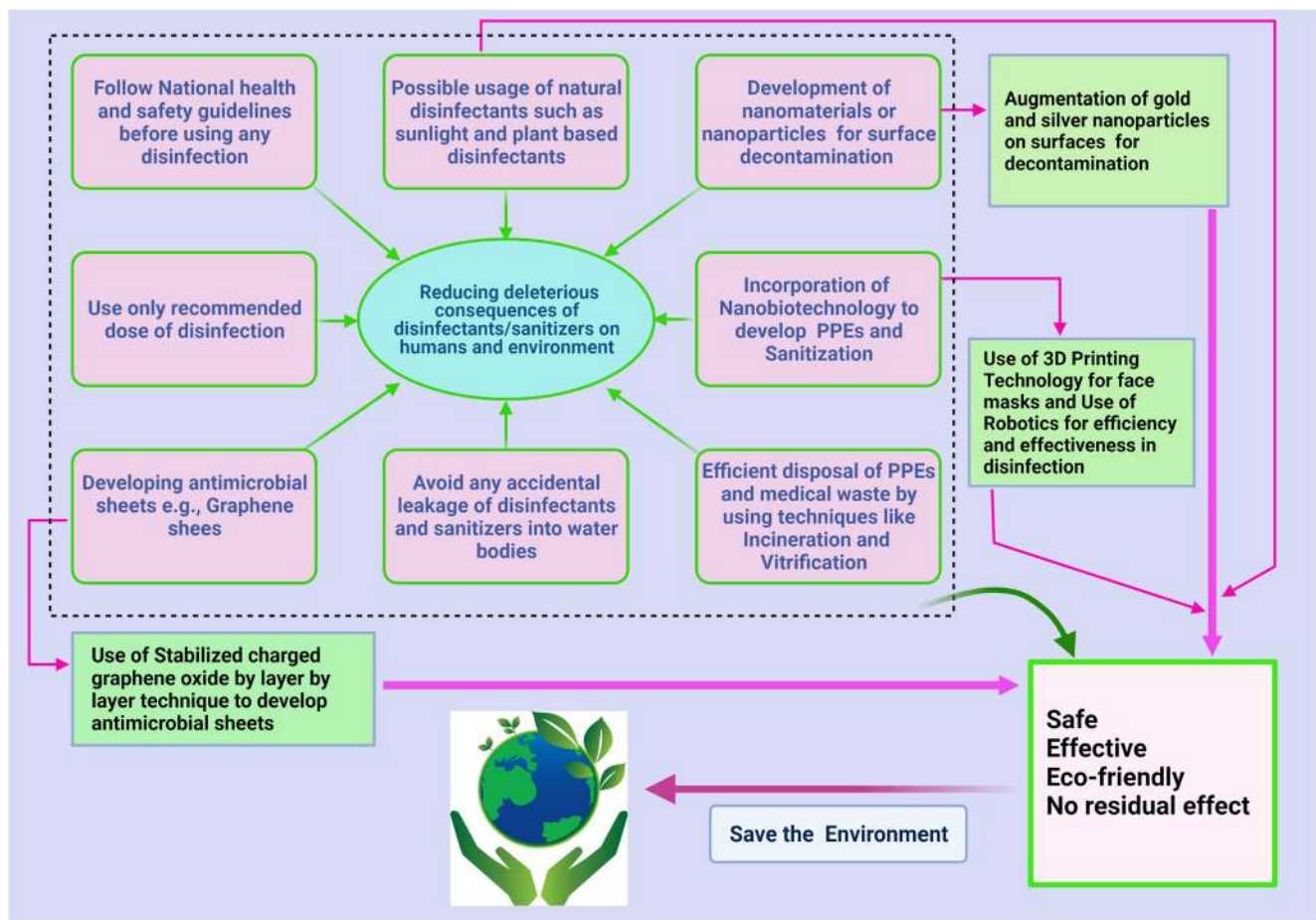


Fig. 3 Mitigation strategies to reduce deleterious consequences of disinfectants in human and environment during COVID-19 pandemic. The figure was created with [BioRender.com](https://www.biorender.com)

tables, and beds of the contaminated/isolated areas and hospitals) for 30 min. A concentration of 0.5 g/L of chlorine is recommended for semi-contaminated areas. In case dilution of the disinfectant is required, it should not affect the final recommended concentration and should never be used in combination with other compounds.

- While using disinfectants, wear appropriate PPE, such as goggles, gloves, long-sleeved shirts, long pants, and masks. The use of an appropriate mask for a specific purpose is essential rather than using any non-specific mask (Agrawal et al. 2020). For the community at large and for HCWs, surgical masks or three-layer cotton masks can be used. For HCWs during aerosol-generating procedures for a patient with COVID-19, respirator masks are recommended (Agrawal et al. 2020).
- Ensure proper ventilation while conducting disinfection. Chlorine-based disinfectants with usual concentrations of 4% and 6% or glutaraldehyde-based disinfectants with higher vapor levels than the recommended 1.12–3.4% especially require well-ventilated rooms (Ghafoor et al. 2021; Kampf et al. 2020). There should be exhaust duct hoods, air systems with 7–15 air changes per hour,

ductable fumigation hoods with disinfectant vapor absorbers, or straightener lids in dip baths (Foliente et al. 2001; Ghafoor et al. 2021).

- Keep disinfectants away from the reach of children and pets. Children are particularly susceptible to poisoning by disinfectants (Ghafoor et al. 2021) with ingestion being the common exposure route (Rosenman et al. 2021).
- Discard disposable protective items, such as gloves and masks, after using disinfectants, since they have limited efficacy (6–12 h) and are heat-sensitive, and thus, cannot tolerate the sterilization process (Rowan and Laffey 2020). Not only does the structure of PPE and masks change upon washing and drying, but changes are observed in also their quality and efficacy, such as through the deterioration of their filtration properties (Konda et al. 2020; Sharma et al. 2020).
- Wash hands with soap and water after conducting disinfection, and apply the appropriate hand sanitizer.
- Avoid spraying chloride- and hypochlorite-containing disinfectants to the most possible extent, as they are more harmful to surfaces, other organisms, and the environment than their alternatives (Lin et al. 2020); additionally, there

are currently related concerns surrounding the enrichment, bioaccumulation, and biomagnification of disinfectants (Chen et al. 2021). Alcohol-based disinfectants, soaps, and detergents along with water and radiation can be comparatively beneficial; nevertheless, all specified options are detrimental when adopted in excess.

Conclusion and future prospects

The COVID-19 pandemic ushered in several challenges with its emergence and seemed to be unrestricted through current mitigation strategies. Considering the urgency of the situation caused by the global spread of SARS-CoV-2 with rising morbidity, alarming mortality, and global economic fallouts, the trend of efforts is shifting from strategies of lockdown, quarantine, testing, isolation, and treatment to the creation of an atmosphere of clean, healthy, and safe surroundings that provides a healthy working environment. Several prevention strategies, such as avoidance of close contact with sick people; avoiding touching eyes, nose, and mouth; staying home when sick; covering the mouth when coughing and sneezing; and undertaking the approaches for frequent disinfection and sanitization of hands and touched objects, fomites, and surfaces, are important to prevent virus transmission. In this context, a variety of chemicals and other virucidal agents have been used globally as disinfectants to render the environment free from SARS-CoV-2 to the highest extent possible to prevent further spread. Disinfectants are proving to be beneficial in this regard and have gained considerable attention recently as being effective, affordable, convenient, and readily available antimicrobial agents. Applications have been identified in every aspect of life, including at home, the office, healthcare facilities, other industries, and the surrounding environment. However, there remain concerns regarding the side effects on animal and human health, the environment, and ecological balance.

There is an urgent need for developing eco-friendly technologies that offer safer and more effective disinfection methods to combat the ongoing pandemic, along with conferring protection to the environment and living beings from the potentially hazardous effects of chemical disinfectants. Alternate and improved strategies are being devised for minimizing adverse effects. In this context, the use of graphene sheets as coatings for face masks offers a promising strategy for fighting COVID-19 by minimizing the risk of further transmission. The graphene coating of face masks is of particular interest because it can be reused as it is superhydrophobic, thereby reducing the likelihood of adherence of infectious drops, and its strong light-absorbing properties renders sterilization upon exposure to sunlight possible. Moreover, nanotechnology and nanomedicine approaches have been harnessed to develop novel disinfection and treatment strategies to tackle this pandemic more effectively.

The current pace of research and the evolution of numerous novel disinfectants against COVID-19 provides hope for the development of safe, effective, and convenient disinfectants that are affordable to all and accessible under diverse environments with minimum or no potential risk to health and surroundings. Meanwhile, during disinfectant use, precautionary and preventive measures should be adopted. An environmental impact assessment of the escalating use of disinfectants is urgently needed. Clear and comprehensive guidelines for disinfectant application are also necessary at regional, national, and international levels to reduce the deleterious consequences to both humans and the environment.

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Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

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