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SHORT RESEARCH AND DISCUSSION ARTICLE

Resolving the "health vs environment" dilemma with sustainable disinfection during the COVID-19 pandemic

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Abstract
The overuse of disinfection during the COVID-19 pandemic leads to an emerging "health versus environment" dilemma that humans have to face. Irresponsible and unnecessary disinfection should be avoided, while comprehensive evaluation of the health and environmental impacts of different disinfectants is urgently needed. From this discussion, we reach a tentative conclusion that hydrogen peroxide is a green disinfectant. Its on-demand production enables a circular economy model to solve the storage issues. Water, oxygen, and electrons are the only feedstock to generate H_2O_2. Upon completion of disinfection, H_2O_2 is rapidly converted back into water and oxygen. This model adopts several principles of green chemistry to ensure overall sustainability along the three stages of its whole life cycle, i.e., production, disinfection, and decomposition. Physical methods, particularly UV irradiation, also provide sustainable disinfection with minimal health and environmental impacts.

Keywords Chemical safety · Health vs environment · Sustainable disinfection · Circular economy · On-demand production · UV irradiation · Hydrogen peroxide

The "health versus environment" dilemma

Health, safety, and environment (HSE) is deemed as a unity that is critical to sustainable and high-quality development of human society. However, the on-going COVID-19 pandemic provokes an unusual conflict between health and environment, i.e., the excessive use of disinfectants during the pandemic harms the environment and the ecosystem. As far as safety and health are concerned, effective disinfection is essential in hospitals, airports, train stations, and other densely populated public indoor spaces during the pandemic. Meanwhile, the surging use of disinfectants and antiseptics poses risks of air (Lou et al., 2021) and water (Chu et al., 2021) pollution, ecological risks (Cui et al., 2021), antibiotic resistance, and biodiversity loss (Lu and Guo, 2021). The polluted water and air in return causes human health concerns (Ghafoor et al., 2021). These complex conflicts among biosafety, human health, and the environment are becoming an unfamiliar dilemma and grand challenge that the humans have to face today and in the future.

There is no point to use antibiotics during the pandemic (Chen et al., 2021) since they only inactivate bacteria but not virus. Large-scale spraying or fumigation of chemical disinfectants in outdoor spaces such as streets should also be cautious and is not recommended by the WHO (2022), because of the following three reasons: (1) the outdoor areas not considered potential routes of infection, (2) the disinfectants are easily inactivated in presence of dirt, (3) the residue and by-product of disinfectants are health and environmental hazards. Early study by van Doremalen et al. (2020) reveals that the virus remains infectious for several hours in aerosol and up to days on surface. However, Zhang et al. (2022) show that the exposure by aerosol inhalation is 1000 times higher than by contact of contaminated surface. Therefore, prudent evaluation of the exposure risks is required in order to avoid unnecessary or pointless disinfection, particularly large-scale deployment such as spraying squads, vehicles, robots, or drones. The irresponsible mass use of disinfectants is believed to be associated with misinformation,

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unnecessary panic and anti-rationalism among the public (Prasad, 2022), as well as bureaucracy and wrong decision-making of governing agencies. Sensible and responsible use of disinfectants under recommended guidelines (Cui et al., 2021) alleviates the environmental burdens to some extent. On the other hand, switching into more environmentally friendly disinfectants may offer an inherently effective solution to this complex dilemma.

Comprehensive evaluation of the health and environmental impacts of disinfectants

Different disinfectants vary in their biocidal mechanisms and disinfection by-products. The residual disinfectants and by-products can cause different health, environmental, and ecological hazards (Table 1). Quaternary ammonium compounds (QAC) enter the environment as both water and soil pollutants. Upon adsorption on fine particles, QACs also form air pollutants that can enter the human body by both inhalation and ingestion (Dewey et al., 2022). Sodium hypochlorite (bleach) is a potent oxidative disinfectant, whose residue and by-products mainly form water and air pollution. The airborne pollutants cause various respiratory damages/diseases. When dissolved in water, it leads to the formation of N-nitrosodimethylamine (NDMA) in presence of organic nitrogen (Mitch and Sedlak, 2002). NDMA is a persistent and highly hepatotoxic carcinogen with allowable levels as low as 10 ng/L. Both QACs and hypochlorite have been identified as phytotoxins (Cui et al., 2021) and incur anti-microbial resistance (Jia et al., 2022), but their other ecological effects remain unclear. In fact, there still lacks a method for quantitative and comprehensive evaluation of the life-cycle health and environmental impacts of these disinfectants. Alcohols such as ethanol and isopropanol are one of the most commonly used disinfectants. They are generally considered safe as handwash or rub, but large-scale use for air and surface disinfection is still not completely safe, particularly to the vulnerable population such as children and pregnant women. To effectively inactivate virus, a high concentration (≥75%) is often required, which leads to the release of volatile organic compounds, i.e., VOC pollution. Nonetheless, alcohols pose much lower health and environmental concerns compared to QACs and chlorine-based disinfectants.

What makes a sustainable disinfectant?

Hydrogen peroxide (H_2O_2) is also a widely used disinfectant with low potential health and environmental risks, as compared to the QACs or chlorine-based disinfectants. Vaporized H_2O_2 (VHP) at ppm level is proven effective for disinfection of PPEs (Cheng et al., 2020), hard surfaces, and indoor air (Poppendieck et al., 2021) during the pandemic. Its biocidal effect originates from radical-induced oxidation of DNA, proteins, and membrane lipids (Linley et al., 2012), which is unlikely to develop antibiotic resistance in pathogens (Khan et al., 2019). With a short half-life of 24 h in atmosphere and several hours in water (Subpiramaniyam, 2021), H_2O_2 eventually decomposes into water and oxygen, causing no secondary pollution or bioaccumulation. Despite its potent biocidal effects, VHP at concentrations up to 0.5% induces no skin irritation or inhalation toxicity in animal tests (Mohanan et al., 2021). The health risk by inhalation is also low if the VHP spraying time is precisely calculated according to the room size (Hesam et al., 2022). Upon completion of VHP disinfection, the residual H_2O_2 concentration drops to 0.6 ppm in 2 h on fabrics (Cheng et al., 2020), lower than the 1 ppm ACGIH threshold limit value. Although long-term inhalation of H_2O_2 at 10 ppm and above does induce adverse effects in the respiratory track (Hartwig 2019), its fast decomposition and low usage can offset its potential long-term health risks. Due to its inherent safety to humans, the environment, and ecosystem, H_2O_2 has been proposed as a sustainable alternative for tap water disinfection instead of the conventional chlorination (Richards et al., 2021).

With the similar oxidation-based biocidal mechanism and safe by-product (oxygen), ozone has been manifested as a powerful disinfectant for airborne virus, but much less effective for contaminated surfaces (Mazur-Panasiuk et al., 2021). However, ozone is classified as an air pollutant with multiple health risks, and hence is not as safe as H_2O_2. H_2O_2 is also greener and safer than alcohols because: (1) its usage

Table 1 An incomplete list of health, environmental, and ecological risks of three commonly used disinfectants, i.e., quaternary ammonium compounds, sodium hypochlorite, and alcohols (source: Dewey et al., 2022; Cui et al., 2021; Parveen et al., 2022; Ria et al., 2020)

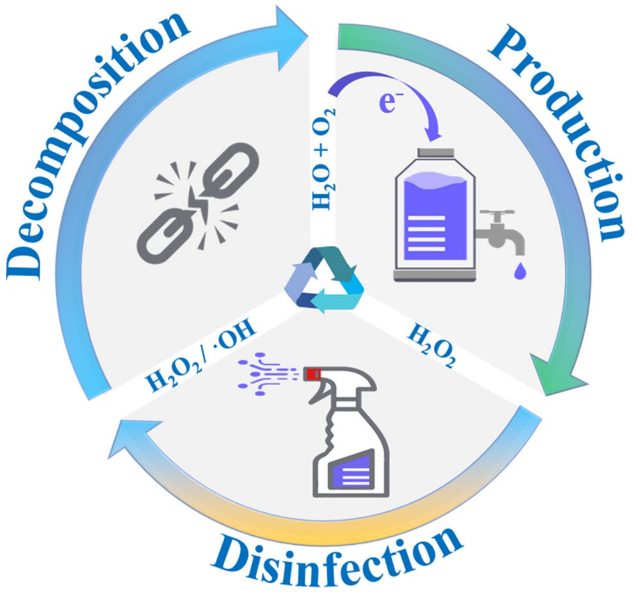
	Health risks	Environmental and ecological risks
Quaternary ammonium compounds	Asthma, chronic obstructive pulmonary disease, reproductive toxic	Water, soil, and air pollution, eco-toxicity, phytotoxicity, food chain accumulation, anti-microbial resistance
Sodium hypochlorite	Damage to airway and respiratory systems, carcinogenic	Water and air pollution, phytotoxicity, corrosive, anti-microbial resistance
Alcohols	Irritant to eyes and airways	Air pollution, anti-microbial resistance

is low since the required concentration of alcohol is outstandingly higher, (2) alcohols can be oxidized to acetaldehyde and yields ozone which produces peroxyacetyl nitrate (PAN) in presence of NO_x (Willey et al., 2019). To sum up, H_2O_2 is a highly effective yet environmentally-benign disinfectant because of its low usage, short half-life, low likelihood of antibiotic resistance, and human and ecological safety. Likewise, a comprehensive assessment of all these aspects (Fig. 1) is highly recommended for future evaluation and comparison of the environmental impact of different disinfectants.

A circular economy model for sustainable disinfection enabled by on-demand production of green disinfectants

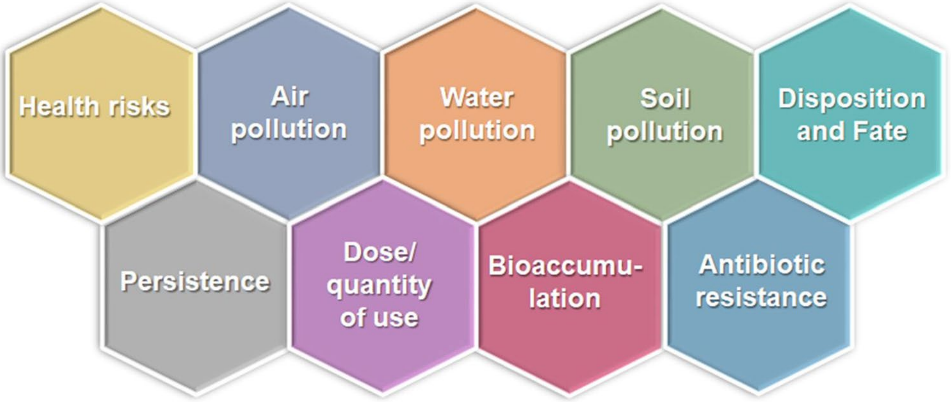
In spite of these multiple HSE benefits, high quantity use of H_2O_2 can be troublesome because of the inventory, logistic, and storage issues, particularly considering its fast self-decomposition. At the outbreak of a pandemic, H_2O_2 also suffers from supply shortages. In situ on-demand production by electrochemical reduction of oxygen (ORR) from air is a promising technology to produce H_2O_2 for disinfection. The key performance parameters of this technology include the ORR selectivity, energy consumption, H_2O_2 concentration, cost, scalability, and stability of electrodes. Current electrode materials are unable to simultaneously meet all requirements, i.e., carbon-based electrodes are generally low in selectivity and energy efficiency, while emerging nanomaterials and precious metals (Richards et al., 2021) are costly and difficult to scale up. A recent work (Wang et al., 2021) reports that H_2O_2 at a concentration of 240 ppm can be obtained on carbon cloth modified with conducting polymer PEDOT. This process shows high selectivity toward H_2O_2 (current efficiencies up to 88.7%), with a low electric energy consumption of 4.7 kWh/kg H_2O_2. Moreover, the electrode is made of low-cost commercial materials that can be easily scaled up to meet commercial demands. This inherently green technology uses only air and electricity to produce H_2O_2 that can be used directly for disinfection or converted to more oxidizing hydroxyl radicals. A more recent report (Li et al. 2022) achieved a record-high H_2O_2 concentration of 20 g/L using gas diffusion electrode in a divided electrolyser.

Combining the efficient on-demand production and the aforementioned HSE benefits, we propose a H_2O_2-based circular economy model for sustainable disinfection (Scheme 1). In the production stage of this model, the input materials are water, oxygen, and electrons. The in situ produced H_2O_2 serves as a green disinfectant and may turn into even shorter-lived hydroxyl radicals or other reactive oxygen species (ROS). Upon completion of disinfection, H_2O_2 and ROS decompose into their original feedstock, water and oxygen, completing the circular economy model as shown in Scheme 1. Therefore, the on-demand production overcomes the storage issue of H_2O_2, fully



Scheme 1 A circular economy model for H_2O_2-based sustainable disinfection

Fig. 1 List of criteria for assessing the environmental and ecological impacts of disinfectants



unlocking its potential as an effective and intrinsically green disinfectant. The concept of circular economy has been proposed as a more sustainable solution than the end-of-pipe technology toward pollution control and resource efficiency. In this perspective, it also offers a feasible solution to tackle the "health versus environment" dilemma caused by the COVID-19 pandemic. The life cycle sustainability of this model is because it adopts several principles of green chemistry, i.e., catalysis, prevention, safer chemicals, renewable feedstock, design for degradation, and inherently safer chemistry. Solving global chemical safety issues not only requires planning and management, but also relies on intrinsically greener chemistry and processes.

Physical methods as alternative disinfection

Disinfection free from chemicals is also feasible in many cases. For hand hygiene, washing with soap and water is an effective yet safe and green method (Mahmood et al., 2020). Heat treatment at 75 °C for 30 min has been proven effective in disinfecting contaminated N95 masks without lowering their filtration efficiency (Campos et al., 2020). Ultraviolet (UV) irradiation shows efficacy and several advantages as a ubiquitous physical disinfection method. The UVC spectra between 200 and 280 nm are generally effective toward the coronavirus (Raeiszadeh and Adeli, 2020), though Ma et al. (2021) further point out that the far UVC region (<230 nm) shows the highest effectiveness. UV is able to achieve efficient and rapid virus reduction at relatively low energy input between 2 and 40 mJ/cm^2 (Raeiszadeh and Adeli, 2020), while being safe and environmentally friendly. The application of UV spans from wastewater treatment to air and hard surface disinfection. One major safety consideration is that UV exposure can cause eye and skin damage. Therefore, it is imperative for people to evacuate prior to operation of the UV lamp, while the operators and other on-site personnel should wear personal protective equipment. Another potential hazard of UV disinfection is that ozone is inevitably generated from atmospheric oxygen. This problem can be mitigated by ventilation or filtration (Tang et al., 2022) after the disinfection, to reduce the ozone concentration below the TVL value of 0.1 ppm. UV irradiation can be coupled with photocatalysts, such as titanium dioxide (TiO_2), to generate highly oxidizing radicals and achieve more potent virus eradication. This strategy is particularly effective at treating virus laden aerosols. Another physical method for aerosol disinfection is the use of non-thermal plasma (Mohana et al., 2021), though it is not as energy efficient as the combination of UV with photocatalyst.

Summary and recommendations

The increased use of disinfectants during the COVID-19 pandemic poses health risks to humans and adverse impacts to the environment and ecosystem. There is still a lack of method for quantitative and comprehensive evaluation of the life cycle health and environmental impacts of different disinfectants. From our discussion above, to achieve both effective disinfection and minimal HSE impact, we give tentative suggestions as follows. For hand hygiene, soap and water handwash and alcohol sanitizer are both sufficient for removing pathogens. For disinfecting N95 respirators, other PPEs, or apparatus, heat, UV irradiation, and H_2O_2 vapor treatment are recommended. For wastewater treatment, advanced oxidation processes based on radical chemistry or UV irradiation are optimal choices. For decontaminating surfaces, effective scrubbing or cleaning, followed by H_2O_2 vapor and UV irradiation are prioritized methods. For air disinfection, H_2O_2 vapor, UV irradiation, or photocatalyst-based air filter coupled with UV are recommended.

Author contribution Chuang Peng and Tao Wu conceptualized and supervised this work. Wanru Chen prepared the original draft. Hangqi Yang contributed to the literature survey and preparation of the figure. All authors read and approved the final manuscript.

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Declarations

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