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The practicality and prospects for disinfection control by photocatalysis during and post-pandemic: A critical review

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ABSTRACT

The prevalence of global health implications from the COVID-19 pandemic necessitates the innovation and large-scale application of disinfection technologies for contaminated surfaces, air, and wastewater as the significant transmission media of disease. To date, primarily recommended disinfection practices are energy exhausting, chemical driven, and cause severe impact on the environment. The research on advanced oxidation processes has been recognized as promising strategies for disinfection purposes. In particular, semiconductor-based photocatalysis is an effective renewable solar-driven technology that relies on the reactive oxidative species, mainly hydroxyl (•OH) and superoxide (•O2−) radicals, for rupturing the capsid shell of the virus and loss of pathogenicity. However, the limited understanding of critical aspects such as viral photo-inactivation mechanism, rapid virus mutagenicity, and virus viability for a prolonged time restricts the large-scale application of photocatalytic disinfection technology. In this work, fundamentals of photocatalysis disinfection phenomena are addressed with a reviewed remark on the reported literature of semiconductor photocatalysts efficacies against SARS-CoV-2. Furthermore, to validate the photocatalysis process on an industrial scale, we provide updated data on available commercial modalities for an effective virus photo-inactivation process. An elaborative discussion on the long-term challenges and sustainable solutions is suggested to fill in the existing knowledge gaps. We anticipate this review will ignite interest among researchers to pave the way to the photocatalysis process for disinfecting virus-contaminated environments and surfaces for current and future pandemics.

1. Introduction

The advent of novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first declared in Wuhan (China) in December 2019 (Contreras et al., 2020). Since then, the world population has been drenched under an unprecedented health emergency that has not been experienced from the time of the Spanish flu (WHO, 2020b). The progression of coronavirus infectious disease 19 (COVID-19) from epidemic to global concern was in a trice with fatal consequences (Del Rio and Malani, 2020). The still escalating COVID-19 pandemic continues to ravage the world by infecting 229 M and causing fatalities over 4 M as of September 21, 2021 (Worldometer, 2021). A paradigm approach of strategic preparedness and timely communal response were instigated to fight against the high-risk contagiousness of SARS-CoV-2. In the initial phase of pandemic situation, many countries imposed mandatory lockdown and isolation of infected people in quarantine centers to subsidize the community spread of COVID-19 (Kumar et al., 2021b; Phan et al., 2020). Despite the stringently enforced lockdown attempts, the scaling up rates of COVID-19 cases was observed worldwide. The principal virus transmission routes of COVID-19, as reported...
by the World Health Organization (WHO), include direct contact with fomites, infected persons, and inhalation of respiratory droplets (Organization, 2020).

Recent studies have indicated an even more crucial concern of waterborne transmission of the SARS-CoV-2 into the sewage system by the fecal-oral way (Bishai, 2021; Teymoorian et al., 2021). During the early stage of the epidemic, Medema et al. conducted sewage surveillance of six cities in the Netherlands and reported the presence of 2.6–3.0 genes copies per mL by March 4, 2020. With the prevalence of COVID-19, the SARS-CoV-2 RNA increased up to 790–2200 gene copies per mL, indicative of sewage monitoring a critical subject to control virus spread (Medema et al., 2020). An experimental survey was performed at Ahmedabad wastewater treatment plant from September 3, 2020 to November 26, 2020 wherein 116 wastewater samples were analyzed, out of which 111 samples were detected with SARS-CoV-2 genes. A sharp increment in effective gene concentration was observed in October (<454 copies/L) < September (<3047 copies/L) < November (<10,729 copies/L) with the quantification of infected individuals (Kumar et al., 2021c). A conceptual proof study was established by Ahmed et al. in the untreated wastewater in Australia, confirming the quantitative predictions of viral RNA concentrations measured to the actual number of COVID-19 cases (Ahmed et al., 2020). Likewise, the samples collected from secondary treated wastewater were examined for the existence of SARS-CoV-2 in Japan (Haramoto et al., 2020). Similarly, several other reports corroborate viral transmission to wastewater which might intensify the alarming pandemic. Furthermore, another risk factor arises from the airborne transmission, where the air serves as a vector to carry droplet nuclei for up to 3 h after being coughed or sneezed out by an infected person (Aydogdu et al., 2021). An additional implication is the viability of the SARS-CoV-2 for a prolonged period of 21 days in the soil load (Kasloff et al., 2021). The surface stability of SARS-CoV-2 was evaluated by Doremalen et al. over different fomites at a temperature range of 21–23 °C with a 50% tissue culture infectious dose per mL. The experimental results indicated viability of SARS-CoV-2 up to 3 h in air, 4 h on copper, 24 h on cardboard, 48 h on steel, and more than 72 h on plastics (Van Doremalen et al., 2020). The possibility of fomite transmission is considered hypothetical and minor compared to direct contact, aerosol/droplet transmission, or waterborne route (for Immunization, 2021). The principal perception to reduce the risk of being infected by SARS-CoV-2 is blocking the transmission route.

Fig. 1. Schematic illustration showing advantages and disadvantages of different types of disinfection methods.
Future research is intended to flatten the SARS-CoV-2 transmission by the scaling-up innovation of various disinfection technologies. Fig. 1 summarizes various virus disinfection methods with their unique advantages and disadvantages. The two broad categories of conventional disinfection routes are physical and chemical techniques. The physical disinfection techniques involve heat sterilization, adsorption, UV-irradiations, electronic radiations, exposure to gamma rays.

In contrast, chemical disinfection involves the application of chemicals to disinfect the virus. The most common chemical derived method is chlorination (using chlorine gas, chloramines, hypochlorite solution, chlorine elements) as oxidizing agents to combat the viral particles. For instance, 20 mg/L chlorine dioxide resulted in complete inactivation for SARS-CoV within 30 min, yet the chlorination method is opposed owing to the inevitable generation of carcinogenic and mutagenic by-products (Wang et al., 2005). The chemical-free UV radiation technology (photolysis) has been a fast-growing classical disinfection strategy during the COVID-19 pandemic (Ontiveros et al., 2020). However, the cost-inefficiency due to the continuous requirement of electric supply and the usage of toxic mercury lamps with a short life-span appears to be the major drawbacks of this technology. On the contrary, UV-light emitting diodes (UV-LEDs) overcome the issue associated with the toxicity of mercury lamps; nonetheless, the low wall plug efficacy values and comparatively high costs still limit the wide-scale applicability of UV-LEDs (Moreno-Andrés et al., 2020). Overall, the existing conventional methods have not been applied on an industrial scale and are at an intermediate level due to their lack of information on reactor designs, chemical reactions, and the impact of operational variables.

Thereby, in response to the step-wise intensifying situation of COVID-19, the worldwide requirement of environment-friendly advanced oxidation processes (AOPs) serves as a potential substitute to conventional disinfection techniques (Nasir et al., 2021). The AOPs include ozonation, photo-Fenton, ultrasound, and photocatalysis, which have efficiently treated virus contamination, as demonstrated in Fig. 2. The AOPs curb the alleviation of infectious viruses in the environment by generating reactive oxidative species (ROS) such as hydroxyl (•OH), superoxide (•O2−), holes (h+), and peroxide (O22−) radicals (Gan et al., 2013; Kokkinos et al., 2021; Li et al., 2018b). The potent method ozonation utilizes ozone (O3) as an oxidizing agent, which has exhibited excellent performance against waterborne viruses, including rotaviruses, Ebola virus, feline calcivirus, and hepatitis A virus (Bayarri et al., 2021).

**Fig. 2.** Diagrammatic representation of significant advantages and disadvantages of various types of advanced oxidation processes (AOPs).
Several evident reports suggest ozone effectiveness against airborne and surface viruses, though the kinetics are slightly lower than in aqueous solution (Tseng and Li, 2008). The Fenton-based AOPs ($\text{H}_2\text{O}_2/\text{Fe}^{2+}$) mechanism depends on the selection of iron-based catalysts, accompanied by limitations; solubility of iron species, continuous pH monitoring, and sludge formation due to the accumulation of iron hydroxide as a secondary product (Giannakis et al., 2017).

Solar-driven semiconductor photocatalysis is a cost-effective, renewable, and environment-friendly process that could overcome the limitation of harmful by-products generation for an effective viral inactivation mechanism (Hasija et al., 2021a; Kumar et al., 2020a; Sharma et al., 2019). It is worth clarifying that the photocatalytic viral inactivation process is targeted on the structure of the virus involving genetic core (RNA or DNA) damage, protein oxidation, and shape rupture/distortion. The viral inactivation by photocatalysis process is proposed by three routes (Zhang et al., 2019); (i) physical damage of capsid protein shells of viruses which causes their inactivation. (ii) Metal ion toxicity in synergy with photocatalysis induces the release of metal ions upon the surface to fasten the viral inactivation kinetics. (iii) Chemical oxidation is the most effective photocatalytic virus disinfection process due to reactive oxidative species targeting the virus-cell wall and cytoplasmic membrane leading to inactivation. Concerning photocatalysis as an alternative route for combatting the SARS-CoV-2, understanding the actual mechanism of virus inactivation is vital. Typically, photocatalytic viral disinfection involves the generation of electron-hole pairs after illuminating the semiconducting material with light having a wavelength more than or equal to the bandgap energy. After that, the photoinduced charge carriers further interacts with $\text{H}_2\text{O}$ and $\text{O}_2$ to generate ROS such as $\cdot\text{OH}$, $\cdot\text{O}_2^{-}$, and $\text{H}_2\text{O}_2$. The resulting ROS attacks the cell membrane and boosts the protein capsid rupture leading to eflux of viral RNA surrounded by the protein layers. As a result, the coenzyme A present in the cell membrane got damaged and inhibited the respiration of the cell, which eventually led to the deactivation of the cell (Hasija et al., 2021b; Parra-Ortiz and Malmsten, 2021). However, developing a deep understanding of the major steps involved in the interaction of the virus with host cells, such as cellular linking and entry, replication of the viral genome, and viral proteins expression. Lastly, the assembly, maturation, and exocytosis can further help to boost photocatalytic viral inactivation. To date, diverse photocatalysts have been explored for photocatalytic viral inactivation; however, the research from bench to extensive scale application of photocatalysts is still in infancy.

In this context, the article aims to exemplify mechanic insights of virus disinfection by the semiconductor photocatalysis process to address the problem of the pandemic era. The review begins with assessing current implications due to COVID-19 and an overview of the widespread prevalence of SARS-CoV-2 in the environment. We present a brief account of the currently practiced disinfection technologies and possible limitations. The highlight of the review is to make readers understand the potentials of photocatalysis in relevance to virus disinfection phenomena. An elaborative discussion on the reported literature represents the role of photocatalysts for virus inactivation, considering the types, modalities, and practical aspects of photocatalytic disinfection technology. At last long-term challenges concerning the photocatalytic virus inactivation phenomena with possible sustainable solutions during the pandemic and beyond are proposed.

2. Current research on continuous disinfection control strategies

The world is focusing on the applicability of several types of physical and chemical disinfection methods to battle against the novel coronavirus and controls its spread (Ghappure et al., 2020). During the rapid spread of COVID-19, the immediate communal response has augmented the frequency of disinfecting surfaces, thereby stretching the bulk production of chemical disinfectants. The WHO recommended that the most pragmatic way to prevent SARS-CoV-2 is via frequent disinfection using alcohol-based formulations (WHO, 2020a). Being an enveloped virus, SARS-CoV-2 is easily prone to disruption with disinfectants in the name of sanitizers (Hirose et al., 2021). For instance, during the peak spread of SARS-CoV-2 infection in China, massive production of disinfectants (4597 t/d), antiseptics (205 t/d), and ethanol for medical usage (906 t/d) was observed with huge spike in the sales of hand-sanitizer (2, 315%) on Sunning e-commerce platform (Allison, 2020; News, 2020a). Similarly, in Japan, a hefty hike in alcohol disinfectants (2,000%) was reported by a local company in April 2020 to overcome the shortage (News, 2020b). In the same way, an apparent spike of 166% and 343% of multipurpose cleaner and aerosol disinfectant, respectively, was seen in the USA, which drastically affected their supply chain (Guynn, 2020).

Interestingly, a total of 1,963.58 t of disinfectants were utilized for wastewater disinfection in Wuhan between 29 January to 18 February 2020 (net, 2020). Notably, for efficient SARS-CoV-2 disinfection at the surface, keeping the ethanol content up to 62-71% or 0.1% of sodium hypochlorite in conventional disinfectants (Kampf et al., 2020). However, the huge increment in the usage of antiseptics and disinfectants possessing corrosive chemicals can be substantially harmful for the urban lives, ecosystem along with extensive energy waste (Klemes et al., 2020).

Another pivotal low-cost approach is the chlorination process applicable on a large scale, as reported by the experiment of Zhang et al. wherein a high dose of sodium hypochlorite is used to disinfect SARS-CoV-2 contaminated hospital sewage (Zhang et al., 2020). One of the significant challenges during the chlorination process is the presence of ammonia and excessive generation of residual by-products. Other than liquid disinfection, the alternative vastly employed disinfection technique is exposure to UV-irradiations. Disinfection efficiency of UV was reported by Darnell et al. wherein the complete inactivation of SARS-CoV was claimed with 6 min of 254 nm light irradiations (Darnell et al., 2004). Also, the high oxidizing potential of ozone has been exploited for virucidal activity. Ronaldo et al. claimed a reduction in efficiency of $2 \log_{10}$SARS-CoV-2 after exposure to ozonated water for 60 s (Martins et al., 2021). A synergistic outcome of UV-illumination, ozonation, and chlorination has been reported to inactivate 99.99% of SARS-CoV-2 in wastewater (Koivunen and Heinonen-Tanski, 2005). The surge in the employment of UV chambers, UV-driven sterilization devices, UV-disinfection trolleys, honeycomb air heater-based systems, and fogging towers against SARS-CoV-2 is accompanied by major concerns involving lack of safety protocols and release of chemicals in the

![Fig. 3. Proposed viral inactivation mechanisms induced by photocatalysts.](image-url)
environment (Sarada et al., 2020).

However, to optimize the energy consumption and environmental footprints of these techniques, a more in-depth assessment is required with a potential alternative for disinfecting water, air, and surfaces. Certainly, photocatalysis is an advanced “green disinfection” strategy targeted for wide-scale viruses present in surface, air, and wastewater owing to the high redox abilities of produced ROS. (Byrne et al., 2015; Kühn et al., 2003). However, the exact mechanism of photocatalytic semiconductors against viruses is not explored substantially. However, from the present research, it is supposed that photocatalysis has shown significant antiviral activity by employing various semiconductor materials under UV-visible irradiation, which instigate researchers to exploit photocatalysis against SARS-CoV-2 further. Collaborative research in this perspective can be of significant interest to overcome the challenges accompanying conventional treatment methods owing to the resistance of virus via mutations.

3. Semiconductor photocatalysts

Semiconductor photocatalysts have gained significant consideration in recent years owing to their great potentials in emerging renewable energy technologies, along with environmental protection and remediation (Kumar et al., 2020b, 2021a; Raizada et al., 2020b). To date, various semiconducting materials such as metal oxides (Bazzill, 2011; Raizada et al., 2020b), metal sulphides (Munyai and Hintso-Mhita, 2021; Sharma et al., 2021), metal-free (Hasija et al., 2021a; Li et al., 2017), bismuth-based (Meng and Zhang, 2016) and organic frameworks (Patia et al., 2020; Xia et al., 2021) have been explored with different photocatalytic applications. For the disinfection of pathogenic microorganisms, photocatalytic materials offer significant potential to generate ROS including •OH, H2O2, H+, and •O2− after the electronic excitation under visible light irradiation. The following section will summarize an all-inclusive discussion on types, modalities, the role of photocatalysis, and practicability aspects of semiconductor-based photocatalysts for the disinfection process.

3.1. Role in disinfection

After exposing a semiconductor photocatalyst under light illumination, the absorption of a photon (hv) having energy greater than or equal to the semiconductor bandgap tends to excite the electron from VB to CB, leading to the generation of e−-h+ pairs, as shown in Fig. 3. Considering TiO2 as an example, the initial steps of excitation and consequent generation of e−-h+ pairs can be represented as (Dalrymple et al., 2010):

\[ \text{TiO}_2 + hv \rightarrow e_{cb}^-(\text{TiO}_2) + h_{vb}^+(\text{TiO}_2) \]  

The next step involves the interaction of holes with H2O or hydroxide ions (OH−), leading to highly reactive •OH radicals. Typically, the generated •OH radicals are attached with the hydrated TiO2 and participate in photo-oxydation reaction as chief oxidative species (Ilermann, 1999; Wong and Chu, 2003), represented by Eqs. (2) and (3):

\[ h_{vb}^+ + \text{Ti}^{IV} \rightarrow \text{Ti}^{III} + •O \]  
\[ h_{vb}^+ + \text{Ti}^{IV} + \text{OH}^{-} \rightarrow \text{Ti}^{III} + •OH \]  

The oxidation of compounds can be directly carried by h_vb only before their capture within the particle or at the surface of it. Moreover, the chemical features of the compound, along with reaction conditions, mainly dominate the degradation mechanism. Even though the presence of •OH radicals is significantly crucial for complete photocatalysis of pathogenic microorganisms as investigated by Cho and his co-workers for photo-inactivation of E. coli (Cho et al., 2004). On the other side, the e_{cb} are trapped at the Ti^{IV} surface sites resulting into the formation of Ti^{III}. The surface adsorbed oxygen at Ti^{III} sites participates into the formation of •O2− radicals via charge transfer process as shown by Eqs. (4) and (5):

\[ Ti^{IV} + e_{cb}^- \rightarrow Ti^{III} \]  
\[ Ti^{III} + O_2 \rightarrow Ti^{IV} + •O_2^{-} \]  

Therefore, the generation of ROS by utilizing semiconductor photocatalysts under the exposure of evergreen sunlight makes the process particularly attractive and viable for the disinfection process. Moreover, it has been observed that photocatalysis enables oxidation of most of the organic compounds which are present in the microorganisms as 96% of the cell’s dry weight contains macromolecules involving proteins, lipids, poly saccharides, lipopolysaccharide, and nucleic acids (Dalrymple et al., 2010). The rest, 3% of the dry weight, comprises amino acids, nucleotides, sugars, and monomer precursors, with the remaining 1% inorganic ions. Interestingly, TiO2 has been reported to damage amino acids and DNA under photocatalytic conditions as an effective semiconductor material. However, the complex constituents of microorganisms possess distinct physicochemical resilience to safeguard cell survival.

Moreover, apart from the individual features of these components, the structural arrangements confer extra resistance to inactivate pathogens and microorganisms. However, there still exist major concerns related to photocatalytic disinfection which needs further research attention, such as i) which particular set of routes cause inhibition and inactivation of microorganisms? ii) under what period and reaction conditions does the process of cell inactivation occur? and iii) how does the photo-disinfection process vary with different microorganisms? In order to clarify these questions, different mechanisms of cell destruction have been proposed based on the most critical targets at extracellular sites and intracellular sites of cells (Dalrymple et al., 2010). Nevertheless, the problem of photocatalyst’s size, agglomeration in water, restricted diffusion of surface-bound radicals, and encounter of released radicals with oxidizable substrates of cell wall further makes the process a little complicated to understand. Moreover, besides a direct attack, •O2− radicals and H2O2 inside the cell tend to form •OH radicals by Fenton’s process involving free iron (Arun et al., 2019). Furthermore, as a result, •OH radicals are free to attack the biomolecules present inside the cell.

3.2. Types and modalities

3.2.1. Types

In 1985, for the very first time, Matsunaga and his co-workers reported the biocidal activity of nanomaterials (Pt loaded TiO2) under the photo-illumination, causing the oxidation of coenzyme A followed by photochemical oxidation of cell wall leading to the inhibition of cell respiration (Matsunaga et al., 1985). After this discovery, TiO2 photocatalyst was substantially exploited for antibacterial (Yadav et al., 2016), antiviral (Miyachi et al., 2020), and the inactivation of other microbes (Mathew et al., 2018). The disadvantage associated with TiO2 is its activity under the exposure of UV-light only, which can cause adverse health effects (Foster et al., 2011). Other than TiO2, transition metal oxides used for photo-inactivation of microorganisms involves WO3, ZnO, CuO, and Fe2O3 owing to their excellent visible light activity and ability to generate reactive species beneficial for the disinfection process. Interestingly, WO3 is a magnetic semiconductor material that can absorb the whole solar spectrum along with remarkable physicochemical stability, which forms the rationale for exploring disinfection features of WO3 for water, air, and surfaces. For instance, Ghezzi et al. reported a WO3 coated metallic mesh filter integrated with a cotton fabric treated with metallic Cu nanoparticles in the liquid phase for the rapid inactivation of SARS-CoV-2 (Ghezzi et al., 2020). In order to evaluate the photocatalytic antiviral activity, a viral plaque assay in Vero cells along with an analogous quantitative PCR to measure viral
RNA content was performed. After 10 min of exposure under light, 98.2% viral inactivation was observed which reached 100% after 30 min of irradiation with a noticeable decrease in SARS-CoV-2 RNA by 1.5 log$_{10}$ (Fig. 4a).

Carbonaceous materials involving graphene (Maqbool et al., 2021) and carbon nitride (g-C$_3$N$_4$) (Kumar et al., 2020a) also offer significant potential for physicochemical microbial inactivation. Typically, the inherent features of g-C$_3$N$_4$ such as broad visible light absorption region, biocompatibility, negligible toxicity, photo-stability, and chemical firmness make it a suitable candidate for photocatalytic disinfection processes. The photocatalytic virucidal process is a complex phenomenon with a complicated mechanism. Therefore, less work is reported on the antiviral activities of these materials. However, efforts have been made to explore the mechanistic insights and photo-inactivation properties of g-C$_3$N$_4$ for Bacteriophage MS2 (Li et al., 2016). The virus inactivation was evaluated concerning the breakage of proteins and nucleic acids by reducing protein concentration from 9.8 μg/mL to 0 μg/mL after 6 h visible light illumination (Fig. 4b). To further ascertain the cause of MS2 particles death, RNA of photocatalytically treated MS2 was analyzed with qRT-PCR, which depicted 4.5 log decline in viral RNA, confirming inhibition in viral reproduction. Heterostructure formation by integrating two or more semiconductor materials is another optimal approach to improve the charge migration/isolation and boost photocatalytic performance. For instance, the heterostructured graphene oxide/Ag nanoparticles (GO/AgNPs) exhibited broad-spectrum viral inhibition ability by suppressing porcine reproductive and respiratory syndrome virus (PRRSV) along with porcine epidemic diarrhea virus (PEDV) in contrast with the individual bare photocatalysts (Du et al., 2018). Mechanistic investigations revealed that the GO/AgNPs system prevented PRRSV entry into host cells with 59.2% inhibition efficacy and an incremented generation of interferon-α and corresponding stimulating genes leading to direct blocking of the proliferation of the virus.

3.2.2. Modalities

The configuration of photocatalytic reactors also plays a crucial role in disinfection of pathogenic microorganisms. Generally, the three widely used photocatalytic reactors are wall reactors (immobilized catalyst on reactor window), slurry reactors (aqueous suspension possessing suspended catalyst particles), and fixed bed reactors equipped with catalyst coated materials. Extensive research efforts have been carried out in order to develop advanced photoreactors or to modify the existing ones for water and air disinfection such as (1) packed-bed photoreactors, (2) monolithic photoreactors, (3) photocatalytic membrane reactors, and (4) microreactors (Asadi et al., 2014; de los Milá-gros Ballari et al., 2020). Various merits and demerits associated with these reactor designs are summarized in Fig. 5 (da Costa Filho and Viljar, 2020). Typically, the packed bed photoreactors possess tubular or annular geometry with a photocatalyst catalytic bed coating comprising inert glass spheres, rings, or random pieces (Tytgat et al., 2012). The intact arrangement provides a large catalytic surface area leading to effective mass transfer for surface reactions. However, constant light exposure on the whole depth of the photoreactor is considerably challenging.

Similarly, the internal monolithic structures acting as catalyst support also offer substantial surface sites for improved molecular adsorption and mass transfer, with a major drawback of even light illumination at the catalytic surface (Avila et al., 2005). In the case of a photocatalytic membrane reactor, a gas flow via photocatalyst coated membrane pores increment the contact area between reactants and catalysts, resulting in improved mass transfer (Benard et al., 2010). Despite that, the production rate and mechanical resistance induced by diffusion are the critical limitations associated with membrane photoreactors. For effective chemical process intensification, micro-structured photoreactors with 10–1000 μm dimensions provide a noticeable surface-to-volume ratio with efficient mass transfer, comparatively less molecular diffusion distance, and uniform illumination of photocatalytic surface in contrast with conventional photoreactors (Coyle and Oelgemöller, 2008).

Of note, the process of photocatalytic reactor design for disinfection of pathogenic microorganisms is a complex phenomenon with substantial efforts to build a system with effective irradiation of the entire catalytic surface through optimal light sources like optical fibers, LEDs etc. It is also essential to consider that the crucial factors underlying photoreactor designing for organic compounds degradation are significantly different for disinfection. Since the bactericidal and virucidal processes are entirely different from the mineralization of organic compounds, the complex cell structure comprising protecting layers with a distinct thickness and the ability to regrow makes the process even more complex. Considering the crucial factors like complex viral cell structure, environmental impact, and physical parameters play a substantial role in reactor designing, spinning disc reactor overcomes the drawbacks of a fixed bed and monolithic reactors and represents efficient photoreactor configurations (Buck et al., 2018; Chen and Chen, 2014). With controllable process modules, this system exhibits enhanced light penetration, mass transfer, photonic efficiency, and pH regulator to boost the •OH radicals formation. Such photocatalytically active system can be an essential tool for the disinfection process.

3.3. Practical consideration

The photocatalysis process is considered an adaptable and effective means to disinfect harmful microorganisms with potential applications.
in different fields involving medical, industrial, and wastewater treatment. The bactericidal and virucidal abilities of photocatalysis make it a viable approach to further explore and apply in various applications as discussed below:

3.3.1. Medical sector

In the medical sector, photocatalysis offers significant potential in the sterilization of medical equipment under the exposure of UV–visible light along with a semiconductor photocatalyst (Saravanan et al., 2021). For instance, coating implants such as dental implants, disks, and plates with TiO$_2$ photocatalyst are crucial for disinfection purposes (Kumar et al., 2021d). Other than that, coating personal protective equipment (PPE) like masks is also beneficial for preventing and controlling the SARS-CoV-2 spread. For instance, Li et al. developed a TiO$_2$, and N-doped TiO$_2$ coated face mask along with the polyvinyl alcohol, polyethylene oxide, and cellulose nanofibres (Fig. 6a) with 100% bactericidal activity and presented a fascinating solution to fight against the COVID-19 pandemic (Li et al., 2021). The photocatalytic face masks showed self-sterilization ability and substantial reusability, which can help tackle the associated plastic pollution of used masks.

3.3.2. Industrial applications

Nowadays, coating of automobile glass and window glass with semiconducting material involving TiO$_2$, polymer-based nano-composites, ceramic-glass coatings is in the limelight owing to their hydrophobic and antimicrobial activities, which help maintain the glasses clean and fog-resistant (Buruga and Kalathi, 2018; Singh et al., 2021). Moreover, photocatalytic paints and polishes are an integral approach for surface disinfection of different microorganisms. For instance, TiO$_2$ and modified TiO$_2$ photocatalysts are vastly utilized in paints for surface disinfection and degradation of volatile organic compounds (Fig. 6b) (Kaiser et al., 2013). However, the same efficiency and reliability of such materials are still unknown due to less research in this area. Nevertheless, the practical strategy would be useful in the fight against SARS-CoV-2 for surface disinfection. A photocatalytic air filter is another potential tool for air disinfection. For instance, Stanford et al.
3.3.3. Wastewater treatment

For wastewater disinfection, TiO₂ photocatalyst is a potential candidate with appropriate features and has displayed great potential in the virus inactivation involving bacteriophage Qβ, phage MS2, phage f2, human adenovirus, and murine norovirus (Cho et al., 2005; Lee et al., 1998; Zuo et al., 2015). Moreover, the desirable features of TiO₂, such as cost-effectiveness, physicochemical firmness, non-toxicity, and apt potentials for redox reactions at the surface, enable its photocatalytic applications for H₂ production, pollutant degradation, CO₂ reduction, and N₂ fixation (Zhao et al., 2015). Photocatalytic water disinfection is an optimization technique that can overcome the bottlenecks of traditional disinfection methods by minimizing the generation of toxic by-products and large amounts of chemicals. Other than TiO₂, various semiconductor materials involving ZnO, graphene, BiVO₄, 8-C₃N₄, metal-organic frameworks have been successfully incorporated in photocatalytic wastewater treatment (Liu et al., 2019; Wang et al., 2015).

4. Long-term challenges & sustainable solutions

The current requirement of developing intelligent and impressive strategies to combat COVID-19 expedites the research community towards employing advanced oxidation technology-based photocatalysis for disinfection purposes. Considering the virucidal features of semiconductor photocatalysis, they play an influential role in coating layers for facemasks, membrane-based air-filters, and wastewater treatment. Moreover, the involvement of distinct semiconductor materials with a considerable solar-spectrum response and inherent properties reduces the transmission risk and makes the process cost-efficient and viable. Despite so several desirable properties, the photocatalytic disinfection process is associated with particular inherent challenges for the long term applicability, as discussed below:

- One of the fundamental limitations of photocatalysis for antiviral activity is the low solar light harnessing the ability of semiconductor materials, limiting the effective ROS generation and oxidative destruction of viral species. Most of the semiconductor oxides show less photocatalytic activity due to broad bandgap energy and a higher rate of electron-hole reassembly than others. Also, the UV-light active semiconductor materials exhibit modest penetration, which restricts their utilization as antiviral agents for external surfaces. On the contrary, the visible- and/or NIR-light active photocatalytic materials show profound penetration ability leading to effective oxidation destruction of the viral cell (Parra-Ortiz and Malmsten, 2021). Of note, vast modification strategies such as metal/non-metal doping, co-doping, heterostructure formation, defect engineering have been systematically explored to overcome the hurdle associated with less energy utilization and conversion (Imtiaz et al., 2019). However, the research on modified nanomaterials for antiviral activity still needs further exploration.

- Physicochemical stability of semiconductor photocatalyst under stringent reaction conditions is a critical parameter that influences the whole photocatalytic process (Hasija et al., 2019; Sudhaik et al., 2018). Moreover, considering the stability of the virus in the environment for a considerable period, it becomes necessary that the photocatalytic material must exhibit significant stability and reusability to fulfill the economic criteria. Utilizing metal-free photocatalysts or the combination of advanced heterojunction systems can potentially enhance the photo-stability aspects with improved performance (Huang et al., 2014; Li et al., 2018a).

- Efficient recovery of suspended photocatalysts during water disinfection is a challenging phenomenon. The possible toxicity and the chemically functionalized surface of photocatalysts necessitate the removal of nanosized materials after the disinfection process and before the release/reuse of treated water. Magnetic isolation is a significant operation of deploying nanosized suspended particles from the reaction mixture. Moreover, integration of certain potential photocatalytic materials having difficulty removing the magnetically separable materials can solve the challenging issue of recovery (Linley et al., 2013).

- Photoreactor configuration for large-scale catalytic disinfection process is a vital factor worth exploring. Limited studies include the impact of photocatalytic reactor design on the inactivation process. Therefore, future research should involve fundamental and applied research for better photocatalytic performance (Saravanan et al., 2021).

- Another substantial challenge involves the rapid viral mutation and the complexity in understanding the mechanistic insights of virus inactivation. Viruses offer stronger photo-inactivation resistance than other microbes due to structural and geometric differences. Moreover, the long duration of SARS-CoV-2 in the environment and

Fig. 6. Classical model showing structural and functional designing of a reusable mask. Recyclable PVA, PEO, and nanocellulose materials were mixed in nanomeshes through an electrospinning process followed by deposition of photocatalytic N-TiO₂. PVA, PEO, and nanocellulose with eco-friendly and biodegradable (nanocellulose has excellent mechanical strength) properties were used as precursors. The nanofibers fabricated by the electrospinning process provide superior breathability and good filtration ability for nanoparticles. Similarly, N-TiO₂ professionally revitalizes masks by facial light radiation to destroy the infected bacteria and offers reusability of maskable, Reproduced with permission from American Chemical Society (Copyright © 2021) (Li et al., 2021). (b) Designed nanomaterials show advantages and protection in paints and lacquers. The nanomaterials in paints improve hydrophobia, resilience, antibacterial properties, scratch and bleaching resistance, UV light filtration, self-cleaning, photocatalytic ability, and increased resistance. In protection, studies of paints with and without designed nanomaterials validate no harmful effect (nano-related) on health, Reproduced with permission from Elsevier (License No. 5161400903726) (Kaiser et al., 2013).
its rapid mutation ability expedite the transmission risk, complicating the inactivation process. Therefore, a comprehensive understanding of fundamental reaction mechanisms which occur during disinfection is of significant interest in amending and modeling the photocatalytic process.

Overall, it is crucial to expand the research on available photocatalytic systems to overcome the mentioned limitations for the efficient deactivation of targeted viruses like SARS-CoV-2. Even though the scientific community has developed several disinfection technologies after the outbreak of the COVID-19 pandemic, we anticipate that photocatalytic disinfection is a sustainable solution to lessen the environmental impact.

5. Concluding remarks

In conclusion, scientists worldwide are actively exploring an effective solution to combat the COVID-19 pandemic, considering the potential health risk. Sunlight-driven semiconductor photocatalysis has emerged as a potential alternative strategy with considerable merits of the process, high efficiency, and energy-efficient procedure for the disinfection of water, surface, and air. Hence, the present study entails an overview of current disinfection technologies utilized to control the virus spread. For practical consideration, different types, modalities, and roles of photocatalysis in disinfection have been comprehensively discussed. Based on the current research on disinfection control strategies, various long-term challenges and possible sustainable solutions concerning photocatalytic disinfection technology have been proposed. Although significant progress has been attained in an exploration of semiconductor photocatalysis-driven disinfection; however, it is still challenging to design highly efficient photocatalytic systems with scale-up applications. Typically, investigating fundamental disinfection reactions is crucial to developing a deep understanding of the process. To this end, the research on photocatalytic cell membrane peroxidation with mechanistic insights is relatively less explored. Moreover, most studies have not examined the kinetics of photocatalytically induced protein oxidation via radical generation. Consequently, the synergistic relationship between the oxidation kinetics and death kinetics of the cell is still missing. Hence, future research in this area must explore the quantitative relationship between the genetic core damage, protein oxidation, shape rupturing/distortion, and the fundamental parameters of the photocatalysis process, which substantially influence the disinfection process. It is anticipated that by overcoming the inherent limitations of photocatalysis, its potential for disinfection control can be further explored for filling the existing research gaps.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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References

Ahmed, W., et al., 2020. First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: a proof of concept for the wastewater surveillance of COVID-19 in the community. Sci. Total Environ. 728, 138764.
Allison (Ed.), 2020. The Hand Sanitizer Market in China - Demand after COVID-19, Arun, J., et al., 2019. Application of Nano-PHoto-Catalysts for Degradation and Disinfection of Wastewater. Advanced Research in Nanosciences for Water Technology. Springer, pp. 249–261.
Assad, A.A., et al., 2014. Isovaleraldehyde elimination by UV/TiO2 photocatalysis: comparative study of the process at different reactors configurations and scales. Environ. Sci. Pollut. Res. 21, 11178–11188.
Avila, P., et al., 2005. Monolithic reactors for environmental applications: a review on preparation technologies. Chem. Eng. J. 109, 11–36.
Aydogdu, M.O., et al., 2021. Surface interactions and viability of coronaviruses. J. R. Soc. Interface 18, 20200796.
Batrill, M., 2011. Fundamental aspects of surface engineering of transition metal oxide photocatalysts. Energy Environ. Sci. 4, 3275–3286.
Bayarri, B., et al., 2021. Can ozone inactivate SARS-CoV-2? A review of mechanisms and performance on viruses. J. Hazard Mater. 126586.
Benard, S., et al., 2010. Comparing monolithic and membrane reactors in catalytic oxidation of propene and toluene in excess of oxygen. Catal. Today 156, 301–305.
Bishai, M., 2021. A Comprehensive Study of COVID-19 in Wastewater: Occurrence, Trace Quantification, and Impacts on Public Health. Management of Novel Coronavirus Disease (COVID-19). Elsevier, pp. 115–144.
Buick, C., et al., 2018. Influence of bacterial, environmental and physical factors in design of photocatalytic reactors for water disinfection. J. Photochem. Photobiol. Chem. 366, 136–141.
Buruga, K., Kalabhi, J.T., 2018. A facile synthesis of halloysite nanotubes based polymer nanocomposites for glass coating application. J. Alloys Compd. 735, 1807–1817.
Byrne, J.A., et al., 2015. A review of heterogeneous photocatalysis for water and surface disinfection. Molecules 20, 5574–5615.
Chen, K.-J., Chen, Y.-S., 2014. Intensified production of biodiesel using a spinning disk reactor. Chem. Eng. Process: Process Integrifaction. 78, 67–72.
Cho, M., et al., 2004. Linear correlation between inactivation of E. coli and OF radical concentration in TiO2 photocatalytic disinfection. Water Res. 38, 1069–1077.
Cho, M., et al., 2005. Different inactivation behaviors of MS-2 phage and Escherichia coli in TiO2 photocatalytic disinfection. Appl. Environ. Microbiol. 71, 270–275.
Contreras, L.E.V., et al., 2020. Remedies for Disinfectant Resistance. Infection and Disinfection in the post COVID-19 era. Elsevier, pp. 135–140.
Cuesta, F., de los Milagros Ballari, M., et al., 2020. Photocatalytic reactor modeling: application to future engagement in the global climate crisis. J. Clean. Prod. 125178.
Coyle, E.E., Oelgemöller, M., 2008. Micro-photochemistry: photochemistry in microstructured reactors. The new photochemistry of the future? Photochem. Photobiol. Sci. 7, 1313–1322.
da Costa Filho, B.M., Vilar, V.J., 2020. Strategies for the intensification of photocatalytic oxidation processes towards air streams decontamination: a review. Chem. Eng. J. 391, 123531.
Dalymply, O.K., et al., 2010. A review of the mechanisms and modeling of photocatalytic disinfection. Appl. Catal. B Environ. 98, 27–38.
Darnell, M.E., 2004. Inactivation of the coronavirus that induces severe acute respiratory syndrome, SARS-CoV. J. Virol Methods 121, 85–91.
de los Milagros Ballari, M., et al., 2020. Photocatalytic disinfection using advanced oxidation processes for chemical pollution abatement. Heterogeneous Photocatalysis 265–301.
Del Río, C., Malani, P.N., 2020. COVID-19—new insights on a rapidly changing epidemic. JAMA 323, 1339–1340.
Du, T., et al., 2018. Antiviral activity of graphene oxide-silver nanocomposites by preventing viral entry and activation of the antiviral innate immune response. ACS Appl. Bio Mater. 1, 1286–1293.
for Immunization, N. C., 2021. Science Brief: SARS-CoV-2 and Surface (Fomite) Transmission for Indoor Community Environments. CDC COVID-19 Science Briefs [Internet]. Centers for Disease Control and Prevention (US).
Foster, H.A., et al., 2011. Photocatalytic disinfection using titanium dioxide: spectrum and mechanism of antimicrobial activity. Appl. Microbiol. Biotechnol. 90, 1847–1868.
Gal, H., et al., 2013. Enhanced visible-light-driven photocatalytic inactivation of Escherichia coli by Bi2O2CO3/BNiNO7 composites. J. Hazard Mater. 250, 131–137.
Garparre, R., et al., 2020. Knowledge and Practices Regarding Safe Household Cleaning and Disinfection for COVID-19 prevention—United States, May 2020. Wiley Online Library.
Ghezzi, S., et al., 2020. Rapid inactivation of SARS-CoV-2 by coupling tungsten trioxide (W3O) photocatalyst with copper nanoclusters. J. Nanotechnol. Nanomat. 1.
Giannakis, S., et al., 2017. Iron oxide-mediated semiconductor photocatalyst vs. heterogeneous photo-Fenton treatment of wastewater. Impact of the oxide particle size. J. Hazard Mater. 339, 223–231.
Guyon, J., 2020. Looking for Lysol Spray and Clorox Wipes? COVID-19 Wiped Out Disinfectants, but Here’s when You Can Buy Again.
Harmo, E., et al., 2020. First environmental surveillance for the presence of SARS-CoV-2 RNA in wastewater and river water in Japan. Sci. Total Environ. 737, 140405.
Hasija, V., et al., 2021a. Advanced activation of persulfate by polymeric g-C3N4 based nanocomposites for glass coating application. J. Alloys Compd. 735, 1807–1817.
Hasija, V., et al., 2021b. Photocatalytic inactivation of viruses using graphitic carbon nitride-based photocatalysts: virucidal performance and mechanism. Catalysts 11, 1448.
Hasija, V., et al., 2019. Recent advances in noble metal free doped graphitic carbon nitride based nanohybrids for photocatalysis of organic contaminants in water: a review. Appl. Mater.Today 15, 494–524.
Herrmann, J.-M., 1999. Heterogeneous photocatalysis: fundamentals and applications to pervaporation of various types of aqueous pollution. Catal. Today 53, 115–129.
Hirose, R., et al., 2021. Disinfectant effectiveness against SARS-CoV-2 and influenza viruses present on human skin: model-based evaluation. Clin. Microbiol. Infect. 27, 1042 e1-1042 e4.
Huang, J., et al., 2014. Metal-free disinfection effects induced by graphitic carbon nitride under visible light illumination. Chem. Commun. 50, 4338–4340.
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Imtiaz, F., et al., 2019. Semiconductor nanocomposites for visible light photocatalysts of water pollutants. Concepts of Semiconductor Photocatalysis. https://doi.org/10.5772/intechopen.92398

Kaiser, J.-P., et al., 2013. Is nanotechnology revolutionizing the paint and lacquer industry? A critical opinion. Sci. Total Environ. 442, 282–289.

Kampf, G., et al., 2020. Persistence of coronaviruses on inanimate surfaces and their inactivation with different disinfectants. J. Hosp. Infect. 104, 246–257.

Kasloff, S.B., et al., 2021. Stability of SARS-CoV-2 on critical personal protective equipment. Sci. Rep. 11, 1–7.

Klemm, J.J., et al., 2020. The energy and environmental footprints of COVID-19 fighting measures–PPF, disinfection, supply chains. Energy 211, 118701.

Koviven, J., Heinonen-Tanski, H., 2015. Peracetic acid (PAA) disinfection of primary, secondary and tertiary treated municipal wastewaters. Water Res. 39, 4445–4453.

Kokkinos, P., et al., 2021. Enhanced oxidation processes for water and wastewater viral disinfection. A systematic review. Food and Environ. Virology 1–20.

Kühn, K.P., et al., 2003. Disinfection of surfaces by photocatalytic oxidation with titanium dioxide and UVA light. Chemosphere 53, 71–77.

Kumar, A., et al., 2021a. C, N-Vacancy defect engineered polymeric carbon nitride towards photocatalysis: viewpoints and challenges. J. Mater. Chem. 9, 111–153.

Kumar, A., et al., 2020a. Perspective and status of polymeric graphitic carbon nitride based Z-scheme photocatalytic systems for sustainable photocatalytic water purification. Chem. Eng. J. 391, 123496.

Kumar, A., et al., 2020b. An overview on polymeric carbon nitride assisted photocatalytic CO2 reduction: strategically manoeuvring solar to fuel conversion efficiency. Chem. Eng. Sci. 116219.

Kumar, A., et al., 2021b. Impact of COVID-19 on Greenhouse Gases Emission: A Critical Review. Science of The Total Environment, p. 150349.

Kumar, M., et al., 2021c. Advanced oxidation processes for water and wastewater viral disinfection. A systematic review. Food and Environ. Virology 1–20.

Klemeš, J., et al., 2004. Time dependent development of the environmental quality in a Czech city: temporal variations of UV radiation and SARS-CoV-2 RNA. Sci. Total Environ. 399, 769–777.

Klein, J.-P., et al., 2013. Is nanotechnology revolutionizing the paint and lacquer industry? A critical opinion. Sci. Total Environ. 442, 282–289.

Kokkinos, P., et al., 2021. Advanced oxidation processes for water and wastewater viral disinfection. A systematic review. Food and Environ. Virology 1–20.

Kühn, K.P., et al., 2003. Disinfection of surfaces by photocatalytic oxidation with titanium dioxide and UVA light. Chemosphere 53, 71–77.

Kumar, A., et al., 2021a. C, N-Vacancy defect engineered polymeric carbon nitride towards photocatalysis: viewpoints and challenges. J. Mater. Chem. 9, 111–153.

Kumar, A., et al., 2020a. Perspective and status of polymeric graphitic carbon nitride based Z-scheme photocatalytic systems for sustainable photocatalytic water purification. Chem. Eng. J. 391, 123496.

Kumar, A., et al., 2020b. An overview on polymeric carbon nitride assisted photocatalytic CO2 reduction: strategically manoeuvring solar to fuel conversion efficiency. Chem. Eng. Sci. 116219.

Kumar, A., et al., 2021b. Impact of COVID-19 on Greenhouse Gases Emission: A Critical Review. Science of The Total Environment, p. 150349.

Kumar, M., et al., 2021c. Wastewater Surveillance-Based City Zonation for Effective COVID-19 Pandemic Preparedness Powered by Early Warning: A Perspectives of city development. Environ. Sci. Technol. 55, 2901–2910.

Klein, J.-P., et al., 2013. Is nanotechnology revolutionizing the paint and lacquer industry? A critical opinion. Sci. Total Environ. 442, 282–289.

Kokkinos, P., et al., 2021. Advanced oxidation processes for water and wastewater viral disinfection. A systematic review. Food and Environ. Virology 1–20.

Kühn, K.P., et al., 2003. Disinfection of surfaces by photocatalytic oxidation with titanium dioxide and UVA light. Chemosphere 53, 71–77.

Kumar, A., et al., 2021b. Impact of COVID-19 on Greenhouse Gases Emission: A Critical Review. Science of The Total Environment, p. 150349.

Kumar, M., et al., 2021c. Wastewater Surveillance-Based City Zonation for Effective COVID-19 Pandemic Preparedness Powered by Early Warning: A Perspectives of city development. Environ. Sci. Technol. 55, 2901–2910.

Klein, J.-P., et al., 2013. Is nanotechnology revolutionizing the paint and lacquer industry? A critical opinion. Sci. Total Environ. 442, 282–289.

Kokkinos, P., et al., 2021. Advanced oxidation processes for water and wastewater viral disinfection. A systematic review. Food and Environ. Virology 1–20.

Kühn, K.P., et al., 2003. Disinfection of surfaces by photocatalytic oxidation with titanium dioxide and UVA light. Chemosphere 53, 71–77.