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Review

Nanomaterials Aspects for Photocatalysis as Potential for the Inactivation of COVID-19 Virus

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Abstract: Coronavirus disease-2019 is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and is the most difficult recent global outbreak. Semiconducting materials can be used as effective photocatalysts in photoactive technology by generating various reactive oxidative species (ROS), including superoxide ($\bullet O_2^-$) and hydroxyl (•OH) radicals, either by degradation of proteins, DNA, and RNA or by inhibition of cell development through terminating the cellular membrane. This review emphasizes the capability of photocatalysis as a reliable, economical, and fast-preferred method with high chemical and thermal stability for the deactivation and degradation of SARS-CoV-2. The light-generated holes present in the valence band (VB) have strong oxidizing properties, which result in the oxidation of surface proteins and their inactivation under light illumination. In addition, this review discusses the most recent photocatalytic systems, including metals, metal oxides, carbonaceous nanomaterials, and 2-dimensional advanced structures, for efficient SARS-CoV-2 inactivation using different photocatalytic experimental parameters. Finally, this review article summarizes the limitations of these photocatalytic approaches and provides recommendations for preserving the antiviral properties of photocatalysts, large-scale treatment, green sustainable treatment, and reducing the overall expenditure for applications.

Keywords: SARS-CoV-2; heterogeneous catalysis; light adsorption; mechanism of inactivation; photocatalysis

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1. Introduction

The coronavirus disease 2019 has spread from person to person on a global scale. This dangerous respiratory syndrome (SARS-CoV-2) has caused pandemic-scale illnesses that spread primarily through the airborne transmission of infected people's droplets and/or aerosols. The coronavirus has been found in common places, particularly in health centers, raising the possibility of this communicable disease [1,2]. Economic devastation was already visible as the epidemic spread, demonstrating that it was one of the largest economic shocks in history [3]. The COVID-19 crisis demonstrates the significance of immediate action to mitigate the epidemic's health and lay the groundwork for long-term recovery [4]. Several countries have made significant efforts to address this problem. As COVID-19 is widespread all over the world, many restrictions were followed, such as six-foot distance, lockdown, quarantine, and stay-at-home [5]. Symptoms usually appear within 2–14 days, and specific treatments, medicines, and vaccinations are not obtainable. Modern high-tech equipment, such as polymerase chain reaction (PCR) and X-ray crystallography, help understand the physicochemical properties and anatomy of viruses [6,7]. For sample testing, the cost increases in tandem with the number of clinical studies.

Recent research has demonstrated the enormous potential of photocatalytic material surfaces for the inactivation of SARS-CoV-2 [8]. Several different photocatalyst nanomaterials have been used as antibacterial or antiviral materials for photo-induced bacterial

and viral infections and self-cleaning properties [9]. In addition, a photocatalytic system using semiconductors made of graphene oxide (GO) to cure cancer has been identified. GO can be employed as an antibacterial and anticancer agent owing to its excellent properties. Porcine herpes virus was used to investigate GO's antiviral activity, and the results showed that GO inhibited viral infection in noncytotoxic samples [10,11]. The development of reusable TiO_2 nanowire-based air filters as photoactive materials have been described for the first time [12]. The filters were significantly more efficient to a greater extent because of their large surface area, polycrystalline counterparts, and super-hydrophilicity. Thus, it is a promising photocatalyst owing to the chemical species that are adsorbed on its surface's highly potent ability to oxidize when exposed to light [13]. Photocatalytic activities are generally influenced by structural and surface modifications, including specific surface area, particle shape, size, and adsorption nature [14]. Therefore, this review discusses the most recent photocatalytic systems, including metals, metal oxides, carbonaceous nanomaterials, and 2-dimensional advanced structures, for efficient SARS-CoV-2 inactivation.

2. Photocatalysis: Concept and Technology in Biomedical

In primary photocatalysts, the catalytic components are linked to single metal oxides, carbonaceous materials, or two-dimensional advanced materials [15]. The photocatalytic mechanism is illustrated in Figure 1. Many carbon-based carriers and semiconductor materials have enhanced the quality of photocatalytic degradation through their active surface area, improving the absorption of visible light, forming effective p- and n-type semiconductor nanojunctions, and suppressing interfacial charge recombination [16,17].

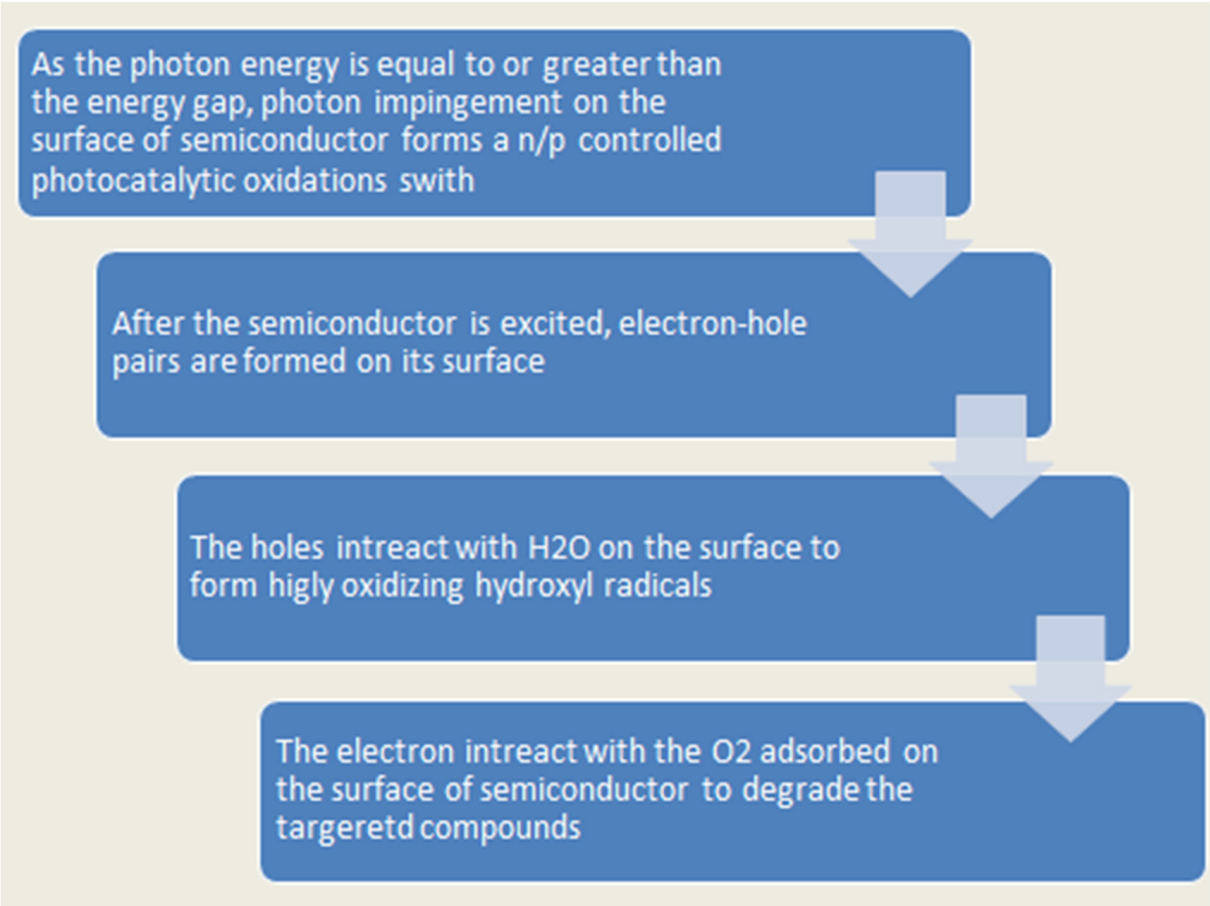

Figure 1. General photocatalysis mechanism.

Many studies on photocatalysis have reported operational parameters that can influence process efficiencies, such as the intensity of light, solution pH, wavelength, and the

presence of O_2 (Table 1). These factors have been shown to have a prominent impact on light penetration, catalyst activation, reaction rate/order, organic molecule adsorption, and catalyst stability during catalytic reactions [18,19].

Table 1. Operation parameters that affect the catalytic performance in the photocatalysis process.

Operational Parameters	Effect on the Photocatalytic Performance	References
Light sources	• The rate of the photocatalytic process increases with light intensity. • The inclusion of a photocatalyst in water decreases the energy requirement.	[20,21]
pH	• The pH level has a significant impact on how well semiconductor catalyst particles degrade in particle aggregations, where their bandgap edges are located in the reaction fluid, how charged their surfaces are, and how organic contaminants adhere to them. • The impact of pH is related to the surface charge of the catalyst and the ionic form of the substrate. • The catalyst particles are protonated and positively charged because the pH is below the point of zero. • The surface is deprotonated and more negatively charged at high pH levels.	[22,23]
Oxidants	• The surface was deprotonated and negatively charged at high pH levels. • Stimulation of hydroxyl radical formation. • The oxidation reaction and charge separation are facilitated by the ability of peroxide to absorb light.	[24,25]
Surface modification by doping	• Non-metallic metal doping and co-doping lead to impurity energy and improve the absorption of visible light by the catalyst. • Doping with non-metal type reduces the band gap of the semiconductor and gathers the photocatalytic response of visible light. • The carbon-doped increase the reaction rate. • With metal doping, the electronic configuration of the dopant ions is related to the subsequent photocatalytic characteristics, and the metal ions affect carrier recombination and electron transport.	[26,27]
Semiconductor compounds	• The combination of semiconductors and narrow-bandgap semiconductors reduces the energy required for light activation. • Extending the spectral response of semiconductor photocatalysts. • Facilitating electron-hole pair separation. • Present heterogeneous junctions between the compounded semiconductor for the separation of carriers and reduced recombination of electron-hole pairs produced by light.	[28,29]
Precious metal deposition	• Metals and semiconductors have different Fermi levels. As both are in contact, electrons transfer from the Fermi level of the semiconductor to the Fermi level of the metal. • Effectively serves as an electron barrier to stop electrons and holes from recombining.	[30,31]

In this context, significant research efforts have been made to immobilize photocatalysts efficiently; in most cases, photocatalysts require energy to overcome the bandgap energy required for electron excitation [32]. This additional energy is required because of insufficient light penetration and adsorption, which significantly increases cost requirements. Furthermore, charge carrier, recombination rate, transfer rate, and charge carrier transit time are factors that limit the use of photocatalysts [33,34]. During the breakdown process, these harmful components create a high possibility for the conversion of phenol derivatives, acidic compounds, and ionic species [35]. Several modifications to improve the catalytic performance have been reported, including precious metal deposition, doping of elements, and recombination of holes and electrons [20,30]. These modifications result in a smaller bandgap and recombination process at a lower rate, consuming low energy. Hence, it is highly used because of its non-toxicity, high selectivity, and efficiency in treating Alzheimer's disease, disabling contaminants, bacterial/virus disinfection, and water treatment.

2.1. Photocatalysts in Alzheimer's Sickness

Alzheimer's disease (AD) is an age-related brain disorder that affects memory and is caused by environmental, lifestyle, and genetic factors. There are several treatments avail-

able for this disease, each with its drawbacks (Table 2). Through technology development in recent years, photocatalysts have been used in the treatment of Alzheimer's disease by oxygenating the substrate under the influence of a small amount of light as the energy source [36]. Photooxygenation of amyloid protein (Aβ) is associated with Alzheimer's disease. Table 3 lists the properties of the β protein that are suitable for use in photocatalyst technology. Treatment plans for Alzheimer's disease that inhibit Aβ aggregation have been deemed both therapeutic and preventive. The treatment involved oxygenating Aβ and aggregating it under light irradiation. Selective oxygenation of amyloid-β (Aβ) aggregates a peptide that is associated with the emergence of Alzheimer's disease. In this state, a photocatalyst containing oxygenated Aβ in a test tube is typically used. An amyloid structure can be distinguished as a photocatalyst combined with a peptide that accepts Aβ to reduce the toxicity of Aβ aggregates to cells [37].

Table 2. Photocatalysis in Alzheimer's treatment with its details and limitation.

Treatment	Details	Limitation	References
Enzyme degradation	Type of enzymes including neprilysin, insulin-degrading enzyme, and endothelin-converting enzyme.	• The large-scale production of these enzymes on a big scale is expensive, labor-intensive, and intricate for widespread use. • Most of these enzymes are not affected by Aβ oligomers. • The enzyme cannot distinguish between Aβ plaques and proteins with typical biological functions. • High potential for adverse side effects.	[37–39]
Fullerene derivatives treatment	Fullerene derivatives with specific affinities for decomposing Aβ peptides in conjunction with photoirradiation.	• Not easily utilized for more biological research • Low biological matrix solubility • Modification difficulty	[40,41]
Inorganic compounds as antitumors	Inorganic ligands inhibit and degrade Aβ peptide aggregation at a very early stage	• Require a specific condition for the Aβ degradation process.	[42,43]
Inorganic nanomaterials (carbon nanotubes, graphene oxide, carbon quantum dots, and graphene-like nanosheets of molybdenum disulfide)	Demonstrate specific suppression of amyloid aggregation.	• Inhibitors of amyloid only slow down or halt the aggregation process of amyloid proteins but do not destroy the existing amyloid deposits without external energy input. • The aggregation state of amyloid protein is thermodynamically favorable. • Temporospatial control over the length and placement of conventional treatments in vivo is challenging to implement.	[44–46]
Photodynamic therapy	Neoplastic tissue-containing porphyrin mixture may fluoresce in the UV, visible, and near-infrared spectrums	• Strong phototoxicity for the treatment • Minimal invasiveness	[47,48]
Uv excitation-based strategy	Destruction of amyloid fibrils with laser assistance under long-wavelength UV radiation results in the breakdown of Aβ peptide monomers and oligomers.	• UV light with invasive energy hindered its clinical application.	[49,50]

Table 3. General characteristics of Aβ protein cell in photocatalyst application.

Characteristics	Details	References
Stability	High ordered stability Aggressive potency depends on thermodynamics and interaction with an aqueous medium	[20,51]
Toxicity	Able to be attenuated via the photocatalysis process	[24,52]
Reactivity	Ability to form a covalent installation of hydrophilic oxygen atoms in the presence of light and catalyst Formation of less undesired side reactions	[53,54]
Molecular mechanism	Self-assembly of mature b-sheet-rich amyloid fibrils from Aβ peptides in the pathogenesis	[55]

Many photoactivated photosensitizers have been developed and have been used to inhibit and degrade amyloid proteins. Natural organic dyes and photocatalysts composed of metal oxides are frequently used as photoactive agents. Examples of porphyrin derivatives that can prevent Aβ aggregation under blue light include meso-tetra 94-sulfonate phenyl) porphyrin. Both the neuronal cells and the Drosophila AD model confirmed that it reduced the cytotoxicity of Aβ [56]. Additionally, it has been demonstrated that Aβ 42 fibrils can be destroyed by methylene blue when exposed to red light up to 630 nm with a longer wavelength. These therapies are inexpensive and simple, but a lengthy evaluation of their photodegradation and biosafety in mammalian animal models is required [57].

2.2. Photocatalysts in the Treatment of Emerging Contaminants

Conventional methods such as adsorption, membrane separation, precipitation, chemical coagulation, and biodegradation are used to remove or degrade dyes. Owing to their short- and long-term toxicity, emerging contaminants such as perfluorinated compounds, endocrine-disrupting chemicals, pharmaceuticals, and personal care products are frequently found in wastewater, surface water, groundwater, and drinking water at concentrations between mg/L and ng/L [58]. They are also difficult to degrade using traditional water treatments, owing to their high stability. Modern sewage treatment facilities frequently struggle to remove compounds present in extremely low quantities. Consequently, effluent discharge and the reuse of sludge have emerged as major causes of pollution in both aquatic and terrestrial environments [59]. However, they present limitations such as high operating costs, production of secondary sludge, use of large quantities of chemicals, large treatment plants, and inefficiency at low concentration levels. Advanced photocatalysis has been shown to effectively degrade trace organic pollutants under benign conditions, while producing very few byproducts, allowing the removal of chemically stable and non-biodegradable organic contaminants (Table 4).

Table 4. The photocatalytic performance of different semiconductors towards the degradation of emerging contaminants compounds.

Nanosemiconductor	Photocatalytic Performance	References
TiO_2	Naproxen was removed 75% of the time with xenon light for a 2-h exposure time.	[60]
TiO_2	85 to 100% of IBP was degraded after 3 h.	[61]
TiO_2	Progesterone, triclosan, ofloxacin, acetaminophen, hydroxyphenyl, DCF, IBP, and caffeine were destroyed using 5 mg/L TiO_2.	[62]
ZnO	90% degrade under solar irradiation in 90 min	[63]
ZnO-coated via activated carbon	Under UV irradiation, 99% of tetracycline at 40 mg/L broke down in an hour.	[64]

Table 4. *Cont.*

Nanosemiconductor	Photocatalytic Performance	References
GO-WO_3	Under visible-light irradiation, sulfamethoxazole was removed in 3 h with a 98% clearance rate.	[65]
g-C_3N_4/Nb_2O_5	81% removal of drug amiloride	[66]
Au/Ag/AgCl	97% degradation of IBP 98% degradation of clofibrate acid under solar irradiation	[67,68]
TiO_2/g-C_3N_4	Under sun radiation, TiO_2 photodegrades at a rate that is four times faster than pristine TiO_2.	[69]
TiO_2-rGO	90–97% degradation of ibuprofen, sulfamethoxazole, and carbamazepine at reaction rates of 8.98, 12.6, and 4.3 10^{-3}/min, respectively under high-pressure UV light of 140 W.	[70]
TiO_2-CNTs	100% removal of 10 ppm tetracycline at a high reaction rate of 64.2 $\times$ 10^{-3}/min under a 12 W UV lamp.	[71]

2.3. Photocatalysts in Degradation of Emerging Pollutant Molecules

The textile, printing, plastic, pharmaceutical, food processing, and cosmetic industries generate a considerable amount of colored wastewater that often reaches natural waters, decreasing their transparency, preventing light penetration, impairing photosynthesis efficiency, and affecting aquatic plant growth. Hence, polluted molecules can be degraded by photocatalysis on solid and water surfaces [72]. Photocatalytic paints and polishes also play an important role in pathogen surface disinfection. TiO_2 and modified TiO_2 photocatalysts are commonly used in paints to clean and break down volatile organic compounds (VOCs) [20]. However, the effectiveness and dependability of such materials remain unknown because of the lack of research in this area [16]. In contrast, photocatalytic air filters can be used to sterilize air. For example, a graphene-based air filter induced by a laser can be used to encapsulate germs and can be purified using a photocatalytic membrane filter [73]. The particles and bacteria were captured by a porous photocatalytic membrane, which was then periodically broken down and rendered inactive by high-temperature and Joule heating.

2.4. Photocatalysts in Medical Applications

A significant tool is required to inhibit rapid transmission and increase the inactivation rate of dangerous bacteria. From this perspective, semiconductor photocatalysts have been identified as promising avenues for the disinfection of medical equipment. TiO_2 photocatalysts must be applied to disinfect implants such as dental implants, discs, and plates. In addition, covering PPE such as veils can aid in halting and preventing the transmission of SARS-CoV-2 [74,75]. The COVID-19 pandemic can be fought with the help of a face mask coated with TiO_2 and N-doped TiO_2, polyvinyl alcohol, polyethylene oxide, and cellulose nanofibers, all of which have a comprehensive bactericidal effect [76]. Photocatalytic face masks have shown great reusability and self-sterilization ability, which may reduce the amount of plastic pollution caused by the masks used. The peroxide produced on the nano-porous TiO_2 surface successfully killed airborne bacteria and viruses including SARS-CoV-2. Prefabricated filters have been used as purification or conditioning agents [77]. Therefore, the above-mentioned environmentally friendly, recyclable, and sustainable solutions could be a great way to address the present COVID-19 pandemic.

2.5. Photocatalysts in Disinfection

Photocatalysis has been investigated for the decontamination and disinfection of SARS-CoV-2 [78]. The high biodegradability, filterability, breathability, and mechanical

strength of photocatalytic self-sterilizing masks enable their handling and minimize harm to the environment as shown in Figure 2a [79]. Figure 2b shows the schematic view of the structure of the air cleaner and the porous ceramic substrate [80]. For instance, they created a self-sterilizing N-TiO_2/TiO_2 air filter with coated bacterial disinfection and laser-induced graphene (LIG), which are conductive and microporous materials. It is well known that this offers benefits over advanced homogeneous-phase oxidation techniques [81].

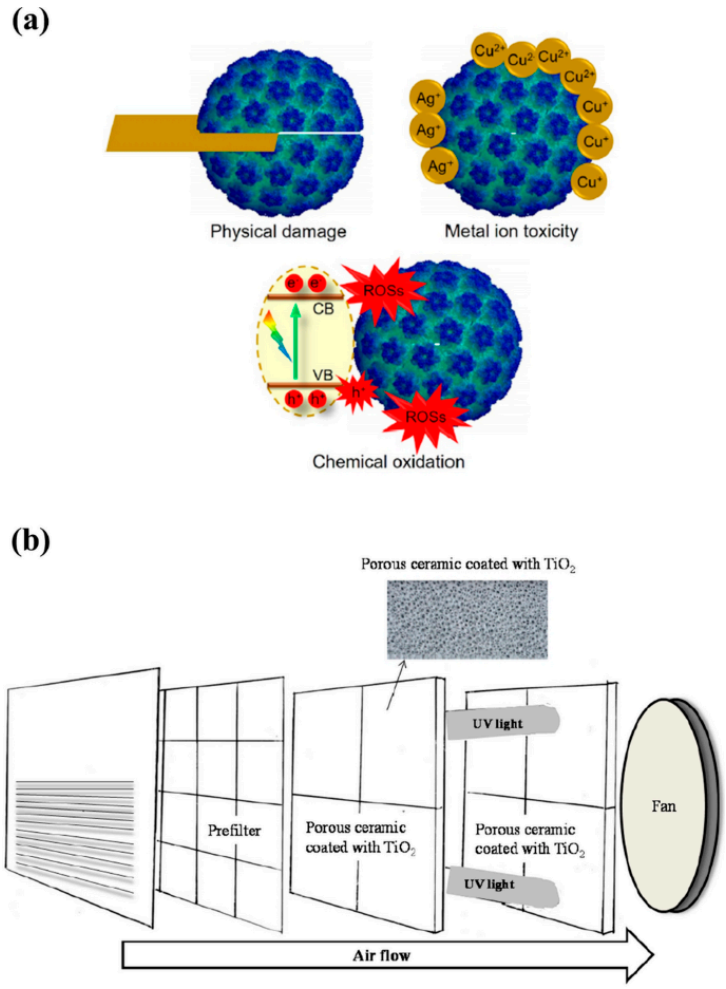

Figure 2. (**a**) The structure and chemical properties, the efficiency of inactivating viruses, and the mechanism of inactivating viruses [79] (**b**) The schematic view of the structure of the air cleaner and the porous ceramic substrate [80].

For instance, viruses are eliminated from the water via size exclusion in physical processes such as heating, adsorption, and filtration [22,82]. Nonetheless, they are challenging to eliminate and deactivate owing to their small size and distinctive characteristics. Chlorination, which uses chlorine gas, chloramines, or a hypochlorite solution, is one of the most commonly used methods for virus disinfection [83]. Chlorination was found to effectively eliminate SARS-CoV-2 in a previous study. Unfortunately, the production of mutagenic and carcinogenic disinfection byproducts has led to opposition to chlorination. Similarly, chlorination produces water with a bad flavor and smell. Fighting against epidemics is of great importance [47,84]. The photocatalytic system is perfect in this respect because of its strong solar radiation, minimal startup costs, and viability for a longer duration. Wastewater treatment using nanotechnology has been documented in the literature. Antibiotic-resistant *E. coli* (Gram-negative) and *Staphylococcus aureus* (Gram-positive) bacteria that were sown in greywater were rendered inactive by the bimetallic bio-nano particles [77,85]. The protein and carbohydrate components of the bacterial cell wall are reportedly disrupted, leading

to the inactivation of bacterial cells. The functional groups in the bacterial cell wall have broken C-C bonds. A new disinfection technique for neutralizing human viruses can be developed by combining solar disinfection (SODIS) and nanotechnology. ZnO is the most commonly utilized nanoparticle for wastewater disinfection, which theoretically makes the antiviral activity more effective when exposed to sunlight [86]. The photocatalytic system is perfect in this respect because of its strong solar radiation, minimal startup costs, and viability for longer durations [87].

2.6. Photocatalysts in Water Treatment

TiO_2 photocatalysts are promising candidates for wastewater treatment with the necessary properties and have shown tremendous promising results for SARS-CoV-2 using bacteriophages MS_2, phage f2, human adenovirus, and murine norovirus. Furthermore, TiO_2 has advantageous properties such as affordability, firmness, harmlessness, and suitable potential for redox reactions, allowing for photocatalytic applications in the synthesis of H_2, degradation of pollutants, reduction of CO_2 [88], and fixation of N_2 [89]. Photocatalytic water disinfection can overcome the limitations of conventional disinfection techniques by reducing the production of hazardous byproducts and significant quantities of chemicals. Other semiconductor materials have been effectively applied in photocatalytic wastewater treatment, including ZnO, graphene, $BiVO_4$, g-C_3N_4, and metal-organic frameworks. TiO_2 is one such material [90].

3. General criteria of Photocatalyst in COVID-19 Treatment

Wastewater discharged from hospitals contains a variety of toxins including pharmaceutical residues, chemicals, radioisotopes, and microbiological infections. Notably, adenoviruses, hepatitis A virus (HAV), and polioviruses have been discovered in hospital wastewater. For affected patients residing in apartment buildings, drainage plumbing systems have been suggested as a potential route for transferring SARS-CoV-1 coronavirus to sewage systems [89,91]. Coronaviruses are transferred through aerosols or microscopic water droplets.

3.1. Functioning of Inactive Virus

Viral capsids and viral DNA are produced as a result of viral capsid formation and viral DNA release by TiO_2 photocatalysis, which inactivates viruses by degrading their proteins and genomes [77,92]. In this instance, the four steps that comprise the virus inactivation process are (a) modification of the protein sequence, (b) disruption of the protein conformation, (c) disruption of the protein aggregate size, and (d) disruption of the ability of the spike virus protein to bind to other proteins in the host cells (Figure 3). When using TiO_2, the amount of ROS produced is influenced by the particle size, surface area, porosity, and structure, which in turn reduces the effectiveness of inactivation. Yoshizawa et al. (2020) [93] inactivated the contagious bursal disease virus using photocatalytic scrubber oxidation and UV radiation (IBDV). They discovered that uracil dimerization in viral RNA is the principal cause of the UV inactivation of viruses [94]. Additionally, it has been reported that a photocatalytic system based on a non-woven fabric made of Cu/TiO_2 attained bioaerosol inactivation (up to 70%) owing to cell death. Through the deterioration of viral proteins, TiO_2 thin films also significantly disinfected the influenza virus. The degradation was dependent on UV illumination time and purpose. When the photocatalyst surface and viral particles meet, the aforementioned mechanisms are affected, thereby increasing the photocatalytic effectiveness because more ROS are produced [95]. The efficiency of the proposed photocatalyst was improved by the addition of silica to TiO_2 nanoparticles because silica increased the band gap of the TiO_2 nanoparticles, which increased OH ions. Viral inactivation was achieved using silica-doped TiO_2 nanoparticles. The silica-doped TiO_2 was attributed to an increase in the adsorption rate of the virus onto the catalyst and higher generation of $OH^{\bullet}$, which is reasonable for inactivation (Figure 3) [96]. Notably, the inclusion of silica does not expand the surface, which results in the formation of a

photocatalyst [77,91]. Several variables are crucial for the effectiveness of the inactivation of airborne viruses [97]. A continual model for the virus might not be specific to other airborne viruses, because photocatalytic mechanisms have varying efficiencies for rendering viruses in the air inactive [98]. The photocatalytic procedure, by adjusting the photocatalytic rate, was significantly affected by environmental conditions such as temperature and humidity for virus inactivation.

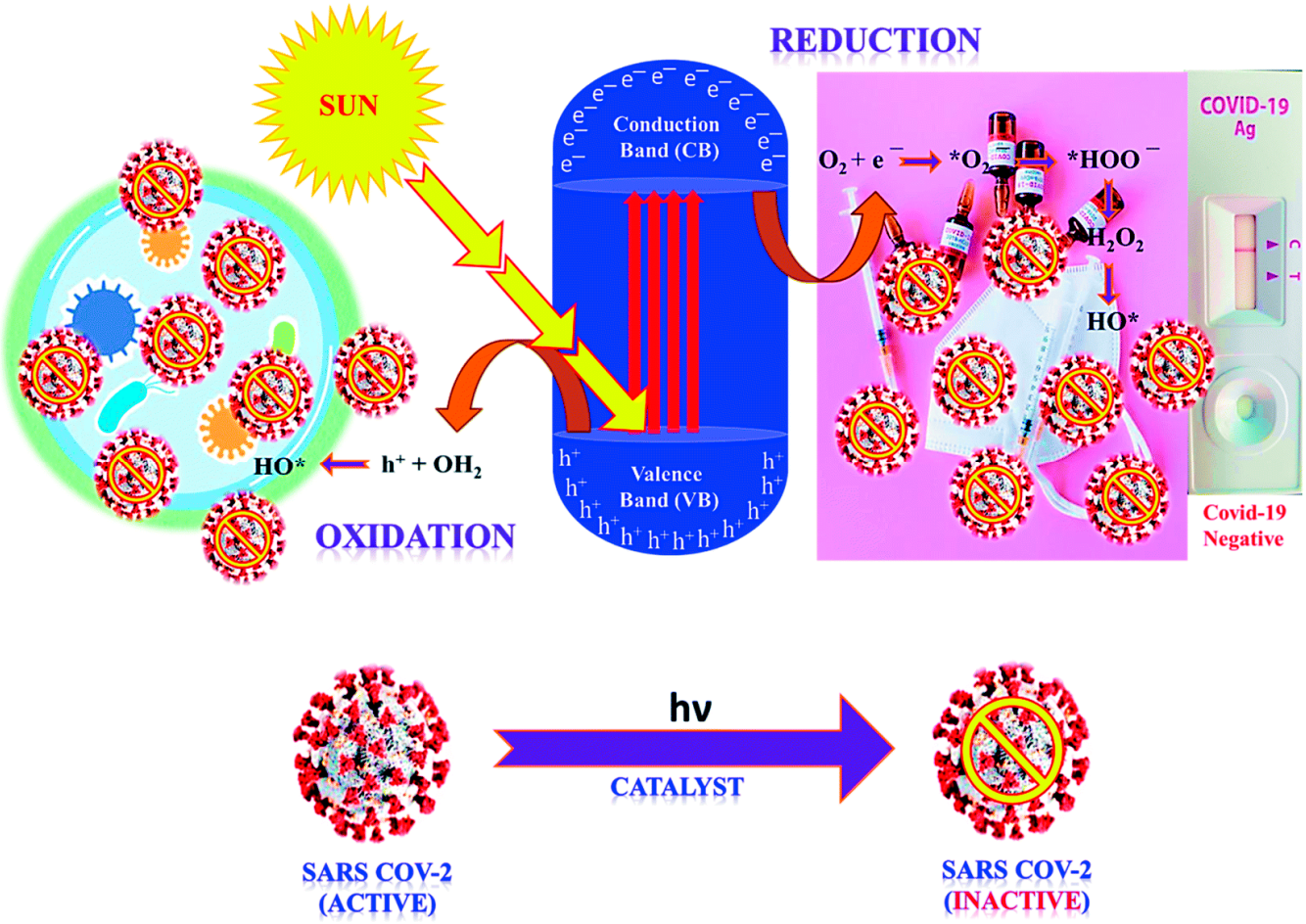

Figure 3. Viral inactivation process of SARS CoV-2 by nano-semiconductor under light irradiation [96].

3.2. Highly Light Sensitivity Photocatalyst System

Different methods, such as doping with non-metals, linked semiconductors, metal deposition, and defect-induced visible-light-active photocatalysts, have been used to increase the spectral responsiveness of TiO_2 to visible light. Ceramic plates with TiO_2-coated surfaces can be activated for hepatitis B virus release by poor ultraviolet light, sunlight, or indoor sunlight [16,99]. Through the deterioration of viral proteins, UVA and TiO_2 thin films may be successfully employed to decontaminate the influenza virus in the air (Figure 4). The duration and strength of UV irradiation affect the inactivation effect [100]. To prevent from working of SARS-CoV-2 in indoor settings, a tungsten trioxide-based photocatalyst with ultraviolet irradiation fixed on a filter combination and an antiviral fabric-treated copper nanocluster has been used [91]. After 10 min, the viral load decreased to 98%, and after 30 min, the virus was completely inactivated. After 30 min, the SARS-CoV-2 RNA burden dropped by 1.5 log10, indicating that SARS-CoV-2 was effectively inactivated.

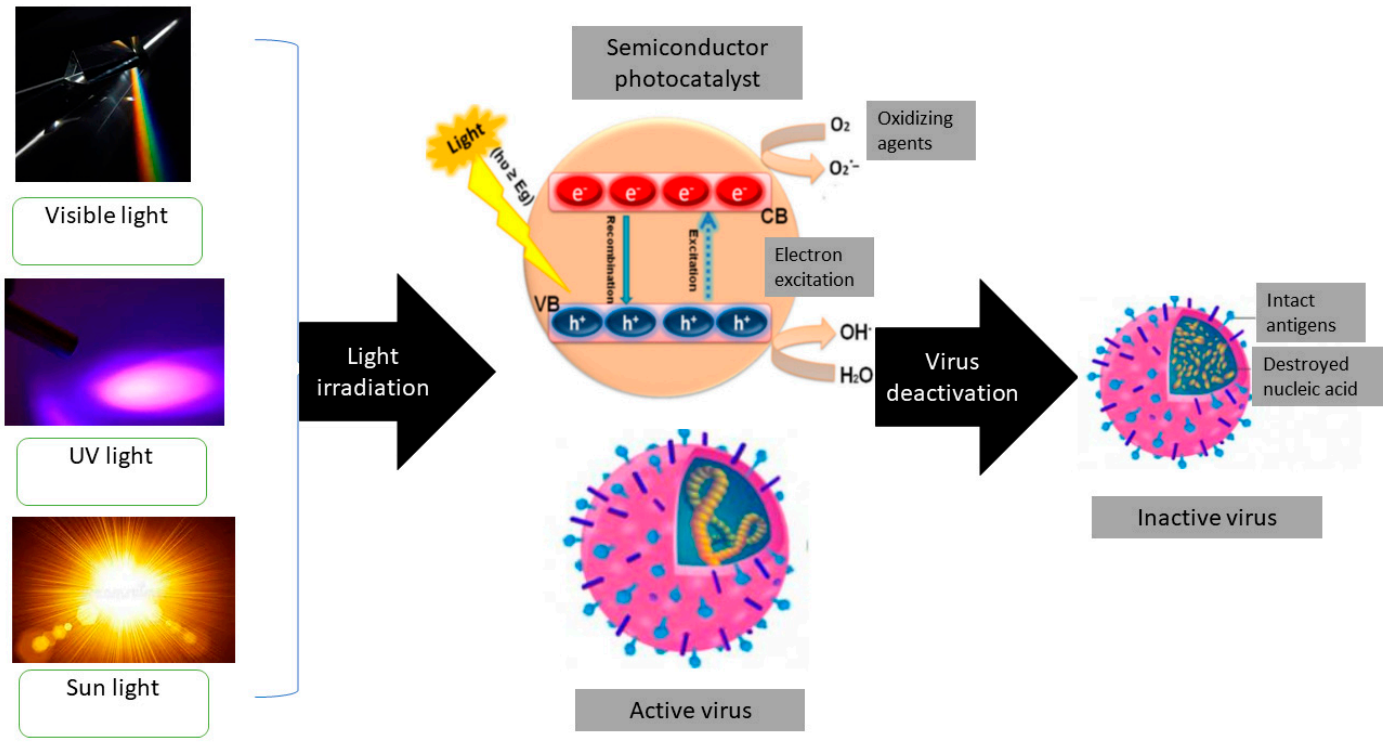

Figure 4. Photocatalytic processes for removal of airborne viruses from indoor air.

LEDs have also been used as light sources for photocatalytic devices. In a related study, Bono et al., 2021 [101] investigated the use of LEDs and solid alveolar foam as efficient and economical technologies for inactivating airborne viruses using photocatalysts. They performed this study by first introducing an LED photocatalytic system with TiO_2/−SiC solid alveolar foams to prevent airborne viruses, such as T2 bacteriophages [90]. Additionally, a UV-LED air purifier device was used to inactivate the influenza virus linked to aerosols. In this instance, the aerosol-associated influenza virus in indoor air was effectively inactivated by a TiO_2-coated aluminum plate exposed to UV-LED radiation [98].

3.3. Anti-Bacterial Properties

To create surfaces that are both antibacterial and antiviral free from germs or viruses, the anti-bacterial properties of nanomaterial can be used. To combat SARS-CoV-2, several nanomaterials composed of metals, semiconductors, and alloys have been suggested. Contagious viruses have been observed close to patients in public places and hospitals or residences, antiviral nanomaterial-based surfaces, or coatings. This could successfully function both indoors and outdoors, as it would be more promising for these reasons. In this regard, photocatalytic surfaces may hold more promise as they oxidize, deactivate, and eliminate microorganisms in environments with typical ambient lighting, i.e., they work well inside. Recent research has demonstrated the enormous capability of material surfaces to inactivate SARS-CoV-2 [96]. TiO_2 is well known for its ability to photo-degrade organic pollutants, promote bacterial and viral disinfection, and possess self-cleaning properties. It is a promising photocatalyst because, when exposed to ultraviolet (UV) light, the chemical species adsorbed on its surface are substantially oxidized [102]. TiO_2-based photocatalysts generate highly oxidizing free radicals under the influence of UV irradiation and are known to have bactericidal and antiviral effects against a variety of bacteria and viruses, including influenza, rotavirus, and SARS-CoV-2. To successfully impact photocatalytic performance, surface changes by combining with other functional anti-microbial/viral nanomaterials are one of the key elements, along with the modification of the material [103]. This makes TiO_2 highly desirable for surface, air, and water disinfection, which could be helpful for

inactivating SARS-CoV-2 and affecting individuals and the environment. It has been demonstrated that when exposed to UV light, TiO_2 NPs may have harmful impacts on both people and the environment by inducing oxidative stress, which can lead to cell damage, genotoxicity, inflammation, immunological response, and other problems [95].

3.4. Non-Toxic Photocatalyst System

The application of photocatalysts in thin-film coating forms remains a significant component of the technology used in daily life, particularly in hospitals or homes for the prevention of bacteria and viruses. Handling nano-powder photocatalysts can lead to severely limited secondary issues, such as the separation of the photocatalyst from the solution or immersion during the photocatalytic reaction, as well as health issues [22,104]. In the absence of light, the TiO_2 nanocrystal forms, sizes, and orientations have also demonstrated the ability to deactivate microbial agents. In particular, highly textured (004) anatase-nanograin-based nanostructured TiO_2 films have demonstrated exceptionally high photocatalytic performance. Such oriented nanograins display potent bacterial death in ultraviolet light radiation owing to the high Ti atomic density on their planes [105]. The nanostructured TiO_2 surface can greatly benefit from this observation because it can provide antibacterial capabilities even when the surface is not exposed to light or does not receive continuous light. TiO_2-based photocatalysts appear to be important cutting-edge materials for preventing the spread of viruses and their contamination because of their efficient photocatalytic actions for their potential applications in low light using other antimicrobial/viral agents such as Cu/Ag, as discussed above [106]. Figure 5 illustrates the proposed mechanism for the potential photocatalytic inactivation of the AgCN composite photocatalysts [107].

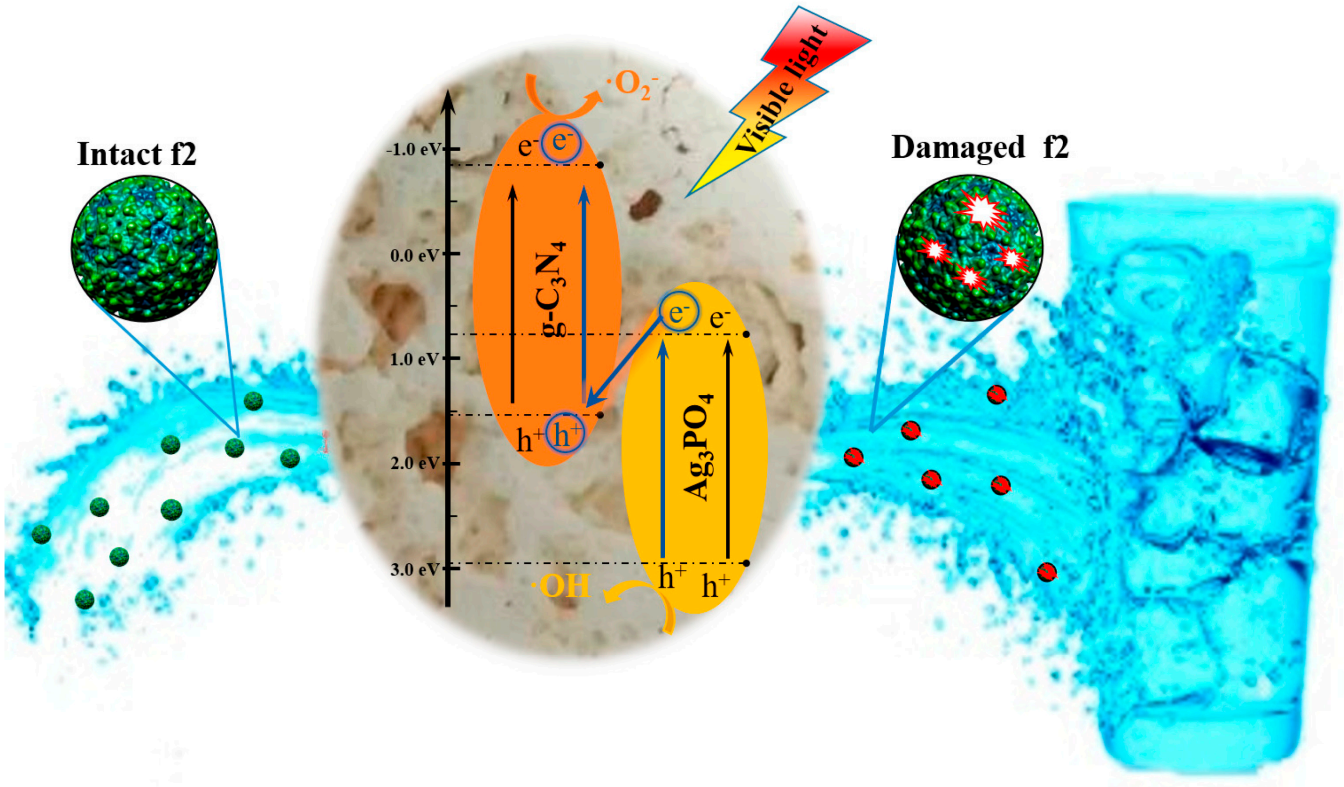

Figure 5. Photocatalytic mechanism of inactivation of bacteriophage f2 by the AgCN photocatalysts under visible light irradiation [107].

4. Mechanism and Setup in COVID-19 Treatment

The process that produces ROS production is crucial for viral destruction. The cytoplasmic membranes strike the components present in the intercellular, including genetic contents inside the microorganism, which are the next steps in the major breakdown of microorganisms after a protracted ROS attack damages the cell wall (Figure 6). Viruses and bacteria that serve as hosts frequently coexist in natural water. Hence, the effectiveness of the inactivation of photocatalytic in a virus/bacterium is crucial from a practical standpoint. Natural organic molecules affect photocatalytic virus disinfection in water systems. The water systems contain natural organic materials (NOMs) such as nucleic acids, carbohydrates, and proteins, in addition to bacteria [77,89]. They may also act as disinfectants and quench ROS production. Therefore, NOMs must be considered when disinfecting viruses.

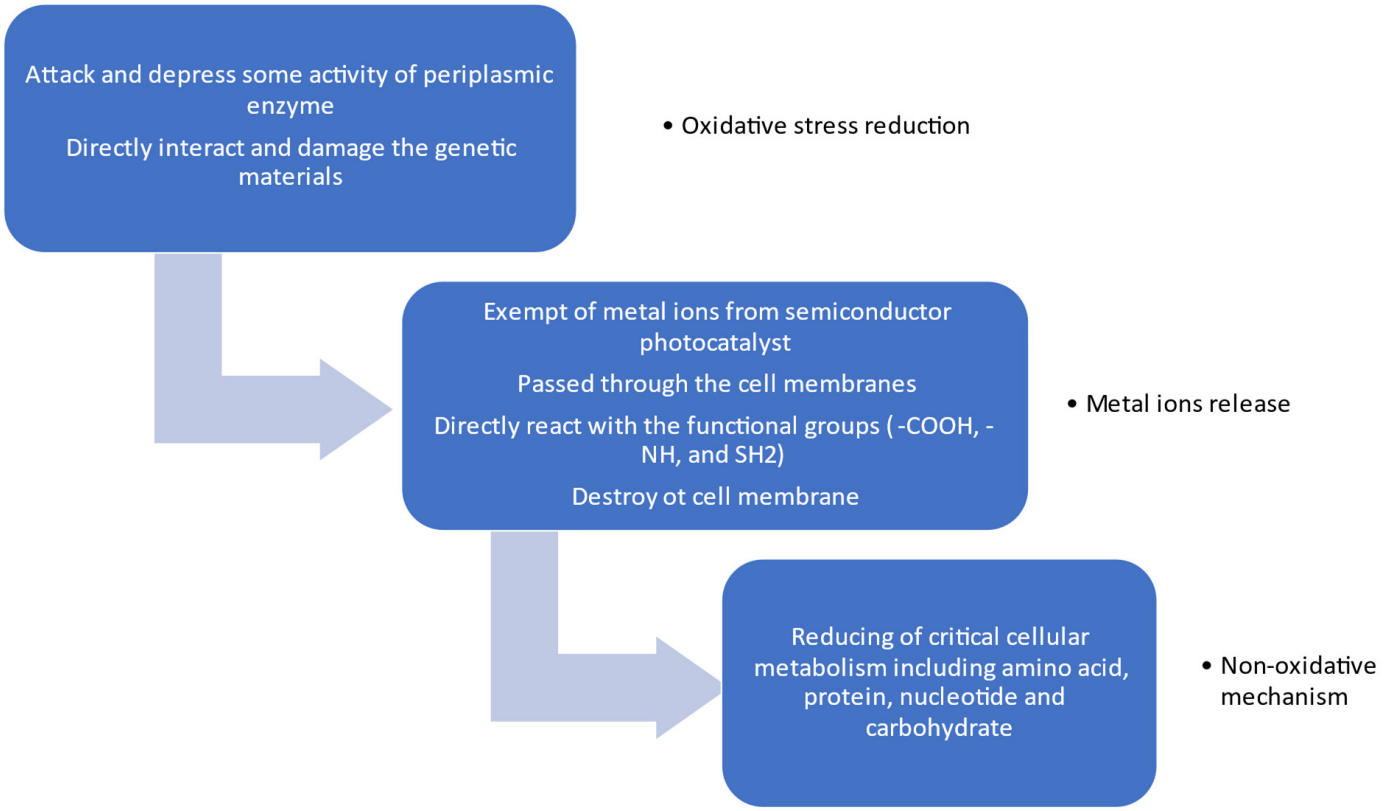

Figure 6. General mechanism of inactivation of COVID viruses by semiconductor photocatalysis system.

4.1. Metal Oxide-Based Photocatalyst

4.1.1. Titanium Oxide

It was already noted that a variety of materials, typically composed of metal oxides, metal sulfides, oxysulfides, oxynitrides, and composites, have been employed as photocatalysts. Among these, TiO_2 is utilized more frequently to sterilize organic substances and microbiological agents. The most effective catalyst for rendering airborne MS_2 viruses inactive was a TiO_2/UV photocatalyst. TiO_2 is utilized in air purifiers as a photocatalyst in the form of a filter. This filter must have a sufficient surface area to pass a certain amount of dirty air while in the air stream [92]. By adopting vacuum UV (VUV, wavelength 200 nm) the performance of the photocatalytic process for air applications can be improved because the light is substantially absorbed in the atmosphere. The hepatitis B virus (HBV) is inactivated using nano-TiO_2 particles and TiO_2-coated ceramic plates acting as a photocatalyst [101]. The inactivation of influenza viruses was accomplished using a thin sheet of TiO_2-coated glass. TiO_2 has been used with other substances, such as copper (II), for the inactivation of airborne viruses. Cu (II)-TiO_2 nanocomposite has

been created and utilized to inactivate viruses in the air, and it had adequate antiviral properties [90]. Currently, numerous works were performed to improve the commercial TiO_2's photocatalytic properties for inactivating microbiological agents. Anatase TiO_2 nanoparticles are a straightforward microwave-hydrothermal approach to manufacturing anatase TiO_2 quantum dots. which resulted in a greater energy gap. Additionally, it demonstrated an increase in UV light absorbance owing to the improved photocatalytic inactivation capabilities of *E. coli*. Additionally, the TiO_2 thin film was able to kill the influenza virus by reducing viral proteins; nevertheless, the duration and strength of the UV irradiation were key factors in this inactivation process. This leads to the conclusion that TiO_2 thin films can be effectively utilized to kill the virus called influenza in the air, as well as other airborne viruses, and to obstruct the spread of viruses through the air [108]. Moreover, a novel method for improving TiO_2's photocatalytic activity involves doping it in metals. Additionally, noted that when Au and Ag are used to adorning TiO_2, a secondary impact of the surface plasmon resonance causes a significant light absorption, increasing the performance of the decorated material [97].

The size of the photoactive TiO_2 after 20 min of solar light was enhanced, by increasing its size and achieving 99.9% antiviral efficacy against SARS-CoV-2. For instance, iron- and nitrogen-doped TiO_2 nanoparticles are effective antibacterial options with good anti-biofilm action and low toxicity toward lung and skin cells [109]. Additionally, several textile fabrics have been successfully coated with photoactive antiviral compounds with large surface areas. Hydrophobic interactions play an important role on coated fabric surfaces for the inactivation of the virus by adsorption process, distortion form, and induction under normal conditions. Therefore, the surface impact was particularly crucial for TiO_2-coated samples to detect virucidal activity at night. For instance, TiO_2 produced from a hydrosol was treated with –OH and –COOH functional groups, which considerably aided in TiO_2 particle retention within the fabric fibers. In addition, after the addition of TiO_2 particles, hydrosols would extend the surface by several orders of magnitude [103]. As a result, the free radicals produced by TiO_2 particles may harm the viral surface proteins, reducing their ability in binding cells and harming the DNA, thereby stopping the activeness of reproduction. Therefore, virucidal activity in other fabrics may also benefit through combining TiO_2 particles with the cellulose fibers. Because the cotton fabric is coated by TiO_2 particles, providing a small amount of resistance to water because of the low adherence among the TiO_2 particles and fibers. Goods made of cotton were typically laundered and reutilized in hospitals [8]. The hydrophilicity of the coated textiles with the expansion in the exterior portion of the TiO_2 particles is responsible for antiviral effects. Additionally, after washing the TiO_2-coated materials for one cycle, similar viral inactivation was observed.

4.1.2. TiO_2-Ag

The higher surface area Ag-TiO_2 systems created in the laboratory demonstrated strong antibacterial capabilities against bacteria and MC3T3-E1 cells. It has been suggested that even in the dark, the process functioned rigorously as a bactericide agent [110]. According to the Schottky barrier effect, the flow of charges from the membrane to the surface and the attachment of Ag and TiO_2 are the mechanisms of bacterial inactivation. Due to the surface plasmon characteristics of the silver nanoparticles placed on the base of TiO_2, Ag-TiO_2 systems may show promise in the ability to kill bacteria like *E. coli* in the dark. According to this theory, respiratory electrons from germ membranes might be transported to silver NPs and afterward to TiO_2, causing microorganisms to gradually remove the electrons completely [111]. Ag-TiO_2-CS filter bed without valence electron was developed to remove and deactivate airborne MS_2 bacteriophage particles. In contrast, photocatalytic elimination, and inactivation of microorganisms and the H1N1 virus were accomplished using an Ag-TiO_2 nanocomposite covering. Owing to the inclusion of Ag, the composite had increased photocatalytic activity and exceptionally potent antibacterial and antiviral actions against infectious viruses and *E. coli* that were greater than 99.99% effective [112].

4.1.3. TiO_2/CuO Hybrid Photocatalyst

The powder form of CuO/TiO_2 may even inactivate its extremely pathogenic delta version of SARS-CoV-2 by coating it with glass. The Cu(I) species in CuO denaturalize spike proteins, leading to SARS-CoV-2 RNA fragmentation in the absence of light [113]. Furthermore, exposure to white light leads to the photocatalytic oxidation of SARS-CoV-2 chemical compounds. The current material that is antiviral will be efficient in inactivating a variety of potential mutant strains and will not be restricted to a particular viral variation according to the mechanism [101]. The CuO/TiO_2 photocatalyst is particularly capable to lower the probability of COVID-19 infection inside buildings where light and darkness are typically intermittently present. This can be ascribed to the varied valence states of Cu. The results obtained through Cu (II) species observed on the surface of TiO_2 nanoclusters show the strong oxidation property predicting the formation of holes and anti-virus Cu(I) species in the visible light through photo-induced interfacial charge transfer. However, the virus can be made inactive by denaturing the proteins in the absence of light using Cu(I) species [114]. This literature analysis showed the antiviral activity of TiO_2-based photocatalysts both indoors and outdoors. As a result, the Cu_xO/TiO_2 photocatalyst can be employed as an antiviral coating substance to lower the risk of viral infection.

4.1.4. Co-Doped TiO_2

A cost-effective electrochemical biosensor for spike protein (RBD) detection of coronavirus was reported for treating the infections caused by SARS-CoV-2 using cobalt-doped TiO_2 nanomaterials [92]. Therefore, functionalized TiO_2 nanotubes were prepared using the electrochemical anodization approach in a wet chemical process to identify SARS-CoV-2 in a rapid time [92]. The designed sensor was able to identify the S-RBD protein of SARS-CoV-2 at extremely low concentrations between 14 and 1400 nM, indicating a linear response for the detection of viral proteins over the tested concentration range. The advantage of this technology was that the sensor could promptly (30 s) identify the viral S-RBD protein with a LOD of only 0.7 nM. [92]. TiO_2 nanoparticles have also demonstrated several advantages, such as catalytic performance, extended surface, and strong antiviral properties [71]. TiO_2 is recognized as one of the most efficient photocatalytic semiconductors owing to its excellent stability and cost-effectiveness. As a result, nitrogen-doped TiO_2 can perform efficient photocatalysis when exposed to light [115]. N-TiO_2 has been used to sterilize pathogens and rejuvenate masks for reuse by simply exposing the mask to light for a certain time [115].During the absorption of light, ROS was produced, in which hydroxyl radicals (OH), has a vital part in adhering to and inactivating SARS-CoV-2 infection [116].

4.1.5. Iron Oxide

It has been demonstrated that the various iron oxides, such as Fe_2O_3 [117] and Fe_3O_4, are used with the SARS-CoV-2 glycoproteins to engage with host cell recipients, and the virus can be inactivated by altering its glycoproteins. Reverse transcription-polymerase chain reaction (RT-PCR) tests can often assess COVID-19 in the laboratory in under two hours [118]. A portable device that uses magneto-plasmonic nanoparticles and plasmonic heating for rapid testing in under 20 min. This nano-PCR equipment has a high sensitivity (500%) and great specificity (500%) and is portable, dependable, and exact (500%). It offers COVID-19 detection and enables the creation of ambulatory clinics for numerous affected people, with exceptional testing accurately [119].

4.1.6. Copper Oxide

The surface coating of both copper and copper oxide nanoparticles has a significant antimicrobial action in resisting SARS-CoV-2 [120]. This served as an inspiration for the development of a clever and simple method to create an antiviral mask. To increase the hydrophobicity of the mask and render it impervious to aqueous droplets, the mask was coated by a non-woven surgical mask with shellac/copper (Cu and CuO) nanoparticles. The obtained photocatalytic mask has outstanding photothermal and photoactivity charac-

teristics for viral activity as well as superior reusability and self-sterilization effectiveness. The temperature of the mask's surface increases to 70 °C as exposed to light, creating reactive radical species that make it easier for viruses with membranes smaller than 100 nm to burst [121].

4.2. Metal-Based Photocatalysts

4.2.1. Silver

To provide an antiviral capability, the silver nanoparticles produced in this case were coated onto the surface of the air filter using spark discharge generation (SDG) technology [122]. The silver node surface in this system is affected by the acceleration of ions and electrons under the influence of the electric field, which causes its surface to vaporize. Ag/TiO_2 with a range of Ag concentrations is improved for the oxidation process of microbial agents. According to Moongraksathum et al. (2018) [123], the virucidal effects of UV-A radiation are markedly enhanced by the presence of silver on TiO_2. To enhance Ag's photocatalytic abilities for inactivating the virus present in the air, Ag might be coated with TiO_2 [9,124]. Depending on the basic TiO_2 material, nAg/TiO_2 increased the inactivation rate of MS_2 five times more, and the potential of inactivating the virus has been improved with silver content. The effectiveness of the nAg/TiO_2 nanoparticles in inactivating the MS_2 virus in drinking water matched the increased hydroxyl free radicals caused by UV absorption irradiation about four times in the 8 W UV-A lamps (in the range of 315–400 nm). Thus, to summarize, the interaction between them results in virus inactivation when Ag nanoparticles are added to TiO_2 [125]. Additionally, it has been noted that silver-doped TiO_2 improves both the adsorption and inactivation of viruses by increasing the generation of hydroxyl free radicals. It must be emphasized as the majority of the aforementioned analysis is aimed at photocatalytic inactivation in liquids, some scientists have also investigated the effects because of the inactivation of viral agents in the air [126].

4.2.2. Copper

Copper (Cu) is used in the process of photocatalysis with different organic molecules present in the air. According to previous reports, the existence of copper on the surface may change depending upon the organic contaminant's interaction with the catalytic surface, thereby increasing its effectiveness [127]. The semiconductor cuprous oxide (Cu_2O) is used as a photocatalyst due to its excellent bandgap absorption. Cu_2O can be a good substitute for the quick inactivation of viral agents through photocatalytic processes for effective antiviral characteristics [128]. The $CuxO/TiO_2$ photocatalyst is used as an antiviral agent by denaturing the viral protein during photocatalytic oxidation. Cu (II) species in CuxO function as electron acceptors, producing Cu(I) species with antiviral activity and holes with high oxidation potential in the valence band, similar to TiO_2 [129]. The $CuxO/TiO_2$ photocatalyst can continue to have an antiviral effect even in the dark owing to the active Cu (I) species [130]. Consequently, it was proposed that the $CuxO/TiO_2$ acting as a photocatalyst can reduce the damaging factors of the viral infection present in the air by applying a photocatalyst coating [131].

4.3. Carboneous-Based Photocatalysts

Carbon-based photocatalysts show the best possible ability to capture natural light and have received a lot of attention because there is no risk of metals seeping into the water supply. Carbon-based substances, such as fullerene, carbon nanotubes, carbon dots, and graphitic carbon nitride, are among the non-metal photocatalysts created for the disinfection of viruses (g-C_3N_4).

4.3.1. Fullerene

The primary mechanism by which fullerene aggregates inactivate viruses is the generation of singlet oxygen ($1O_2$), a ROS. Viral resistance is governed by the structural and chemical makeup of non-enveloped viral capsids [93]. However, the aggregation of

nanoscale particles is the extent of fullerene's potential as a photocatalyst in the process of wastewater treatment [108]. Therefore, it seems most practical to immobilize fullerene to maintain its photoactivity in aqueous systems [129]. The straightforward nucleophilic addition of a primary amine and subsequent transfer of proton immobilizes fullerene on silica gel and polystyrene resin in suitable conditions [132]. It is proposed that these surfaces are coated with a single layer of fullerene without any discernible aggregation. Fullerene immobilization on solid substrates greatly enhanced $^1O_2$ generation in water when exposed to visible light and rendered MS_2 bacteriophages inactive even after repeating the cycles significantly not reducing the photocatalytic activity. In addition, fullerene is immobilized on MCM-41 and exhibits antiviral characteristics toward MS_2 in a water system when exposed to visible light [133].

4.3.2. Carbon Nitride

g-C_3N_4 is a non-metal catalyst frequently helpful for water treatment because it is composed of organic elements, including carbon, nitrogen, and hydrogen, and can break water and generate hydrogen when exposed to light [134]. Through photocatalytic degradation, g-C_3N_4 has been shown to exhibit antibacterial and antiviral properties. According to Figure 7, viral inactivation by photocatalysis is a nonselective reaction brought on by photogenerated e and the ROSs that it produces (mainly ($\bullet O_2^-$) and hydroxyl ($\bullet$OH) radicals) [135]. A typical hydrogen electrode serves as a reference, and the bandgap of g-C_3N_4 is 2.7 eV, which is suitable for visible-light-driven photocatalysts with conductive bands of −1.1 eV and valence bands of +1.6 eV [85].

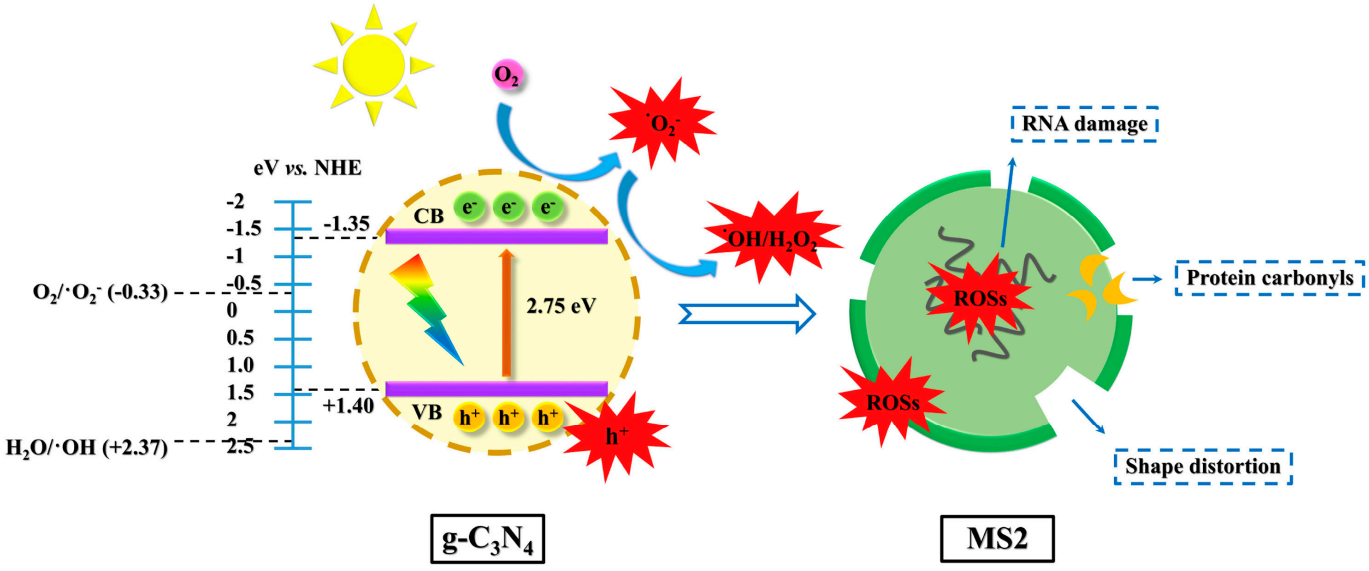

Figure 7. Photocatalytic Inactivation of Viruses Using Graphitic Carbon Nitride-Based Photocatalysts: Virucidal Performance and Mechanism [135].

Kong et al. (2021) [136] employed bacteriophage MS_2 to assess the inefficiency of photocatalytic in g-C_3N_4 for virus disinfection. Under visible light irradiation, bacteriophage MS_2 was fully rendered inactive in 360 min. The 72-h regrowth test was also carried out in complete darkness. No obvious plaques appeared, demonstrating the g-photocatalytic C3N4 inactivation of the virus [137]. By contrasting the efficiency of g-C3N4 for viral deactivation as the visible-driven photocatalyst, such as nitrogen-doped TiO_2 (N-TiO_2), Bi_2WO_6, and Ag@AgCl [138]. It had discovered that g-C_3N_4 deactivated more than 7-log of MS_2, whereas the N-TiO_2 and Bi_2WO_6 photocatalysts deactivated MS_2 by roughly 1-log and 4-log, respectively. Ag@AgCl exhibits the maximum inactivation of MS_2 by the separation of charges and improving the harvesting of photons. The use of silver-based photocatalysts is expensive and can result in health hazards in treated water due to the

dissolution process [139]. Ag_3PO_4/g-C_3N_4 nanocomposites (AgCN) were synthesized hydrothermally and used in a photocatalytic inactivation process to analyze the bacteriophage f2 virus. The combination of Ag_3PO_4 and g-C_3N_4 improved the effectiveness of the proposed Z-scheme mechanism by effective charge carrier separation and broad visible-spectrum absorption. The inactivation of the f2 virus by binary nanocomposite catalysts was tested using radical quenching, and the results showed that the virus was catalytically disinfected with an efficiency of 6.5 log in 80 min due to selective ROS damage to the virus following charge separation through the components of g-C_3N_4 and Ag_3PO_4. As a result, a new, promising nanocomposite photocatalyst for viral disinfection of contaminated water was produced [140]. A new metal-free nanocomposite was created as oxygen-doped g-C_3N_4/hydrothermal carbonation carbon (O-g-C_3N_4/HTCC) microspheres using a two-step hydrothermal procedure. Under ideal circumstances, this nanocomposite demonstrated outstanding virucidal effectiveness for HAdV-2 with visible light absorption to eradicate 5 log in 2 h. As a result, the Z-scheme mechanism has been used to control and improve the antiviral activity of the O-g-C_3N_4/HTCC nanocomposite, with effective OH production leading to severe destruction of the HAdV-2 rigid capsid following an outstanding charge separation process [141]. The primary mechanism of degradation of g-C_3N_4 under natural light involves oxidative damage to the viral surface protein caused by ROS. This leakage and shape distortion ultimately cause the fast removal of genetic materials, specifically RNA, and result in viral death without defoliation [142].

4.3.3. Graphene Oxide

Graphene oxide (GO) exhibits superior hydrophilicity, bonding capacity, and wettability due to its extremely active sites on the margin and in its surface layer than in pristine graphene. GO might harm the viral structure by limiting virus implantation into host cells, GO/PVP nanocomposites have demonstrated high antiviral activity due to their non-ionic behavior [143,144]. However, the inactivation mechanism of GO involves interactions with proteins, causing GO to superficially reduce into the graphene form. The reduced version of GO, known as reduced graphene oxide (rGO), performed along with polysulfated dendritic polyglycerol, demonstrated significant inactivation features against several viruses, including orthopoxviruses, equine herpesvirus type 1 (EHV-1), and herpes simplex virus type 1. (HSV-1) [129]. A freestanding LIG membrane typically consists of a carpet of porous fibers that encourages the capture of microorganisms, specifically bacteria, and limits the growth of filtered microbes. In addition, periodic Joule heating was used to assist the LIG membrane filter [96]. This raised the temperature (to over 300 °C) and aided in the breakdown of bacteria as well as other compounds and microorganisms [96]. Therefore, graphene-based materials have the potential to avoid and combat COVID-19 by fusing with the technology of nanosized membranes as more environmentally friendly and sophisticated photocatalytic techniques [145].

4.4. Dimensional Advanced Materials-Based Photocatalysts

Several two-dimensional materials, including MXenes, metal-organic frameworks (MOFs), and covalent organic frameworks (COFs), can serve as semiconductor photocatalysts for the catalytic deactivation of SARS-CoV-2. They have attractive properties such as good conductivity, layered structure, mechanical firmness, flexibility, large surface area, and high affinity [146].

4.4.1. MXenes

2D carbides and nitrides (MXenes) have a high surface area and porosity, with superior adsorption of molecules and viruses [147–149]. Additionally, these materials encourage the production of ROS, which aids in inactivating the surface-adsorbed virus. The plasmon resonance feature of MXenes, when exposed to visible or infrared (IR) light, aids in the conversion of light into heat (photothermal effect), contributing to the deactivation of viral species and enabling phototherapy [150]. Recently, a Schottky heterojunction with

interfacial engineering was built based on the work function values of $Ti_2C_2T_x$ MXenes linked with Bi2S3 to modify the photocatalytic antibacterial activity of MXenes [151]. The engineering of work functions improved charge carrier transfer and made it possible to quickly kill microorganisms. Additionally, the carbides and nitrides with composites can be used as preservative coatings on PPE, which is promising [152]. In addition, docking analysis of proteomic data utilizing SARS-CoV-2 protein interactions as a comparison has proposed an MXene-dependent antiviral activity mechanism. The ability of MXenes to modulate viral proteins comprising host proteins, such as GRPEL1, NUTF2, and GNG5, controlling the antiviral activity, results in excellent antiviral efficacy. In addition, host and SARS-CoV (red-colored) proteins interact [150,153]. Additionally, the SARS-CoV-2 viral protein NSP15 is involved in nuclear and vesicle trafficking, while NSP7 is implicated in membrane trafficking and GPCR signaling.

4.4.2. Metal Oxide Framework (MOF)

The potential characteristics of MOF are high porosity, stability, tunability, a wide range of host-guest interactions, sorption, and release of ions terming as suitable candidates for a variety of photocatalytic applications, as well as in the biomedical sector. Owing to their exceptional ability to destroy bacterial cell walls, zinc-based imidazole MOFs (ZIF-8) were recently demonstrated as 100% virus-inactivation efficacy against *E. coli* within 30 min under sunlight [154]. Therefore, MOFs can be used to produce filters in industrial quantities for air-cleaning masks, clothing, ventilators, and air purifiers. Bismuth and bismuth-graphene nanocomposites (Bi@graphene) have been developed through recent research to function as photocatalysts when exposed to ultraviolet (UV) light. In addition, compared to pure bismuth nanospheres, the Bi@graphene nanocomposites demonstrated outstanding photocatalytic deactivation against *E. coli*. Thus, highly oxidative ROS production is associated with the enhanced antibacterial activity of nanocomposites [155]. Strong excitation and a quick charge transfer mechanism were produced by the involvement of the Bi surface and graphene. Subsequently, it was reported that aluminum-terephthalate-based MOFs can be used for removing airborne germs and controlling water content for interior applications [156]. Furthermore, monohydroxy terephthalate-based MOFs demonstrated outstanding antibacterial photocatalytic efficacy against *E. coli* bacteria, with 99.94% efficiency under 60% relative humidity. In particular, non-woven fabric air filters with monohydroxy-terephthalate coatings offer effective defense against abrupt variations in air humidity when used externally. By managing the effectiveness of the air, this study provides a significant result to the future scopes of antimicrobials, water adsorbents, and active filters. According to several investigations, the bioactive MOF (bioMOF) effectively disposed of *E. coli*, *P. aeruginosa*, *S. aureus*, and *C. Albicans* have much lower minimum inhibitory concentrations (MIC) [96]. Additionally, bioMOF demonstrated strong cytotoxicity toward the aberrantalytic air purifier epithelioid cervical cancer (HeLa) cell line and HAdV-36 deactivation activity, generating the potential of MOFs against the COVID-19 virus. MOFs and COFs might deactivate SARS-CoV-2 by removing crown-like spike proteins through the perforation of the lipid membrane and allowing the RNA to escape. Although the production of ROS impairs spike proteins, photocatalytic deactivation results in greater virucidal action [157].

5. Challenges in Photocatalyst Treatment

There are some limitations in the photocatalytic system for the inactivation of the virus. Some of them are recovery and reusability, unsafe disinfection, unstable coating, and fiber (Table 5).

Table 5. Common challenges/drawbacks in photocatalysis systems for environmental remediation.

Issue	Associated Problems	Outcome Suggestions	References
Recovery and reusability	• Suspended photocatalyst from the reaction solution • Adsorbed species at the surface of the photocatalyst • Partially degradation of pollutants molecules	• Fabrication of self-recovery photocatalyst • Application of magnetic photocatalyst • Design and develop a second-generation solid catalyst with high separation efficiency and the ability to be recovered and regenerated	[44,55]
Unsafe of disinfection	• The inactivation process is not completed. • The surface of the photocatalyst still contains dangerous virus organisms. • Incomplete recovery from the reaction mixture • Adsorbed of viral species	• Fabrication of a wide range of light adsorption of photocatalyst • Reduction in particle size • Improvement of surface reactivity and functionality of photocatalysis • Catalyst synthesis should be designed to produce catalysts with well-defined crystal structures, high affinity for different organic pollutants, and smaller particle sizes. • Fabricating composites or heterogeneous photocatalysts for efficient energy utilization and recovery	[49,138]
Photocatalytic coatings and membrane filters	• Not suitable for long-run applicability • Reduction in the amount of disposal-generated critical waste	• Development of facile strategies that promote the prevention, disinfection, and reusability of photocatalytic coating materials	[22,54,139]
Wastewater disinfection	• Aggregation of nanosized photocatalytic materials • Fewer surface sites	• Immobilizing photocatalytic materials with the porous or floating substrate • Improve recovery along with agglomeration to enhance reusability • Designing the morphology according to virology • Hybridizing or functionalizing with transition metals ions	[28,31,158]
Long scale applicability	• Agglomeration in water • Restricted surface-bound radical diffusion • Contact of liberated radicals with oxidizable cell wall substrates • Production rate and mechanical resistance induced by diffusion are the critical limitations associated with membrane photoreactors	• Internal monolithic structures acting as catalyst support also offer substantial surface sites for improved molecular adsorption and mass transfer • Fabrication of micro-structured photoreactors with 10–1000 μm dimensions • Effective irradiation of the entire catalytic surface through optimal light sources like optical fibers, LEDs	[29,30]

5.1. Poor Affinity toward Virus Species

The photocatalysts used in the nanosized are fragile and liable to aggregate in real-world water applications. It can limit the activation in a particular region and lower the efficiency of the photocatalyst. Hence, these obstacles must be removed for the degradation process in wastewater treatment independently. The problems faced by the photocatalysts

depending upon fluid environments can be resolved to address the aforementioned difficulties by preventing the movement of the catalyst on a permeable or floating substrate. The porous substrate can be an organic or inorganic membrane for creating the bifunctional photocatalytic membrane, which acts as a filter and photocatalyst in the same chamber. Besides, the addition of a catalyst into the substrate can cause it to settle at the bottom of the substrate. This circumstance can prevent the photocatalyst from being activated by the greatest amount of light. Therefore, it is possible to modify or functionalize the photocatalyst and the substrate ensuring the catalyst is on the top region.

5.2. Slow Degradation Rate

Limited light absorption is one factor that slows the rate of deterioration. In addition, using a translucent or transparent substrate may address the issue of source light usage. Because of its high surface area to volume ratio nature with extreme porosity, electrospun nanofibrous photocatalysts are highly preferred with much interest to use in the disinfection of water systems. However, electrospun nanofibrous photocatalysts are well known to be brittle and weak, and because of their large pore size, they can readily collapse. Because of this problem, they are not suited for long-term use in water treatment. The flexibility and mechanical strength of nanofibrous photocatalysts may be improved after manufacturing. It is difficult to efficiently recover suspended photocatalysts during water disinfection. The nanosized objects should be removed after disinfection and before the release/reuse of treated water. The magnetic isolation procedure is used to remove the suspended particles from the reaction mixture. Additionally, the difficult problem of recovery can be resolved by integrating specific prospective photocatalytic materials that have difficulty in removing magnetically separable elements.

5.3. Highly Cost Treatment

A more thorough evaluation of prospective substitutes for disinfecting water, air, and surfaces is necessary to improve the attenuation of energy and environmental footprint. Because of the significant redox capabilities of the generated ROS, photocatalysis is undoubtedly a cutting-edge "green disinfection" technique that targets widespread viruses found everywhere. The efficiency of ROS formation and annihilation of oxidative virus species are reduced for maximizing the capabilities of semiconductor material through low sunlight. The reassembly of electron-hole at a higher rate and broad bandgap energy causes the majority of semiconductor oxides to exhibit less photoactivity than other materials. The viral cell can be effectively destroyed by oxidation using visible- and/or NIR-light active photocatalytic materials, while UV-light with poor penetration helps to limit the use of antiviral agents. It should be noted that numerous modification techniques were thoroughly investigated to address the problem of insufficient energy utilization and conversion. However, further investigations are required in the field of modified nanomaterials for antiviral action. One crucial factor affecting the entire photocatalytic process is the stability of the semiconductor photocatalyst with difficult reaction factors. Additionally, to meet the economic requirements, the material used as the catalyst should demonstrate sufficient stability and reusability, given the long-term environmental stability of the virus. Advanced heterojunction systems combined with metal-free photocatalysts have the potential to improve performance while enhancing photostability.

5.4. Resistance of Viruses via Mutation

Variations in their structural and geometric features from other microorganisms, such as bacteria and viruses, have been observed as better resistant to photocatalytic disinfection. In contrast to other microbes, viruses are the smallest type among all types of microorganisms; they increase quickly by spreading via the air, causing a variety of diseases through the infected cells. When SARS-CoV-2 enters the human body, similar to COVID-19, it first targets the breathing systems, including the nose, throat, windpipe, and lungs, before harming the organs and killing the entire body. According to a recent

discovery made using protein, SARS-CoV-1, in contrast, is more unstable, moves more quickly all the time, and takes more time to bind to human cells. In contrast to MERS and SARS-CoV-2, COVID-19 has been significantly easier to transfer to humans since it has high stability and is primed to strike the body. Therefore, the creation of a cutting-edge treatment to inactivate targeted viruses, particularly SARS-CoV-2, in the fluid environment is urgently necessary. An intelligent photocatalytic membrane may be created that would reject, adsorb, and photo-catalytically break down the virus based on its geometric and structural characteristics. The structural and geometrical differences between viruses and other microorganisms make them more resistant to photoinactivation. Additionally, the lengthy environmental persistence of the virus and its capacity for fast mutation increases its likelihood of transmission, making the inactivation process more difficult. Therefore, modifying and modeling the photocatalytic reaction needs a thorough knowledge of the chemical mechanisms that occur during disinfection. To overcome the aforementioned obstacles and effectively deactivate targeted viruses such as SARS-CoV-2, further research has to be conducted on photocatalytic devices currently in use. Although the scientific community has created several disinfection technologies since the COVID-19 pandemic outbreak, which gives hope for neutralizing the microbes in the polluted water, photocatalytic disinfection will be a long-term solution to reduce its environmental impact.

6. Conclusions

The widespread COVID-19 pandemic affecting world health calls for the development and widespread use of disinfection for contaminated areas, which are the main sources of the transmission of diseases. The majority of disinfection methods that are currently advised are chemical-based and energy-intensive affecting the environment. Oxidation methods with advancement have been acknowledged as one of the most effective disinfection methods. Different morphologies, surface defects, and antiviral activities have greatly altered the photocatalytic activity of semiconductors toward the inactivation of SAR-CoV-2. Numerous photocatalytic systems and semiconductors have been developed to achieve this goal. However, the widespread use of photocatalytic disinfection technology is constrained by our incomplete understanding of important factors, such as the viral photo-inactivation mechanism, fast virus mutagenicity, and survival for an extended period of time. Additionally, this review paper offers up-to-date information on readily available commercial modalities for a successful virus photoinactivation procedure to validate the photocatalysis process. A thorough discussion of the long-term problems and viable solutions is recommended to address these information gaps.

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