Review

Antiviral Coatings, from the Narrative to Visible Light Active Films

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Laboratory of Materials Science and Nanotechnology, CR-INSTM, Department of Biomedical Sciences, University of Sassari, Viale San Pietro 43/B, Sassari 07100. Italy; plinio@uniss.it

Abstract: The increasing need for effective antiviral strategies has led to the development of advanced surface coatings to combat the transmission of viruses via fomites. The Covid-19 pandemic has dramatically stimulated research in the field, and numerous advances have been made in understanding virus-surface interactions. A crucial step has been the experimental study of viral infection due to interactions with fomites. The alarm created by the pandemic, including the initial uncertainty about the mechanisms of infection spread, put the focus on fomites as a possible cause of virus transmission. Later research showed, however, that such a mechanism is implausible. The knowledge gained about fomites during the pandemic can be used to develop a new generation of biocidal coatings for bacteria and viruses that surfaces can actually transmit. In particular, biocidal coatings photoactivated by visible light represent a promising opportunity.

Keywords: thin films; Covid-19; antiviral coatings; reactive oxygen species

1. Introduction

Common objects with which we frequently come into contact during our daily lives can turn into fomites and become hosts of infectious agents, such as bacteria, viruses, or fungi, and potentially facilitate their transmission from one individual to another[1]. Fomites are defined as the objects in the environment on which infectious agents can survive, becoming a potential vector for person-to-person transmission. The material surfaces are not inherently infectious and the materials become fomites only when contaminated with pathogens. Fomites serve as indirect vehicles for pathogens, enabling the spread of diseases when individuals touch contaminated objects and then their own mucous membranes, e.g., eyes, nose, mouth. Common examples of fomites are the surfaces of door handles, mobile phones, toys, utensils, bed linens, and medical equipment such as stethoscopes and thermometers. Because in our daily lives, we continuously touch surfaces, much care should be taken in the choice of materials in critical environments for health, such as schools, long-term care facilities, surgery and emergency rooms, and more in general hospitals. Such surfaces are defined as "high-touch surfaces", i.e., those surfaces that are frequently "touched" by the hands and represent "the surfaces" most frequently contaminated by microorganisms[2].

The survival of viruses and bacteria on fomites depends on many factors, some external, such as temperature and humidity, and others inherently dependent on the type of material and surface properties, such as porosity and wettability. For fomite transmission to occur, the virus must be transferred from the surface to the mucous membranes (eyes, nose, or mouth) in a sufficient dose to establish infection. Evidence suggests this route is less efficient compared to respiratory droplet or aerosol transmission[3].

The types of diseases and infections that can be potentially caught through fomites include several common respiratory and enteric illnesses. The common viral infectious diseases that could potentially spread via fomites include: Adenoviruses are a group of viruses that are the sources infections in the upper respiratory tract and the eyes[4]; Coronavirus, such as SARS and MERS, which causes upper respiratory infections in both animals and humans[5–8]; Hand foot and mouth disease,

is an infection that gives rise to fever and blisters on the hands, feet, and inside the mouth[9]; Norovirus, responsible for gastroenteritis diseases[10–12]; Rhinovirus, the most common viral infectious agent in humans[13,14]; Rotavirus, which is the leading cause of diarrhoea in infants and young children[15].

2. Viral Infection from Fomites, Narrative or a Scientific Case?

The outbreak of Covid-19 from SARS-CoV-2 has drawn attention to fomites as a possible means of spreading the infection. The Covid-19 pandemic has promoted for the first time a series of systematic studies on the effects of fomites in the spread of viral infections. In the early phase of the pandemic, the alarm created by the possibility of infection through surfaces led to indiscriminate use of disinfectant agents that later proved unnecessary in retrospect.

Early studies on Covid-19 infection showed that the virus in the laboratory can survive on different types of surfaces, such as plastic, stainless steel, and cardboard, from 4 up to 72 hours[16–18]. Later research has provided a more nuanced understanding and it has been demonstrated that transmission of infection through fomites is a very rare, if not impossible, event[19–23]. Interpretation of the results is also not easy due to the lack of protocols that make comparative evaluation of the studies unfeasible[24,25]. Unlike droplet or airborne transmission, proving fomite transmission involves tracing a direct link between a contaminated surface and infection, which is complex and often indirect. On the other hand, laboratory conditions do not replicate real-world environments where desiccation, UV exposure, and cleaning practices reduce the virus viability. Therefore, the assessment of infection should be done with care even if environmental sampling in healthcare settings and public spaces identifies SARS-CoV-2 RNA on frequently touched surfaces[26]. The detection of RNA or even viable virus on surfaces suggests that contaminated fomites may harbor viral material, however, this detection does not confirm that the virus remains infectious in real-world conditions. Furthermore, it should be taken into account that environmental factors like temperature, humidity, and UV light degrade viral particles over time[27,28]. Contact tracing and epidemiological studies have found that most Covid-19 transmission events are associated with close person-to-person contact or shared airspace, rather than surface contact.

One interesting example is cash, which at the beginning of Covid-19 pandemia, was considered a possible medium acting as a fomite for spreading the infection[29]. A risk assessment evaluation has considered that the risk of contracting Covid-19 via person-to-person cash transactions is lower than once per 39,000 days, or 107 years, for a single person[30].

Current understanding places fomite transmission as a secondary route, with respiratory transmission being dominant and epidemiological evidence suggests that respiratory droplets and aerosols are the primary modes by which SARS-CoV-2 has spread. The contribution of fomites is considered relatively minor. However, some context specific risks must be considered, and high-contact, shared surfaces in healthcare settings or public spaces may pose a greater risk, particularly when combined with poor hand hygiene practices[31,32]. For this reason, innovations such as light-activated coatings and metal-based antiviral surfaces (e.g., copper and silver nanoparticles) that can provide passive protection by reducing surface contamination are still a hot research topic.

This brief review is devoted to a general analysis of some aspects related to implementing antiviral coatings. The experience accumulated during the COVID-19 pandemic showed that a critical approach is needed in evaluating the spread of infections from surfaces. Advances in research on the topic have allowed for a more realistic view of the effect of fomites while at the same time opening new perspectives in understanding the interaction of viruses and bacteria with surfaces. The creation of surfaces with effective antiviral properties and the field of application of such surfaces, in light of the COVID-19 experience, will have to be reduced to particular cases and specific types of viruses that can lead to infection by fomites. For this reason, the review focuses on a concise comparative analysis of some critical parameters for antiviral surface design, e.g., the different responses between enveloped and non-enveloped viruses and surface properties. The second part of the article describes a particular case that is a harbinger of important expectations, namely that of antiviral surfaces that

are photoactivated by visible light. In this case, their activity is carried out through the emission of reactive oxygen species, particularly singlet oxygen, capable of destroying or interfering with virus replication.

3. What Kind of Virus, Enveloped and Non-Enveloped

A key consideration in designing an antiviral surface is that it should act as a biocide with broad-spectrum activity against viruses and bacteria. However, the environmental resistance varies significantly between enveloped and non-enveloped viruses due to differences in their structural composition (**Table 1**)[33]. These differences influence their survival on surfaces, resistance to disinfectants, and vulnerability to environmental factors like temperature[34], humidity, and UV light[35].

Enveloped viruses, such as coronaviruses, possess a protective lipid bilayer envelope surrounding the protein capsid and nucleic acid. The lipid envelope contains glycoproteins essential for cell entry, but it is sensitive to environmental conditions and easy to disrupt. Most of the last epidemics, SARS-CoV-2, Zyka, and MERS, as well as the Influenza virus and Herpes simplex virus, are due to enveloped viruses.

Non-enveloped viruses, lack a lipid envelope and are composed of a protein capsid that encases the nucleic acid. The protein capsid is more stable and resistant to environmental stressors. Some examples are the Norovirus, Poliovirus, Rhinovirus.

Enveloped and non-enveloped viruses also have different responses to disinfectants[36]. In enveloped viruses, the lipid envelope makes them vulnerable to detergents, alcohols, and lipid-disrupting agents. In the absence of a lipid envelope, the non-enveloped viruses are more resistant to lipid-dissolving agents. More aggressive treatments, such as bleach (sodium hypochlorite) or oxidizing agents, are necessary. For instance, Norovirus resists alcohol-based sanitizers but is inactivated by chlorine-based disinfectants.

In comparison, the enveloped viruses survive for shorter durations on surfaces due to their sensitivity to desiccation and environmental factors. SARS-CoV-2 survives up to 72 hours on plastic but much less on porous materials like paper. Non-enveloped viruses can survive for weeks to months on surfaces, particularly in dry, low-humidity environments. Norovirus can persist on surfaces for up to two weeks.

For these reasons, particular attention should be given to antiviral surfaces against non-enveloped viruses. They are a source of greater concern in environments like hospitals and cruise ships, where outbreaks of hardy viruses like Norovirus can occur. In general, enveloped viruses are easier to inactivate with detergents and alcohols, whereas non-enveloped viruses are highly resistant, requiring stronger disinfectants and more stringent control measures.

Table 1. The effect of external factors for enveloped and non-enveloped viruses.

External Factor	Enveloped virus	Non-enveloped virus
Desiccation	Sensitive to drying due to dependence on a hydrated lipid envelope	More resistant to drying; capsid structure retains integrity
Temperature	Moderate resistance; extreme heat denatures envelope proteins.	Higher resistance; capsids withstand a wider range of temperatures
Humidity	Stability decreases at low humidity due to lipid degradation	Stability often increases at low humidity
pH	Sensitive to extreme pH changes that disrupt the lipid envelope	Stable across a broad pH range, including acidic and alkaline conditions
UV Radiation	Moderately resistant; UV can damage the viral RNA/DNA	More resistant due to protective protein capsid.
Reactive oxygen species	Weakly resistant, ROS disrupt the lipidic bonds	Resilient to ROS attacks

4. What Kind of Surface?

The properties of surfaces play a key role in determining interactions with viruses and bacteria. These properties include roughness, porosity, hydrophobicity, and surface energy that can govern the inactivation of viruses or prevent their adhesion to surfaces (**Table 2**)[37,38]. Particular attention must be dedicated to the design of surface properties in antiviral coatings[39,40]. A deeper understanding of the chemical-physical interactions of viruses at the interface[41] needs clearly to be further developed[42,43]. Electrostatic secondary bonding, such as van der Waals interaction, hydrophobic effect, and hydrogen bonding play a fundamental role at the interface. Modelling such interactions needs a case by case approach as a function of the surfaces and viruses.

Surface roughness is another parameter that has a direct influence on surface-virus interactions. In fact, an increase in surface roughness results in a higher number of contact points between the surface and the virus. This can translate into better antiviral activity of the system. However, surface roughness must be controlled to prevent antiviral particles from nesting in the roughness, making disinfection more difficult. Smooth surfaces, are often preferred in healthcare settings for easier cleaning and reduced contamination.

Surface energy influences wettability and the adhesion of viruses. In general, low-energy surfaces, such as fluoropolymers, resist protein and viral attachment, while high-energy surfaces promote stronger interactions with antiviral agents or coatings. Surfaces can be active elements, for example by producing reactive oxygen species that attack the structure of viruses, or passive elements, where controlling the surface energy can improve antiviral efficacy.

Porosity is another parameter that can be used in the design of antiviral surfaces[44]. For example, pores can act as reservoirs for antiviral agents, allowing sustained release over time. Porosity allows for deeper penetration of viruses, which might enhance interaction with antiviral agents embedded within the material. On the other hand, surfaces with high roughness or porosity may degrade faster or become harder to clean over time. Furthermore, fabricating surfaces with precise control over roughness, porosity, or surface energy can be challenging and costly.

The adhesion of viruses to surfaces is controlled by another important parameter, which is the degree of *hydrophobicity of the surface*. Hydrophobic surfaces in fact tend to repel water, and this reduces the possible adhesion of aerosol particles containing viruses. On the other hand, hydrophobic surfaces, however, can also facilitate virus adhesion through non-polar interactions with proteins or the virus envelope.

Superhydrophobic surfaces minimize viral attachment by creating self-cleaning effects, where water droplets roll off and remove adhered particles[45].

These surface properties often work synergistically or antagonistically, depending on the material and application. For instance, combining surface roughness with hydrophobicity creates superhydrophobic surfaces, reducing viral adhesion and enhancing self-cleaning properties. Porosity and surface energy, high porosity with low surface energy reduces viral adherence while allowing incorporation of antiviral agents.

Table 2. Effects of Surface Properties on Antiviral Activity.

Surface property	Effect on antiviral activity	Examples and applications	Challenges
Roughness	Increased surface area enhances contact with antiviral agents.	Rough surfaces coated with metals like copper improve viral inactivation.	Can harbor viral particles in crevices, making cleaning difficult.
	Too much roughness may shield viruses from external disinfectants.	Antiviral coatings for high-touch surfaces like door handles.	Requires precise engineering to balance efficacy and cleanliness
Porosity	Porous surfaces act as reservoirs for sustained release of antiviral agents.	Metal-organic frameworks loaded with silver or copper for continuous antiviral action.	Excessive porosity can trap viruses, reducing efficacy of surface cleaning.

	Promotes interaction between viruses and embedded antiviral agents.	Porous membranes used in air and water filters and self-sterilizing materials.	May reduce mechanical strength of materials in some applications.
Hydrophobicity	Hydrophobic surfaces repel waterborne viruses, reducing adhesion.	Superhydrophobic surfaces prevent viral contamination via self-cleaning properties.	Non-polar interactions may enhance adhesion of some enveloped viruses.
	Creates self-cleaning surfaces where water droplets roll off, removing contaminants.	Commonly applied in medical textiles, PPE, and protective coatings.	Requires robust materials to maintain hydrophobicity over time.
Hydrophilicity	Increases viral interaction by enhancing surface wettability.	Hydrophilic coatings with embedded ROS generators improve inactivation efficiency.	Excessive water retention may reduce long-term antiviral efficacy.
Surface Energy	High surface energy promotes strong adhesion of antiviral agents or coatings.	High-energy surfaces, such as titania, enhance ROS production for photodynamic antiviral activity.	Can increase adherence of contaminants if not combined with effective antiviral coatings.
	Low-energy surfaces resist viral adhesion, reducing contamination risk.	Low-energy fluoropolymer coatings are used in touchscreens and medical devices.	Low-energy surfaces may be less effective at retaining antiviral agents.

5. Antiviral Coatings, Different Materials and Strategies

The choice of strategy to fabricate antiviral coatings depends on the intended application, cost, and required durability[46]. Combining multiple approaches, for instance, nanomaterial-enhanced polymer coatings, is an emerging trend to enhance efficacy and broaden applicability. Further research into safe, scalable, and multifunctional coatings is critical to addressing future viral outbreaks. Several materials and processing technologies have been developed so far to obtain antiviral coatings. One of the main issues to be addressed is the capability of the coating to be deposited on different surfaces. Deposition of a film on a metal, glass or polymer surface requires specific methodologies, and not all of them are flexible enough to allow a universal use. In this article, the different antiviral coatings that have been developed so far are not discussed in detail. The reader can refer to several extensive reviews about this subject[47–50]. A short resume of the main advantages and drawbacks of the different surfaces are reported in **Table 3**.

Table 3. Advantages and challenges of the different materials and strategies for antiviral coatings.

Approach	Advantages	Challenges
Metal-based coatings	Broad-spectrum efficacy, durability	Potential toxicity, high cost
Polymer-based coatings	Versatility, metal-free	Limited long-term stability
Photocatalytic coatings	Light-activated, self-cleaning properties	Dependence on light exposure, wavelength and intensity
Nanomaterial-Enhanced	High efficacy, scalability	High cost, potential toxicity
Bio-inspired coatings	Eco-friendly, sustainable	Lower efficacy in some cases

6. Antiviral Coatings Activated by Visible Light

Visible light-activated antiviral coatings provide a practical and safe method for reducing viral transmission in various settings, making them an essential tool in public health and infection control strategies.

Antiviral coatings activated by visible light represent an advanced strategy for continuous disinfection. These coatings use photosensitive materials or catalysts that absorb visible light (wavelengths 400–700 nm) to generate reactive species capable of inactivating viruses, including enveloped ones like SARS-CoV-2.

Visible light excites photosensitizer or photocatalyst in the coating, transferring energy to surrounding oxygen molecules to produce ROS, such as singlet oxygen ($^1O_2$), superoxide anions (O_2^-), and hydroxyl radicals ($\cdot OH$). These ROS attack viral proteins, lipids, and nucleic acids, disrupting the viral envelope, capsid, and genome.

Furthermore, some coatings modify the surface charge under visible light. In some cases the interaction change between viral particles and coating promotes the biocidal activity. Photosensitizers on the coating directly interact with light to transfer energy to viral components, destabilizing their structure.

The main advantage of visible light activation is that unlike UV-C, visible light is safe for human exposure, allowing for continuous antiviral activity in confined environments. This opens the route to applications in specific places such as surgery rooms and space stations[51]. An intrinsic advantage is that using ambient light, reduces the need for UV light sources that can be harmful upon prolonged expositions. The photoactivated coatings can have broad-spectrum activity and be effective against a wide range of viruses, including both enveloped and non-enveloped types and bacteria. The antiviral surfaces, as opposed to disinfectants such as alcohol, whose effectiveness is exhausted almost immediately due to evaporation, have a long-term effectiveness and can maintain antiviral properties over extended periods. However, there are several drawbacks that need to be considered. One is that the effectiveness of the antiviral effect depends on the intensity of the light applied. The duration and intensity of the visible light itself are, therefore, parameters that directly influence the system's response. At the same time, the system does not work in the dark and this can also be a limitation in some circumstances. These limitations can be overcome by using a hybrid approach to the design of the antiviral surface by combining them with other properties. Finally the cost and scalability is another issue to be considered for the technology transfer from laboratory to industry, advanced materials and complex processing techniques may increase production costs.

Some examples of nanomaterials capable of producing singlet oxygen ($^1O_2$) under visible light illumination are typically photosensitizers or catalysts that absorb visible light and transfer energy to molecular oxygen (O_2) to generate $^1O_2$[52]. These materials are employed not only as antiviral-antimicrobial coatings, and environmental disinfection but also in applications such as photodynamic therapy. The systems capable of generating singlet oxygen can be molecules, oxide and metal nanoparticles, carbon based nanostructures, such as fullerenes, carbon dots and carbon nanotubes[53].

Molecular based nanosystems are generally based on porphyrins and phtalocyanines[54]. Porphyrins are organic molecules with strong absorption in the visible light range, particularly in the Soret band (400–450 nm). Phthalocyanines are macrocyclic compounds with also strong visible light absorption and high efficiency in generating singlet oxygen. Other molecules used to generate singlet oxygen are organic dyes like methylene blue and rose bengal. They are well-known singlet oxygen generators, and their incorporation into nanostructures enhances their stability and applicability.

Fullerenes and theirs derivatives are carbon-based nanostructures that can generate singlet oxygen under visible light due to their unique electronic properties[55–57]. Such property has been also observed in carbon dots[58], and carbon nanotubes. Graphene derivatives, such as graphene oxide functionalized with porphyrins or phthalocyanines, have been also developed to enhance singlet oxygen production and photosensitizers under visible light.

Semiconductor nanomaterials are one of the most common choices. Visible light-responsive semiconductors can generate reactive oxygen species, including singlet oxygen, through energy transfer[59]. Zinc oxide (ZnO)[60,61] and titanium dioxide (TiO_2)[62] doped with elements like nitrogen[63], silver[64], or copper to extend their light absorption to the visible range. An alternative is represented by bismuth-based semiconductors[65,66], such as bismuth vanadate ($BiVO_4$) and bismuth oxyhalides (BiOX).

In general, molecular systems, such as the porphyrins are very efficient generators of singlet oxygen but are not very much photostable. Carbon dots represent an interesting alternative, also with respect to oxide semiconductors that need a specific design to absorb light in the visible range.

Table 4. Comparison of Systems for Visible Light-Activated Antiviral Coatings.

System	Mechanism	Advantages	Challenges	Applications
Porphyrin-based coatings	Generates singlet oxygen under visible light via photosensitization.	High efficiency; broad-spectrum activity; customizable.	Potential photobleaching; stability issues in some environments.	Medical textiles, air filters, hospital surfaces.
Phthalocyanine-based coatings	Produces singlet oxygen through photosensitization in the visible spectrum.	High photostability; strong visible light absorption.	Complex synthesis; cost of materials can be high.	Photodynamic therapy, antiviral paints.
Carbon-based coatings	Functionalized graphene or carbon dots generate ROS upon visible light activation.	High surface area; excellent stability; tunable properties.	Cost and complexity of synthesis and functionalization	High-performance antiviral surfaces, electronics.
Metal oxide coatings	Generates reactive oxygen species (ROS) like superoxide and hydroxyl radicals under light.	Durable; scalable; cost-effective.	Requires doping to activate under visible light.	Construction materials, water disinfection.
Nanoparticle-Enhanced Coatings	Embedded metal (e.g., Ag, Au) nanoparticles enhance light absorption and ROS production.	Synergistic effects; can be tuned for specific wavelengths.	High cost of noble metals; potential environmental concerns.	Medical devices, high-touch public surfaces.

7. Effect of ROS

The resistance of enveloped and non-enveloped viruses to reactive oxygen species (ROS) is primarily determined by their structural composition. ROS, such as hydroxyl radicals ($^{\bullet}$OH), superoxide anions (O_2^-), hydrogen peroxide (H_2O_2), and singlet oxygen[67], attack viral components, including lipids, proteins, and nucleic acids, leading to inactivation. However, enveloped and non-enveloped viruses exhibit different levels of vulnerability to ROS due to the differences in their protective structures, as we have previously described.

The lipid bilayer envelope of enveloped viruses is sensitive to oxidative stress. The envelope contains glycoproteins whose disruption inhibits the capability for host cell attachment and entry of the virus. The lipid envelope is highly vulnerable to ROS-induced peroxidation, which disrupts the viral membrane, rendering the virus non-infectious. Oxidative damage to glycoproteins and other envelope proteins further compromises the virus ability to infect host cells. Furthermore, ROS can directly damage the viral RNA or DNA inside the envelope, but the primary target is the lipid envelope. Enveloped viruses, such as SARS-CoV-2 and Influenza, are efficiently inactivated by ROS-generating agents, such as hydrogen peroxide and photocatalytic materials.

In non-enveloped viruses the protection is given by a protein capsid instead of a lipid envelope. The capsid is composed of tightly packed, stable proteins designed to shield the viral nucleic acid. ROS must be able to disrupt the protein barrier of the virus in order to affect its genome. The protein capsid provides significant protection against ROS, reducing the likelihood of direct damage to the nucleic acid. This requires high concentrations of ROS or prolonged exposure to ROS. Viral capsid proteins provide protection against ROS, thereby reducing direct damage to the nucleic acid. It is, therefore, the ROS that can denature the capsid proteins, exposing the nucleic acid to oxidative damage. Non-enveloped viruses, such as Norovirus and Poliovirus, are more resilient to ROS than enveloped viruses and require higher doses or longer exposure to ROS-producing agents for effective inactivation.

The ROS attack to the viruses is, in general, through multiple mechanisms. *Lipid Peroxidation* (Enveloped Viruses): ROS react with unsaturated lipids in the viral envelope, disrupting membrane integrity. *Protein Oxidation* (All Viruses): ROS oxidize amino acid side chains, leading to protein

misfolding, denaturation, and loss of function. *Nucleic Acid Damage* (All Viruses): ROS induce strand breaks, base modifications, and crosslinking in viral RNA or DNA, compromising replication.

An important question to address is the different antiviral action of radicals, such as hydroxyl radicals ($\bullet$OH), superoxide anions (O_2^-), and hydrogen peroxide (H_2O_2), with respect to singlet oxygen[68]. They have distinct chemical properties and mechanisms of action, leading to different antiviral efficacies. Both are effective oxidant agents, but their antiviral efficacy depends on factors like reactivity, selectivity, and stability.

Hydroxyl Radicals ($^\bullet$OH) are extremely reactive and non-selective[69]. Very short-lived in biological systems, with a half-life of nanoseconds. They are generated via Fenton reactions, photolysis of H_2O_2, or photocatalysis for instance by TiO_2 under UV illumination. They are highly effective against both enveloped and non-enveloped viruses due to their ability to damage multiple viral structures and result particularly effective in inactivating enveloped viruses by destroying the lipid bilayer. The higher oxidation power of hydroxyl radicals than singlet oxygen results in higher antimicrobial activity. Their efficacy is limited by short diffusion distance, requiring close proximity to the virus for activity. The high reactivity, however, limits stability and action radius.

Singlet Oxygen ($^1O_2$) is less reactive than $^\bullet$OH but more selective[70]. Singlet oxygen is longer-lived than hydroxyl radicals[71], with a half-life in microseconds in biological systems. It is generated via energy transfer from a photosensitizer (e.g., porphyrins, phthalocyanines) under light activation and a great advantage is that can be produced by illumination with visible light.

In general, it is chemically reactive towards C=C double bonds. Primarily oxidizes specific targets, such as unsaturated fatty acids, leading to membrane destabilization, or sulfur-containing amino acids (e.g., cysteine, methionine) and aromatic residues, impairing viral proteins functionality. It can also causes oxidative damage to guanine bases, interfering with viral replication. Singlet oxygen is highly effective against enveloped viruses due to lipid oxidation. On the other hand, has only moderate efficacy against non-enveloped viruses; less likely to penetrate the capsid and damage internal components. It is more selective than $^\bullet$OH, reducing collateral damage to non-viral components. Compared to hydroxyl radicals it has also the advantage of acting over longer distances due to its relative stability. It has an ideal use in photodynamic therapies and visible light-activated antiviral coatings.

Table 4. Comparison of antiviral efficacy of hydroxyl radicals and singlet oxygen.

Aspect	Hydroxyl Radicals ($^\bullet$OH)	Singlet Oxygen
Reactivity	Extremely reactive, non-selective	Highly selective, moderate reactivity
Target Viruses	Effective against both enveloped and non-enveloped viruses	More effective against enveloped viruses
Action Mechanism	Indiscriminately attacks lipids, proteins, and nucleic acids	Targets specific lipid bonds and amino acids
Stability	Very short-lived	Longer-lived
Diffusion Distance	Limited to immediate proximity	Greater range
Generation Methods	Fenton reaction, photocatalysis	Photosensitizers under visible light
Applications	Suitable for sterilization in high-concentration systems	Ideal for light-activated coatings and surfaces

8. Conclusions

The lessons learned from the COVID-19 pandemic must be carefully considered for the development of antiviral coatings. The cost-effectiveness and real effect on limiting the viral infections are critical aspects that should be part of the choice of developing and using antiviral coatings in an extensive way. In some specific restricted environments, such as emergency and surgery rooms, the application of biocidal surfaces still appears a viable. Biocidal surfaces should have the broadest possible activity, against different types of virus and bacteria. For this purpose the surface design must consider a combination of different properties. These properties must be

carefully engineered to balance a broad and effective antiviral activity with practical challenges like durability and scalability.

Visible light-activated coatings represent a promising innovation, offering safe and continuous disinfection through the generation of reactive oxygen species. These coatings effectively target viral components, with singlet oxygen showing particular efficacy against enveloped viruses. While hydroxyl radicals exhibit higher reactivity and broad-spectrum activity, singlet oxygen stability and specificity make it ideal for long-term applications in well-lit environments.   Future research should focus on optimizing the interaction between material properties, viruses and ROS generation while exploring new strategies to overcome limitations in different environmental settings.

Conflicts of interest: I declare no competing interests.

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