Nanomaterials for Airborne Virus Inactivation: A Short Review

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Received: 16 July 2020 / Revised: 10 October 2020 / Accepted: 14 October 2020 / Published online: 30 October 2020
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Abstract

The coronavirus disease 2019 (COVID-19) that broke out at the end of 2019 spread rapidly around the world, causing a large number of deaths and serious economic losses. Previous studies showed that aerosol transmission is one of the main pathways for the spread of COVID-19. Therefore, effective control measures are urgently needed to contain the epidemic. Nanomaterials have broad-spectrum antiviral capabilities, and their inactivation for viruses in the air has been extensively studied. This review discusses antiviral nanomaterials such as metal nanomaterials, metal oxide-based nano-photocatalysts, and nonmetallic nanomaterials; summarizes their structure and chemical properties, the efficiency of inactivating viruses, the mechanism of inactivating viruses, and the application of virus purification in the air. This review provides insights on the development and application of antiviral nanomaterials, which can help control the aerosol transmission of viruses.

Keywords COVID-19 · Aerosol transmission · Nanomaterials · Antiviral

1 Introduction

The coronavirus disease 2019 (COVID-19) that broke out at the end of 2019 is still a pandemic across the world, which has caused great damage to human health and economic development. Curbing the spread of COVID-19 needs to be considered from three aspects: controlling the source of infection, cutting off the transmission pathways, and protecting susceptible individuals (Wilson and Zumla 2019). Studies have shown that one of the main transmission pathways of COVID-19 is the droplets produced by patients which then form biological aerosols (Ge et al. 2020). This pathway has also been verified in the spread of other viruses such

as influenza viruses (Lindsley et al. 2016), SARS viruses (Tang et al. 2006), etc. Van Doremalen et al. (2020) found that COVID-19 can survive for more than 3 h in aerosols. Besides, some researches and field study reports show that viral RNA from COVID-19 can be detected in the air (Liu et al. 2020; Ong et al. 2020). Therefore, controlling the spread of biological aerosols is the most effective way to inhibit the spread of viruses.

Currently, commonly used measures for protection against airborne viruses include wearing protective clothing and mask (Brienen et al. 2010), increasing indoor ventilation (Sze-To et al. 2014), and chemical disinfecting (Brienen et al. 2010). However, there are several limitations: wearing protective clothing and mask for a long period can be uncomfortable for human; ventilation is not suitable for all indoor environments; and cumbersome chemical disinfection does not have long-term effectiveness. Therefore, more effective measures are in need to continuously and efficiently inactivate airborne viruses with limited effect on the daily life of the public. Current researches have utilized microwave, ozone, ultraviolet, plasma, and filtration technologies to develop indoor purification devices that are able to inactivate viruses in aerosols. The efficiency of microwave disinfection depends on the combined effects of microwave thermal, field and quantum effects (Brondani and Siqueira 2018). Wu and Yao (2014) found that under 700 W of microwave radiation, 90% of the airborne MS2 virus was

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inactivated within 2 min. Ozone takes effect on the polypeptide chain of the viral capsid protein and damages the nucleic acid (Murray et al. 2008). Hudson et al. (2007) designed a portable ozone generator module, which is capable of generating 25 ppm ozone with an inactivation capacity of more than 99.9% for the sample virus. The strong absorption of high-energy ultraviolet light by viral proteins and nucleic acids would destroy the viruses (Wigginton and Kohn 2012) and upper-room ultraviolet germicidal irradiation (UVGI) system is an effective way to control the transmission of viruses by aerosols (Linnes et al. 2014). The mechanisms for inactivating the viruses with low-temperature plasma include the strong oxidation of reactive oxygen species (ROS), the bombardment of high-kinetic energy electrons on the virus shell, and the inhibitory effect of ultraviolet light on nucleic acid synthesis (Pradeep and Chulkyoon 2016). Xia et al. (2019) designed a dielectric barrier discharge non-thermal plasma packed bed reactor to process the gas flow inoculated with virus aerosol, which can reduce MS2 virus by 2.3 log. In terms of the diffusion effect of the nanosize virus particles, high-efficiency filtration is effective to remove viruses in ambient air (Azimi and Stephens 2013). Malaithao et al. (2009) found that high-efficiency particulate air (HEPA) filters can remove 99% of the airborne T7 virus with a particle size of 40 nm.

Virus possesses a size in the nanoscale range and its protein shell is hard. Even if the shell protein is destroyed, it may not be completely fatal. On the other hand, it can be inactivated completely by destroying the nucleic acid (Zhang et al. 2019a). However, it is reported that the virus may be resistant to the treatment by the aforementioned methods (Camara et al. 2017; Carratala et al. 2017). In recent years, studies have confirmed the inactivation effects of nanomaterials on various viruses. Nanomaterials refer to materials with dimensions in the nanoscale range (1–100 nm). Due to large specific surface area, rich surface atom, and high

surface energy, nanomaterials exhibit unique optical, thermal, mechanical, electrical, and chemical properties (McNeil 2009). Nanomaterials can inactivate viruses through physical contact, the generation of ROS, catalytic oxidation, photothermal effects, and metal ion release. Moreover, nanomaterials can be combined with other measures to enhance antiviral performance. Therefore, it is very promising to develop anti-viral nanomaterials and apply them to air purifier filters, building ventilation system, anti-viral fabrics, and anti-viral spraying agents, which assists to control the spread of viruses through aerosols.

In this review, antiviral nanomaterials have been categorized into metal nanomaterials, metal oxide-based nano-photocatalysts, and nonmetallic nanomaterials. Their efficiency and mechanism of inactivating viruses are summarized. In addition, some purification devices aiming for inactivating the airborne viruses are listed as well. We hope that this review will provide inspiration for the development of antiviral nanomaterials to control the aerosol transmission of viruses.

2 Metal Nanomaterials

Numerous studies have shown that metal nanoparticles such as Ag (Lara et al. 2010), Cu (Armstrong et al. 2017), Au (Broglie et al. 2015), Fe (Kim et al. 2011), etc., exhibit broad-spectrum antiviral capabilities, making them widely used in medicines and the disinfection of water or air. Galdiero et al. (2011) suggested that the effect of metal nanoparticles on virus inactivation may play a role before and after viruses enter host cells (Fig. 1a). First of all, the virus can be adsorbed on the metal surface, and the glycoproteins of virus interact with the metal particles and become inactive. Secondly, metal nanoparticles may enter cells and interact with viral nucleic acids to exert their antiviral capability.

Fig. 1 **a** Schematic model of virus infection in eukaryotic cells and antiviral mechanism of metal nanoparticles (Galdiero et al. 2011). **b** Schematic diagram of a nano Ag-loaded filter to remove viruses in the air (Joe et al. 2016)

Nano Ag has been proved to be one of the most widely used antibacterial materials due to its high specific surface area and unique chemical and physical properties (Marambio-Jones and Hoek 2010). Its antiviral properties have also been extensively studied. According to the literature, the anti-viral mechanism of nano Ag is as follows: (1) Nano Ag has a strong adsorption effect on the virus and can interact with the viral envelope or surface protein, affect the interaction between the virus and the cell receptor, thereby preventing the virus from invading the cell (Xiang et al. 2011). This adsorption effect may be related to the size effect of nano Ag (Gaikwad et al. 2013). (2) Nano Ag combined with virus can release Ag ions, which react with viral proteins and inactivate them; or react with viral nucleic acids to prevent viruses from replicating (Hu et al. 2020). (3) The surface of nano-Ag can activate oxygen to produce ROS (Yan et al. 2005), which oxidizes virus and seriously damages its structure (Belanger et al. 2011).

Lu et al. (2008) synthesized Ag nanoparticles with an average particle size of 10 nm, similar to that of hepatitis B virus (HBV). This study found that nano Ag can directly interact with HBV virus particles. The strong binding force between Ag and HBV virus hindered the transcription of viral genetic material and the formation of new DNA. Joe et al. (2014) loaded nano-Ag on the SiO₂ surface, and the obtained SiO₂-Ag (SA) nano-particles were applied on the medium air filter. Under continuous airflow, this study evaluated the pressure drop, filtration efficiency, and anti-virus (MS2) capacity of SA filters. It was found that the filtration efficiency and pressure drop increased with the decrease of the medium flow rate and the increase of the coating amount of SA particles. The increasing coating amount of SA particles resulted in the enhanced antiviral efficiency and finally 99.9% of the virus particles lost their infectivity. However, with the increase of the virus deposition time, the anti-virus efficiency decreased. In the actual environment, viruses may be adsorbed on airborne particulate matter, and the dust trapped on the filter may affect the anti-virus capacity of the filter. Therefore, this group (Joe et al. 2016) then used the dust load test to study the pressure drop, filtration efficiency and antiviral ability of the filter on MS2 virus particles (Fig. 1b), and found that the filtration efficiency and pressure drop increased with the increase of dust concentration. The decreased antiviral capacity may be due to the fact that dust particles hindered direct contact between Ag nanoparticles and virus particles.

Nano Cu, less expensive than Ag, also has broad-spectrum antiviral activity. Its antiviral mechanism remains unclear. One theory is that the negatively charged Cu surface adsorbs viruses through electrostatic action (Szekeres et al. 2018), and Cu ions can catalyze the formation of ROS (Pandey et al. 2019) to oxidize viruses. Han et al. (2005) reported that two metal catalysts, Ag/Al₂O₃ and Cu/Al₂O₃, blocked

the transmission of SARS and other respiratory infections. In this study, these metal catalysts were pressed into wafers and they could destroy the replication and reproduction ability of SARS coronavirus, baculovirus and *E. coli* on the surface. Interestingly, only when the virus on the catalyst surface was in contact with the air, metal catalysts possessed the ability of inactivation. Horie et al. (2008) reported that Cu²⁺ at low concentration could inhibit H9N2 virus infection in MDCK cells. Electron microscopy analysis showed that Cu²⁺-treated H9N2 virus had abnormal morphology. Fujimori et al. (2012) studied the antiviral activity of nano CuI particles with an average particle size of 160 nm and confirmed that nano CuI particles can generate •OH radicals in water, thus inactivating H1N1 influenza virus. Shionoiri et al. (2012) studied the effects of CuI nanoparticles on feline calicivirus (FCV) (as a substitute for human norovirus) infecting Crandell-Rees fetal kidney cells (CRFK). Under the effect of CuI nanoparticles, the infectivity of FCV on CRFK cells decreased by 7log. Electron spin resonance and nano-liquid chromatography–mass spectrometry proved that the high antiviral capacity of CuI nanoparticles was attributed to the generation of ROS caused by Cu⁺, which oxidize amino acids in viral capsid protein. Electrostatic adsorption is one of the antiviral mechanisms of nanoparticles (Darkwah and Ao 2018). To improve the virus-absorbing ability of copper nanoparticles, Mazurkow et al. (2020) used plate-shaped alumina particles to support Cu (oxide) nanoparticles, and evaluated the effect of Cu oxidation state on MS2 virus removal capacity. The results showed that Cu (I) oxide and metallic copper were capable of removing 99.9% of MS2 virus. However, there was almost no virus removal in the presence of Cu (II) oxide. The zeta potential measurement found that the virus inactivation energy can be attributed to the positive surface charge characteristics of Cu₂O and Cu, respectively. Positive surface charge was favorable for the adsorption of negatively charged MS2 virus.

3 Metal Oxide-Based Nano-Photocatalysts

When the incident light energy is greater than or equal to the forbidden bandwidth of the metal oxide semiconductor material, the valence band electrons of the semiconductor are excited to transit to the conduction band, and at the same time, corresponding holes are generated in the valence band to form electron–hole pairs (Pant and Park 2019). Part of the photogenerated electrons and holes migrate to the surface of the material under the effect of the internal electric field (Gupta and Modak 2020). The surface of the catalyst generates •OH radicals, •O²⁻ radicals and other ROS (Ahmed and Haider 2018), which oxidizes adsorbed viruses, causing damage to their proteins (Badireddy et al. 2012) and genes (Ishiguro et al.

2011). Since photocatalysis has the advantages of broad anti-virus range, long-lasting and high efficiency (Zhang et al. 2019a), it can be an alternative disinfection strategy to improve virus disinfection performance. Currently, popular antiviral metal oxide photocatalytic materials are TiO_2 (Yamaguchi et al. 2016), ZnO (Bogdan et al. 2015), Fe_2O_3 (Giannakis et al. 2017), WO_3 (Takehara et al. 2010), etc. As shown in Fig. 2a, in addition to generating virus-oxidizing ROS through photocatalysis, photocatalysts can also cause physical damage to the structure of the virus with the sharp edges on the nanostructure (Hu et al. 2012), while the loaded metal ions can be toxic to the virus (Liga et al. 2011). According to Li's research (Li et al. 2016b), a typical process of photocatalytic inactivation of viruses can be divided into the following three steps: virus shape distortion, virus coat protein oxidation, and virus internal gene leakage or damage.

TiO_2 is currently the most commonly used antiviral metal oxide photocatalyst. It has the advantages of broad-spectrum anti-virus performance, stable structure, non-toxic to humans, and low cost (Laxma Reddy et al. 2017). As early as 1994, Sjogren and Sierka (1994) studied the inactivation effect of TiO_2 photocatalysis on MS2 virus. Subsequent studies have focused on the inactivation of viruses by photocatalysis in water, and in recent years researchers have shifted their focus to the application on inactivating airborne viruses. Zan et al. (2007) studied for the first time the photocatalytic effect of nano- TiO_2 particles and TiO_2 -coated ceramic plates on HBV. The results demonstrated that both TiO_2 suspension and TiO_2 coated ceramic plates were capable of destroying most HBV antigens (HBsAg) under weak ultraviolet light, weak sunlight or indoor sunlight. Further research by Xu et al. (2007) found that the killing effect of TiO_2 on HBV was mainly attributed to the destruction of HBsAg, RNA and casein by photocatalytic oxidation.

As for the application of TiO_2 in virus disinfection, one limitation is the wide bandgap of TiO_2 (3.2 eV for anatase), and thus only 4% of solar energy can be utilized for the photocatalytic sterilization of the material (Daghrir et al. 2013); another limitation is that the high electron–hole recombination rate of TiO_2 reduces its photocatalytic efficiency (Foster et al. 2011). Therefore, researchers have adopted many modification measures to improve the virus-inactivation capacity of TiO_2 under visible light (Dong et al. 2015). Loading nano-metal particles on TiO_2 catalyst is an effective way to improve the photocatalytic efficiency (Gupta and Tripathi 2011). Nanoparticles such as Pd (Li et al. 2008), Ag (Bogdanov et al. 2017), Cu (Zheng et al. 2017), Mn (Venieri et al. 2015) and their oxides are commonly used to enhance the antiviral ability of TiO_2 . By introducing these components with lower external bandgap to combine with TiO_2 , the separation of electron–hole pairs can be promoted, and metal can also be built as active sites on the surface of TiO_2 .

Fig. 2 **a** The major mechanism of nano photocatalysts for virus inactivation (Zhang et al. 2019a). **b** The schematic structure of the air cleaner with TiO_2 coating porous ceramic substrate (Daikoku et al. 2015). **c** The schematic structure of the photocatalytic reactor with $\text{TiO}_2/\beta\text{-SiC}$ foam (Doss et al. 2018)

Kozlova et al. (2010) loaded acidic TiO_2 and Pt-modified acidic TiO_2 on glass plates, respectively, and studied their inactivation mechanics against influenza A virus (H3N2) in aerosols under the light. After 30 min of UVA illumination, the inactivation rate of Pt/ TiO_2 to H3N2 was 99.8%, which was much higher than that of TiO_2 only. This can be attributed to the fact that Pt enhances the efficiency of virus adsorption and semiconductor charge separation.

Moongraksathum et al. (2019) synthesized silver-deposited titanium dioxide (Ag/TiO₂) nanocomposite sol and coated it on a glass substrate to form a thin film. It was found that the sample had almost 100% antiviral effect on H1N1 virus and enterovirus 71 under UVC or visible light irradiation. The particle size of silver on TiO₂ was only 1–3 nm, and mostly in the metallic state. Compared with pure TiO₂, the photocatalytic activity of Ag/TiO₂ was significantly increased. Ag loading can capture excited electrons to inhibit the recombination of electrons and holes in TiO₂, increase the performance of adsorbing viruses, and release Ag⁺ to inactivate viruses. Zheng et al. (2018) prepared a one-dimensional Cu-TiO₂ nanofiber, which could completely inactivate bacteriophage f2 under visible light irradiation. This catalytic performance was attributed to the fact that Cu²⁺ replaces part of the positions of Ti⁴⁺ in the TiO₂ lattice, forming an impurity level lower than the conduction band of TiO₂, which enables the nanofibers to achieve photocatalytic activity under visible light.

For viruses in bioaerosol, some studies have designed air purification devices to inactivate them. Wang (2013) extracted active ingredients with antiviral and antibacterial functions from traditional Chinese medicines, and prepared them as uniform micro-capsules with slow-release properties. The microcapsule, nano ZnO and TiO₂ were coated on polypropylene perforated felt to form a composite air filter with anti-viral performance, and its inactivation rate for influenza A virus was 100%. Daikoku et al. (2015) synthesized a porous ceramic substrate with nano-TiO₂ coated on the wet surface of porous ceramics by fixing fine TiO₂ nanoparticles under negative pressure for an air cleaner (Fig. 2b). This study used ultraviolet light as a light source to test the inactivation energy for influenza viruses in aerosol in a 754-L cabin, and found that influenza viruses could be inactivated in 5 min. A controlled experiment without UV light showed that the virus lost its infectivity after 30 min. In addition, by washing the surface of the substrate with deionized water, the porous ceramic substrate coated with nano-TiO₂ can be reused.

In the photocatalytic purifier, the choice of different light sources has a great effect on the performance of photocatalysts. Kim and Jang (2018) developed a photocatalytic reactor containing a Pd-TiO₂ catalytic framework. This study used VUV light sources that could easily break most of the chemical bonds and then produce ROS and ozone. It was able to inactivate 90% MS2 virus passing through the reactor within the irradiation time of 0.009 s. In addition, for the by-product ozone of the VUV light source, the Pd-TiO₂ catalyst could also reduce it to below the emission limit. Doss et al. (2018) used a 392 nm light-emitting diode (LED) as a light source to irradiate TiO₂/β-SiC solid foam material to build a small flow structure photocatalytic device for air purification (Fig. 2c). TiO₂/β-SiC solid foam material was

made of nano TiO₂ supported on β-SiC foam with medium surface area and large cell size. The study showed that the efficiency of inactivating bacteriophage T2 in the air was determined by the combined effect of the photocatalytic activity of TiO₂/β-SiC solid foam and passive filtering effect. A high efficiency of photocatalytic filtration of viruses was observed with 56 light-emitting diodes, and 3 log decrease was reached within a 60-min running time.

In addition to applying nano TiO₂ to the purifier as an anti-viral filter material, the nano TiO₂ sol can be coated in hospitals and other environments prone to high concentrations of viruses. Furthermore, nano TiO₂ can also be used as a spray to quickly eliminate viruses. Cui et al. (2010) used a one-step method to prepare a 1.6% neutral anatase nano-TiO₂ sol to inactivate avian influenza virus (H9N2). The TiO₂ photocatalytic film demonstrated a significant inactivation efficiency of 100% on H9N2 under the irradiation of 365 nm UV light. In addition, by increasing the UV intensity, extending the UV irradiation time and reducing the amount of virus, the inactivation efficiency of the TiO₂ photocatalytic film on H9N2 can be improved.

4 Non-metallic Nanomaterials

Most of the metal (oxide) nanomaterials that are proved to have great antiviral activity contain heavy metals (such as Ag and Cu), whose toxicity may cause damage to human health or the environment (Rai et al. 2016), no matter in water treatment or air purification. Therefore, it is necessary to find new non-toxic antiviral materials. Studies have confirmed that low toxicity non-metallic nanomaterials (mainly nanocarbon materials) display good antiviral properties. These carbon-containing nanomaterials include fullerenes (Snow et al. 2014), carbon nanotubes (Jang et al. 2016), graphene-based materials (Sametband et al. 2014), graphitic carbon nitrides (g-C₃N₄) (Zhang et al. 2018a). Similar to nano metals and metal oxides, the mechanism of virus inactivation by nanocarbon materials also depends on nanometer size effect, electrostatic adsorption, or photocatalytic oxidation.

Carbon nanotubes (CNTs) are one-dimensional tubular nanomaterials made of graphene sheets curled around a central axis. According to the number of cylinder layers, it can be categorized into single-wall carbon nanotubes (SWCNTs) and multi-wall carbon nanotubes (MWCNTs). Since carbon nanotubes (CNTs) have a high specific surface area, smooth surface and good adsorption performance (Az'hari et al. 2019), they have been applied to inactivate viruses in water (Brady-Estévez et al. 2010b). It was also found that the trapping effect of the nanotube bundles in the carbon nanotube layer, the puncture effect on viruses, and the electrostatic adsorption could effectively remove most viruses

in contaminated water (Brady-Estévez et al. 2010a). Carbon nanotubes are also used in the field of anti-virus in air. Park and Hwang (2014) used aerodynamic deposition (EAD) technology to coat carbon fiber nanotubes on glass fiber air filter media at atmospheric pressure and room temperature to inactivate MS2 virus. Both aerosol counting method and the plaque counting method were used for virus aerosol filtration and anti-virus tests. Carbon nanotube filter had a better filtering effect on suspended bacteriophage MS2 than ordinary air filter, and the pressure drop was very small. By controlling the area density of the coating, the filtration efficiency in the maximum penetration particle size area (100 nm) can be increased to 33.3%, and the anti-virus efficiency can reach 92%. Therefore, carbon nanotube air filters can be used in indoor air purification systems, gas masks and other fields.

Graphene is a hexagonal two-dimensional carbon nanomaterial with a honeycomb lattice composed of sp^2 hybrid carbon atoms. It was featured by large specific surface area, high conductivity and high charge mobility, leading to sufficient surface active sites, good adhesion to microorganisms and the efficient generation of light-induced electron/hole separation pairs (Miao et al. 2019). In addition, as a two-dimensional material, graphene exhibits excellent surface dispersibility and can be used as a substrate for catalytic systems (Georgakilas et al. 2016). It has been used as a highly effective dopant and sensitizer for improving the photocatalytic performance of metal oxide semiconductors (Li et al. 2016a). Akhavan et al. (2012) prepared a graphene-tungsten oxide composite film and applied it to inactivate viruses under visible light. Compared with tungsten oxide and graphene-tungsten oxide film without composite structure, the W–C and W–O–C bonds in the composite structure improved the photocatalytic performance. The MS2 virus protein on the surface of the film was almost completely destroyed after irradiation at room temperature for 3 h, and the RNA outflow increased sharply. After 20 measurement cycles, the RNA outflow of the composite film decreased by 10%, indicating that its photocatalytic performance remained stable within 60 h.

Graphene oxide (GO), as a derivative of graphene, is a flake after graphite is oxidized. The GO surface possesses carboxyl groups, hydroxyl groups, and epoxide groups. These oxygen-rich groups make GO easy to functionalize (Gong et al. 2016). In addition, GO's forbidden bandwidth of 2–4 eV provides good photocatalytic performance. Furthermore, during the process of virus disinfection, the sharp edges of GO can destroy and inactivate virus protein shells. Ye et al. (2015) reported the broad-spectrum antiviral activity of GO against pseudorabies virus (PRV, DNA virus) and porcine epidemic diarrhea virus (PEDV, RNA virus). This study showed that at concentrations below cytotoxicity, GO can significantly inhibit PRV and PEDV infection. When GO was combined with non-ionic polymer PVP, it

showed antiviral activity. However, when combined with cationic polymer PDDA, GO failed to exhibit antiviral activity. These experimental results indicate that the effective anti-viral activity of GO is attributed to the unique single-layer nanosheet structure and sharp edges leading to virus damage, as well as electrostatic interaction with the virus through the negative charge on the surface. The mechanism is summarized in Fig. 3a. GO tablets can also be used as carriers and stabilizers. For example, it can prevent Ag-np agglomeration, achieving a size suitable for antiviral activity, and fix Ag to reduce its biological toxicity (de Faria et al. 2014). Chen et al. (2016) studied the antiviral activity of GO and GO with Ag nanoparticles (Go-Ag) against coated feline coronavirus (FCoV) and non-coated infectious bursa disease virus (IBDV). Go-Ag inhibited 25% of FCoV infection and 23% of IBDV, while GO only inhibited 16% of FCoV infection and shows no antiviral activity against IBDV infection.

Graphene-based nanomaterials have an excellent thermal conductivity which endows them with light-to-heat conversion capabilities (Wang et al. 2018). Deokar et al. (2017) synthesized sulfonated magnetic nanoparticles with reduced graphene oxide (SMRGO) to capture and photothermally destroy herpes simplex virus type 1 (HSV-1). Graphene sheets were anchored uniformly in spherical magnetic nanoparticles (MNP) whose size ranged from 5 to 25 nm. Under the irradiation of near-infrared light (NIR, 808 nm, 7 min), SMRGO showed excellent (99.99%) photothermal antiviral activity. This antiviral effect may be due to high virus capture efficiency, unique sheet structure, high surface area, and excellent photothermal properties of graphene. In addition, the electrostatic interaction of MNP with HSV-1 virus particles seemed to play a crucial role in suppressing viral infections.

$g-C_3N_4$ is a typical polymer semiconductor with a band-gap of ~ 2.7 eV and exhibits catalytic activity even under visible light with bandwidth up to 460 nm (Mishra et al. 2019). In addition, it also has the advantages of high physical and chemical stability, no biological toxicity and low preparation cost (Darkwah and Ao 2018). Li et al. (2016b) first discussed the ability of $g-C_3N_4$ to inactivate viruses under visible light. The MS2 virus was completely inactivated after 360 min of irradiation. This study also investigated the mechanism of virus inactivation (Fig. 3b): photogenerated electrons and their derived ROS ($\cdot O^{2-}$) dominated the inactivation process. Photocatalytic oxidation damaged the virus surface protein, resulting in the leakage and rapid destruction of internal RNA. Subsequently, this group (Zhang et al. 2018b) optimized the light intensity, photocatalyst loading and reaction temperature of photocatalysis through response surface method, reducing the time for completely inactivating the virus to 240 min.

In addition to the single $g-C_3N_4$ photocatalytic inactivation of viruses, there are also studies of combining $g-C_3N_4$

Fig. 3 **a** Speculated anti-viral mechanism of GO (Ye et al. 2015). **b** The proposed mechanism of viral inactivation by g-C₃N₄ under visible light irradiation (Li et al. 2016b)

with semiconductors or constructing heterojunctions to improve the efficiency of photocatalysis. Cheng et al. (2018) synthesized Ag₃PO₄/g-C₃N₄ (AgCN) composite materials and studied the photocatalytic inactivation ability of bacteriophage f2. The combination of Ag₃PO₄ and g-C₃N₄ enhances the visible light response and reduces the carrier recombination rate. Under visible light irradiation, the photocatalytic inactivation efficiency of AgCN composite photocatalyst for bacteriophage f2 reached 6.5 log within 80 min. Hole and •OH radical play an important role in the process of photocatalytic disinfection. Zhang et al. (2019b) combined oxygen-doped graphite carbonitride microspheres (O-g-C₃N₄) with hydrothermal carbonization carbon (HTCC) to prepare a new type of metal-free heterojunction photocatalyst: O-g-C₃N₄/HTCC microspheres. It showed strong absorption toward visible light and high killing efficiency against HAdV-2 virus under visible light irradiation. The mechanism of O-g-C₃N₄/HTCC enhancing virus-killing performance was revealed: the formation of Z-type heterojunctions enhances charge separation, fast charge transfer and reduces charge recombination, promoting the production of •OH, which was responsible for the rupture and deformation of the viral capsid.

5 Perspective

Nanomaterials have broad-spectrum antiviral capabilities and are expected to be used to block the aerosol transmission route of the virus. This review summarizes different types of antiviral nanomaterials, including metal nanomaterials, metal oxide nanomaterials with photocatalytic properties, and nonmetallic nanomaterials. The structural characteristics and chemical properties, the efficiency of inactivating viruses, the mechanism of inactivating viruses, and the virus purification application of antiviral nanomaterial are discussed. Although some progress has been made now, the development and application of antiviral nanomaterials still need to be worked on. Future studies can be focused on follows:

First, the scope of nano-antiviral materials should be expanded. It is known that photocatalytic nanomaterials can produce ROS to destroy the structure of viruses. However, their performance is greatly affected by the light source, which may increase their application cost. Further, the room-temperature catalytic nanomaterials which can activate O₂ to generate ROS without additional energy are promising candidates for air purification, deserving more attention.

Second, the design and selection of antiviral nanomaterials should be optimized according to the application practice. When antiviral materials are applied to air purifiers, the high flow rate allows the virus to obtain higher kinetic energy. Therefore, the physical structure modification of nanomaterials should be strengthened to puncture or break viruses, and the electrostatic effect on the surface of nanomaterials should be increased to enhance the adsorption capabilities toward viruses. In addition, when antiviral nanomaterials are applied onto fabrics such as masks, carbon nanomaterials are the optimum choice due to their good biocompatibility. Moreover, liquid antiviral nanomaterials should be developed. Antiviral nano sols can be coated on indoor surfaces to continuously inactivate viruses, and antiviral nano sprays can be prepared to efficiently disinfect high-viral concentration environments.

Acknowledgements This work was supported by the National Natural Science Foundation of China, China (Grant nos. 51878644) and the National Key Research and Development Program of China, China (Grant nos. 2017YFC0212200 and 2016YFA0203000). This work was also partially supported by Strategic Priority Research Program of the Chinese Academy of Sciences, China (Grant nos. XDA23010300 and XDA23010000).

Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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