

## Review Article

Yao Zhang<sup>#</sup>, Wei Fan<sup>\*</sup>, Yanli Sun<sup>#</sup>, Weichun Chen, and Yifan Zhang

# Application of antiviral materials in textiles: A review

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**Abstract:** Research of antiviral textiles has received considerable attention owing to the continuous emergence of new infectious diseases. Antiviral textiles can effectively inhibit the spread of viruses and significantly reduce the risk of cross-infection and re-infection to protect people's health and safety. In recent years, researchers studied various antiviral materials, which can prevent the spread and reproduction of viruses by killing and reducing their attachment. These materials can be applied to antiviral textiles through finishing and various spinning methods. This review organizes antiviral materials, analyzes their antiviral mechanisms and inhibition effects, and discusses the methods of combining antiviral materials with textiles, as well as their applications in healthcare and public transportation. In addition, prospects for antiviral textile research are proposed. This review provides references for the study of antiviral textiles and may stimulate the continuous research and development of antiviral textiles.

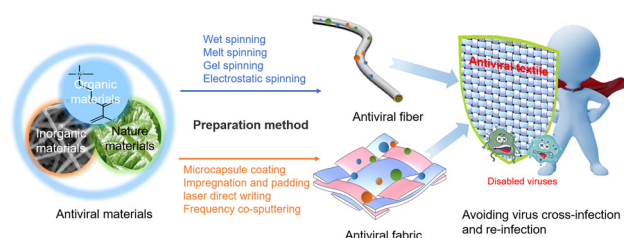
**Keywords:** antiviral materials, antiviral textile, antiviral mechanism, preparation method, application

<sup>#</sup> These authors contributed equally to this work.

**\* Corresponding author: Wei Fan**, Key Laboratory of Functional Textile Material and Product (Ministry of Education), School of Textile Science and Engineering, Xi'an Polytechnic University, Xi'an, Shaanxi 710048, China, e-mail: fanwei@xpu.edu.cn

**Yao Zhang, Yanli Sun, Weichun Chen:** Key Laboratory of Functional Textile Material and Product (Ministry of Education), School of Textile Science and Engineering, Xi'an Polytechnic University, Xi'an, Shaanxi 710048, China

**Yifan Zhang:** Key Laboratory of Composite Material (Ministry of Education), Tiangong University, Tianjin 300387, China



Graphical abstract

## 1 Introduction

Emerging infectious diseases (EIDs) refer to emerging or drug-resistant infectious diseases whose incidence in the population has increased over the past 20 years or signs indicate that their incidence may increase in the future. EIDs have various transmission routes and infection methods; however, humans generally lack sufficient immunity to EIDs, as well as treatment methods. Unfortunately, EIDs have been a consistent threat to people's health and safety over the past 100 years, beginning with the Spanish influenza epidemic in 1918, Asian influenza in 1957, SARS in 2003, H1N1 influenza in 2009, Ebola hemorrhagic fever in West Africa in 2014, Zika virus disease in 2016, and more recently Coronavirus disease in 2019 (COVID-19). According to statistics, in the last 20 years, EIDs have reached as many as 30 kinds. Owing to their rapid spread and high fatality rate, EIDs are a serious health hazard and cause huge economic losses and social impacts [1]. For example, the SARS virus outbreak caused 8,422 confirmed cases and 919 deaths worldwide. In 2014, the West African EVD epidemic confirmed 28,646 cases and 11,323 deaths. To date, the total number of confirmed Coronavirus disease cases has exceeded 105 million, and the death toll has exceeded 2.3 million, causing negative growth in per capita income in more than 95% of countries [2,3].

In terms of emerging diseases control, biological protection textiles play an important role. Reports have shown that they can weaken the spread of viruses and reduce the sudden dangerous occurrence of the pandemic virus through the utilization of protective cloth-

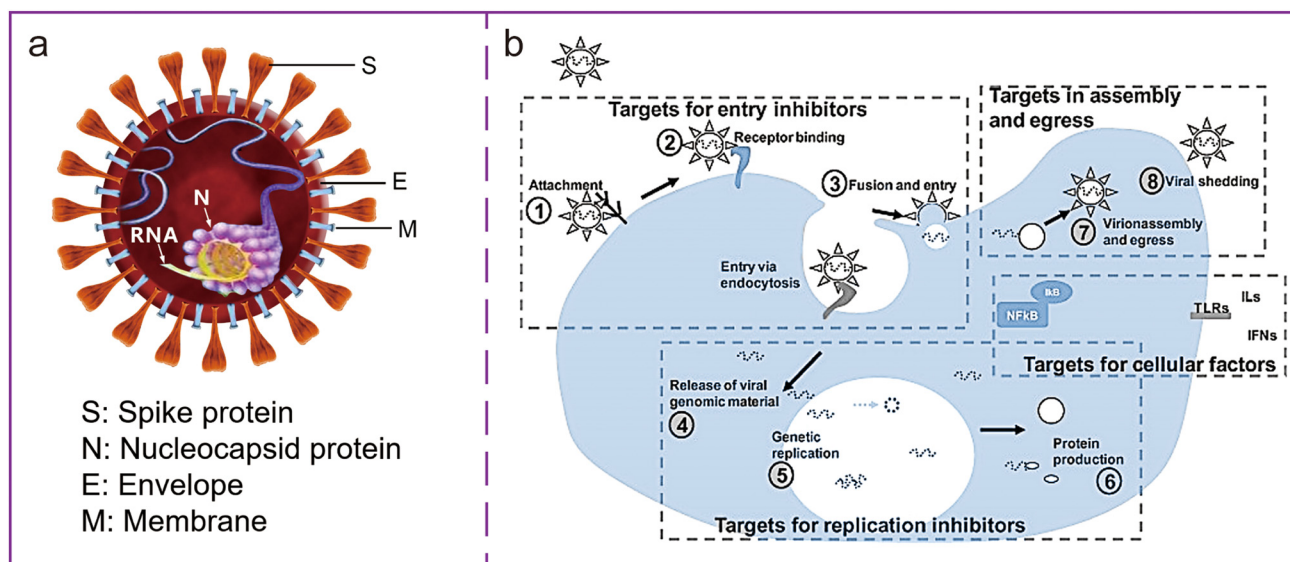
ing, medical-surgical masks, and N95 masks. However, although protective clothing and masks can reduce the spread of the virus, the risk of infection cannot be eliminated [4]. According to studies, viruses can survive on textiles for 2–4 weeks at room temperature [5], which can easily cause re-infection and cross-infection [6,7]. In addition, in 2019, the global daily output of medical masks reached 40 million pieces, and the daily waste generated exceeded 15,000 tons. In 2020, the daily output of masks increased by 20.5 times compared with 2019. Many countries dispose of such waste through incineration, which creates great environmental concern [8]. Antiviral textiles can kill viruses on the surface of the fabric or inhibit the formation of biofilms, reducing the risk of infection/re-infection. Moreover, antiviral textiles can reduce environmental pollution due to their reusability. However, most textiles with antiviral properties have not been industrialized, and there is no systematic research on antiviral textiles. Therefore, the development of antiviral textiles is urgent.

This article summarizes the main antiviral mechanisms of antiviral materials, compares the current benefits and drawbacks of various materials, and analyzes the antiviral activities of various materials. We have comprehensively summarized the combination methods of antiviral materials and textiles, as well as the advantages and disadvantages of these methods, and the application in various fields is also discussed. Finally, we discussed specific existing problems of antiviral textiles and propose the

direction of future development of antiviral textiles. This review provides a foundation for the research and development of antiviral textiles.

## 2 Classification and mechanism of antiviral materials

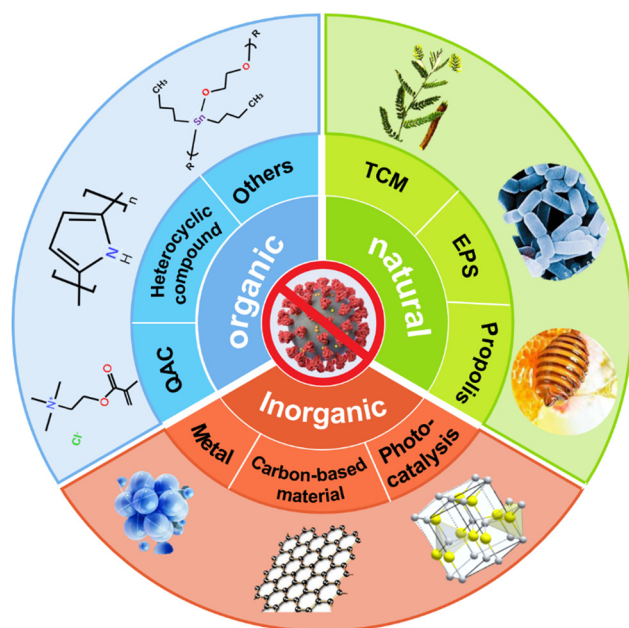
Viruses are mainly composed of genetic material and protein and are a form of material between life and non-life. The genome is composed of one or more nucleic acid molecules (DNA or RNA), and there is a protective shell of protein or lipoprotein surrounding the genome (Figure 1a). Viruses can be classified into nonenveloped and enveloped viruses according to their external structure. The genetic material of nonenveloped viruses is surrounded by capsid proteins, which are resistant to acid and temperature, and are difficult to inactivate *in vitro*. Enveloped viruses not only have a protein shell but also have a lipid membrane, which provides adaptability to different physiological environments and has a longer survival period in the host. However, the lipid membrane cannot tolerate high temperature and acidic environments; hence, it is easier to inactivate *in vitro*. Viruses can survive *in vitro* for several hours and can spread through droplets and contact. Once they enter the host cell, they can reproduce rapidly. The proliferation cycle includes attachment and



**Figure 1:** (a) Coronavirus structure diagram. (b) Major steps in the generalized viral life cycle. Potential targets for inhibitors of entry, replication, assembly, and egress and cellular factors [10].

entry into the host cell (Figure 1b(1–3)), viral messenger RNA transcription, viral genome replication (Figure 1b(4–6)), protein synthesis, progeny virus particle assembly, and budding (Figure 1b(7 and 8)) [9]. Therefore, according to the aforementioned structural characteristics and replication process, the antiviral pathways mainly include: directly destroying the virus structure, interfering with virus adsorption, preventing viruses from penetrating cells, inhibiting virus biosynthesis, inhibiting virus release, or enhancing the host's antiviral ability.

In recent years, researchers have found that a variety of antiviral materials can inactivate viruses through different mechanisms. Currently, however, there is no standard classification of antiviral materials. This article divides commonly used antiviral materials into three categories according to their chemical structure: inorganic, organic, and natural (Figure 2). Inorganic antiviral material is a relatively new type of antiviral material and mainly refers to carbon-based material and those containing metal ions. Organic antiviral materials refer to polymer materials prepared *via* polymerization of compounds with antiviral properties such as quaternary ammonium salts, phenols, and benzimidazoles with other comonomers. Natural antiviral materials are currently mainly derived from plants and active substances with antiviral properties that are obtained through extraction, separation, and purification.



**Figure 2:** Classification of antiviral materials. TCM: traditional Chinese medicine; EPS: extracellular polysaccharides; QAC: quaternary ammonium compounds.

## 2.1 Inorganic antiviral materials

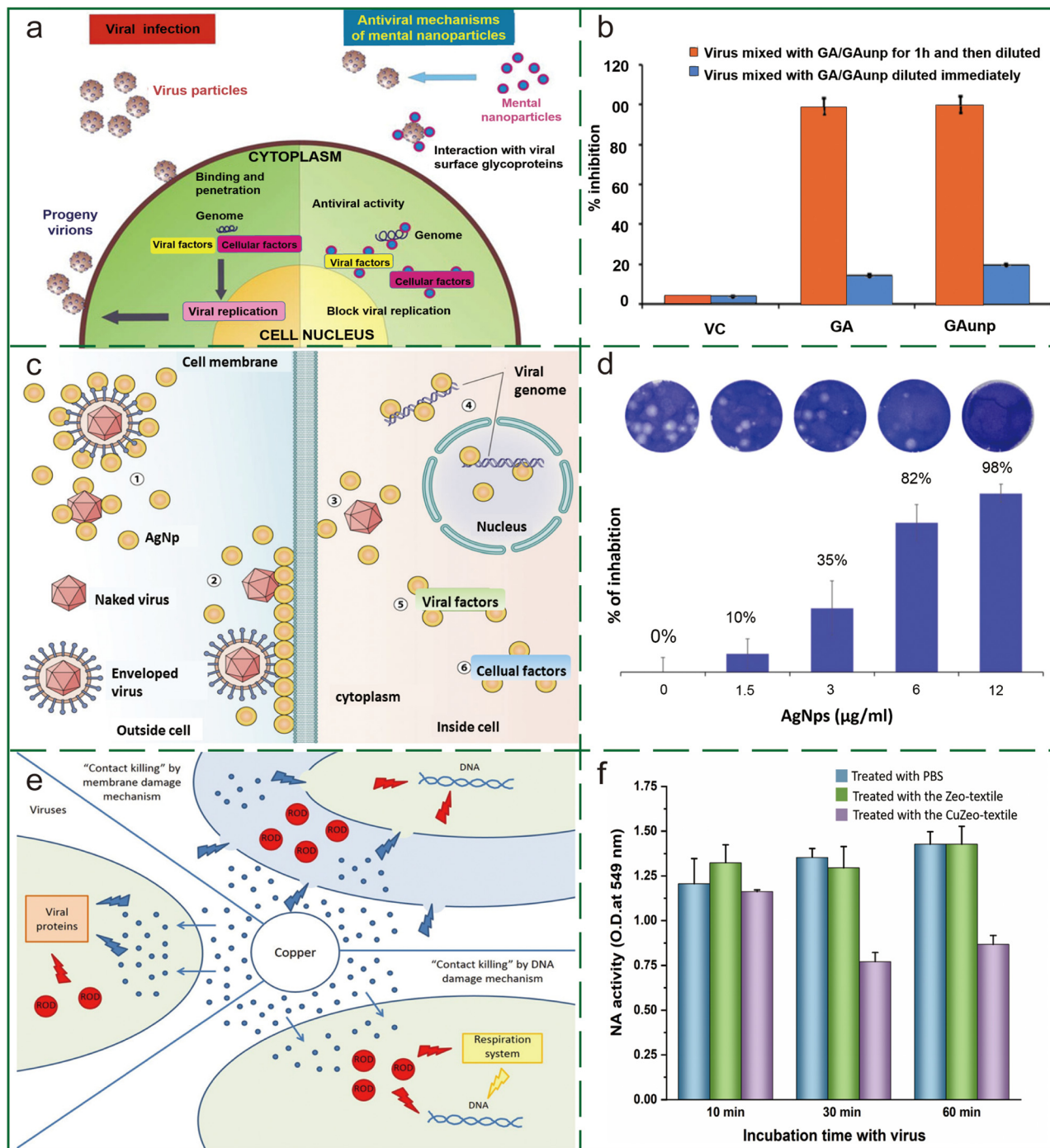
### 2.1.1 Metals and their compounds

Metal nanomaterials have characteristics such as large specific surface area, good stability, great biocompatibility, low toxicity, and easy functionalization, which provide broad application prospects in the field of biomedicine [11]. Metal materials, especially metal nanomaterials, have been proven to have a wide spectrum of antiviral properties. Metal nanomaterials can interact with virus surface glycoproteins to destroy its structure. Metal nanomaterials can also enter cells and affect virus replication by interacting with the viral genome (DNA or RNA) to exert antiviral activity. This antiviral mechanism is shown in Figure 3a. Currently, commonly used metal antiviral materials mainly include gold, silver, and copper.

#### 2.1.1.1 Gold nanoparticles (AuNPs)

AuNPs have attracted considerable attention in nanometer diagnosis and nanomedicine applications due to their small size effect, surface effect, and macroscopic quantum tunneling effect [12] and are often used as carriers for antiviral drugs. The antiviral mechanism of AuNPs has two main pathways: the first is that AuNPs can inhibit the binding of viruses to cell membranes, and the second is that AuNPs can inhibit the proliferation of viruses in cells by binding to the envelope glycoprotein gp120. Di Gianvincenzo *et al.* [13] described that AuNPs coated with sulfonic acid end ligands can bind to human immunodeficiency virus type 1 (HIV-1) envelope glycoprotein gp120 and inhibit HIV infection of T-cells *in vitro* at a nanomolar concentration. Fifty percent density of sulfonated ligand (other ligands are inert glucose derivatives) on 2 nm nanoparticles is sufficient to achieve the high anti-HIV activity. Papp *et al.* [14] tested 2 and 14 nm sialic acid-functionalized AuNPs against influenza viruses. AuNPs achieve antiviral effects through inhibition of the combination of viruses and cell membranes. In addition, they found that the activity of AuNPs depends on particle size and spatial distribution of ligand receptor molecules. Halder *et al.* [15] used gallic acid (GA) as a raw material to perform a one-pot reduction reaction to synthesize highly monodisperse gold nanoparticles (GAunps) with a diameter of 7.68 nm, which can effectively inhibit herpes simplex virus (HSV) infection. GAunp can interfere with virus attachment and inhibit the proliferation of HSV in Vero cells with low toxicity. Synthesized GAunp is less





**Figure 3:** Antiviral mechanisms and antiviral activity of metals and their compounds. (a) Antiviral mechanism of metal nanoparticles [11]. (b) Effect of test compounds on the inactivation of HSV-1 [15]. (c) Potential antiviral principles of silver nanoparticles [27]. (d) The effect of AgNP on RVFV infection in Vero cells [25]. (e) Antimicrobial contact killing mechanisms for copper include membrane degradation, genotoxicity, and potentially ROS [39]. (f) Inhibition of the Ck/Yamaguchi/7/04 H5N1 virus NA after treatment with CuZeo-textile [38].

toxic and more efficient than GA and has been shown to exhibit a significant inhibitory effect on the HSV virus within 1 h (Figure 3b). AuNPs are used more in medicine, mainly as antiviral agents in the body.

#### 2.1.1.2 Silver

Before the discovery of antibiotics, silver was commonly used in the treatment of wounds for antiseptic and



antibacterial purposes. The development of nanotechnology has allowed the further development of silver in the field of antimicrobial. Silver nanoparticles (Ag NPs) have been widely used in medicine, textile, and other fields due to their broad spectrum, no drug-resistance mutations, safety, and relatively low price [16,17]. Reports have shown that Ag NPs can inactivate various types of viruses, such as monkeypox virus, hepatitis B, distemper, and arenaviruses [18–21]. In many studies, Ag NPs have been tested for the inhibition of viruses with different structures (enveloped or nonenveloped viruses) and different genetic information content (DNA or RNA, single or double stranded) [22–24]. The unique physical and chemical properties of Ag NPs have a strong adsorption capacity for viruses and interact to produce chemical reactions, thus exhibiting strong antibacterial and antiviral activities. Rai *et al.* [21] summarized the antiviral mechanism of Ag NPs as follows: Ag NPs (1) interact with viral envelope and viral surface proteins; (2) interact with cell membranes to prevent penetration of virus; (3) block the way for viruses to enter cells; (4) interact with the viral genome; (5) interact with viral factors required for virus replication; and (6) interact with cytokines to produce viral replication (Figure 3c). Vazquez-Muñoz *et al.* [25] found that Ag NPs reduce the infectivity of the Rift Valley fever virus (RVFV) through cell infection tests. Ag NPs at 12 µg/mL can decrease the infection rate by 98% (Figure 3d). Xiang *et al.* [26] reported the inhibitory effect of Ag NPs on H1N1 *in vitro*. Rai *et al.* [27] showed that the addition of Ag NPs as a coating has high inhibitory activity against HIV-1, HSV-1, and HSV-2. Castro-Mayorga *et al.* [28] produced a poly(3-114 hydroxybutyrate-co-18mol%-3-hydroxyvalerate)/Ag NPs nanofiber membrane by electrospinning as an antiviral coating on the surface and demonstrated the strongest antiviral activity at 37°C. This nanofiber membrane has good antiviral activity against nonenveloped feline calicivirus (FCV) and murine norovirus (MNV), and the titer is reduced by 1.42 and 0.14 log TCID<sub>50</sub>, respectively (log TCID<sub>50</sub> is the half lethal dose after 10-fold dilution of the virus suspension and the quantitative unit of the virus infection value).

### 2.1.1.3 Copper and its compounds

Copper, a common antimicrobial material, is widely applied owing to its specific properties such as high efficiency, low toxicity, and broad spectrum. It exhibits a killing effect on infectious bronchitis virus, poliovirus, HIV-1, and so on [29]. In addition, copper can generate toxicity to microorganisms through several parallel nonspecific mechanisms, including damage to the microbial envelope, intracellular proteins, and nucleic acids [30]. Moreover,

nanoparticles formed by copper compounds can combine with oxygen to generate and release reactive oxygen species (ROS), which oxidize the capsid protein of virus to effectively inactivate the virus. The antiviral mechanism is shown in Figure 3e. Numerous researches have shown that copper can reduce the infectivity of enveloped or nonenveloped, DNA or RNA viruses [29,31–35]. Noyce *et al.* [35] found that only 0.1% of influenza A (H1N1) can survive after being in contact with the copper surface for 6 h. In addition, copper ions (Cu<sup>2+</sup>) in CuCl<sub>2</sub> and CuSO<sub>4</sub> solutions at 2.5–250 µM concentration inactivate avian influenza virus (H9N2) subtype viruses within 3–6 h. Upon prolongation of contact time, the inactivation effect toward the virus increases [27]. Copper iodide (CuI) has also shown the inactivation effect toward H1N1 [36] and FCV [37]. Borkow *et al.* [33] dipped ordinary respiratory protective masks in copper oxide and performed antiviral tests on H1N1 and H9N2. Under the condition of simulated breathing, the virus titer reduces by >4.27 and >4.83 log TCID<sub>50</sub>, respectively, after 30 min. Imai *et al.* [38] discovered that highly pathogenic H5N1 and low pathogenic H5N3 viruses are inactivated on copper-treated fabric, in which the titer of A/chicken/Yamaguchi/7/04 (H5N1) in Madin-Darby Canine Kidney (MDCK) cells and eggs declines by >5.0 log<sub>10</sub> and 5.0 log<sub>10</sub> after 30 s, respectively. The titer of A/whooper swan/Hokkaido/1/08 (H5N1) in MDCK cells decreases by 2.3 and 3.5 within 1 and 5 min, respectively. Treatment of A/whistling swan/Shimane/499/83 (H5N3) on CuZeo-textile for 10 min reduces the titer by >5.0 log<sub>10</sub> in MDCK cells and by >3.5 log<sub>10</sub> in eggs. In contrast, such a reduction in titers is not observed on cotton fabrics treated with PBS buffer or containing only zeolite (Figure 3f).

## 2.1.2 Carbon-based nanomaterials

Carbon-based nanomaterials consist of carbon materials with at least one dimension less than 100 nm in the dispersed phase. Carbon-based nanomaterials have been found to exhibit good antiviral properties. In addition to their own nanostructures that may affect viral replication, they can also use their excellent electrochemical and electrothermal properties to inactivate viruses by heating to achieve antiviral properties.

### 2.1.2.1 Fullerene and its derivatives

Fullerene is the third allotrope of elemental carbon. Its antiviral mechanism mainly consists of two aspects: First, it inhibits the activity of internal enzymes of the

virus. Friedman *et al.* [40] studied the ability of C60 (Bucky Ball) derivatives to interact with the active site of HIV-1 protease through modeling and physical and chemical analyses. They found that the main antiviral target of fullerene is HIV viral protease (HIVP), and fullerene inhibits its activity and terminates the life cycle of HIV. Second, fullerene also can be used as a biological structural scaffold for multivalent ligands to simulate virus morphology and inhibit virus reproduction. Muñoz *et al.* [41] reported a water-soluble 13-carbon fullerene modified by 120 peripheral carbohydrate subunits (Figure 4a). The prepared fullerene mimicked the shape of the virus, allowing binding to cell receptors at the early stage of infection, thus inhibiting the entry of the pathogen into the host cell. This has an excellent inhibitory effect on the Ebola virus.

### 2.1.2.2 Graphene and its derivatives

Graphene, a carbon dioxide nanomaterial, is composed of carbon atoms  $sp^2$  hybrid orbitals honeycomb hexagonal lattice and has excellent optical, electrical, and mechanical properties. Graphene can be used to inactivate viruses by photoheating or electric heating due to the virus's inability to withstand high temperatures. Stanford *et al.* [42] showed the ability of laser-induced porous conductive graphene foam to capture bacteria, viruses, and pollutants, which can reduce infection and inactivate viruses by electric heating (Figure 4b). Deokar *et al.* [43] designed and synthesized sulfonated magnetic nanoparticles, which were anchored on graphene sheets. The prepared graphene composite material captured viruses, followed by polymerization through external magnets to promote effective photothermal treatment. Type 1 HSV can be captured, heated, and destroyed. After 7 min of infrared radiation, 99% of the virus is inactivated. In fact, many reports have described that adsorption on graphene and gentle heat treatment at 56°C for 30 min inactivate viruses [44,45].

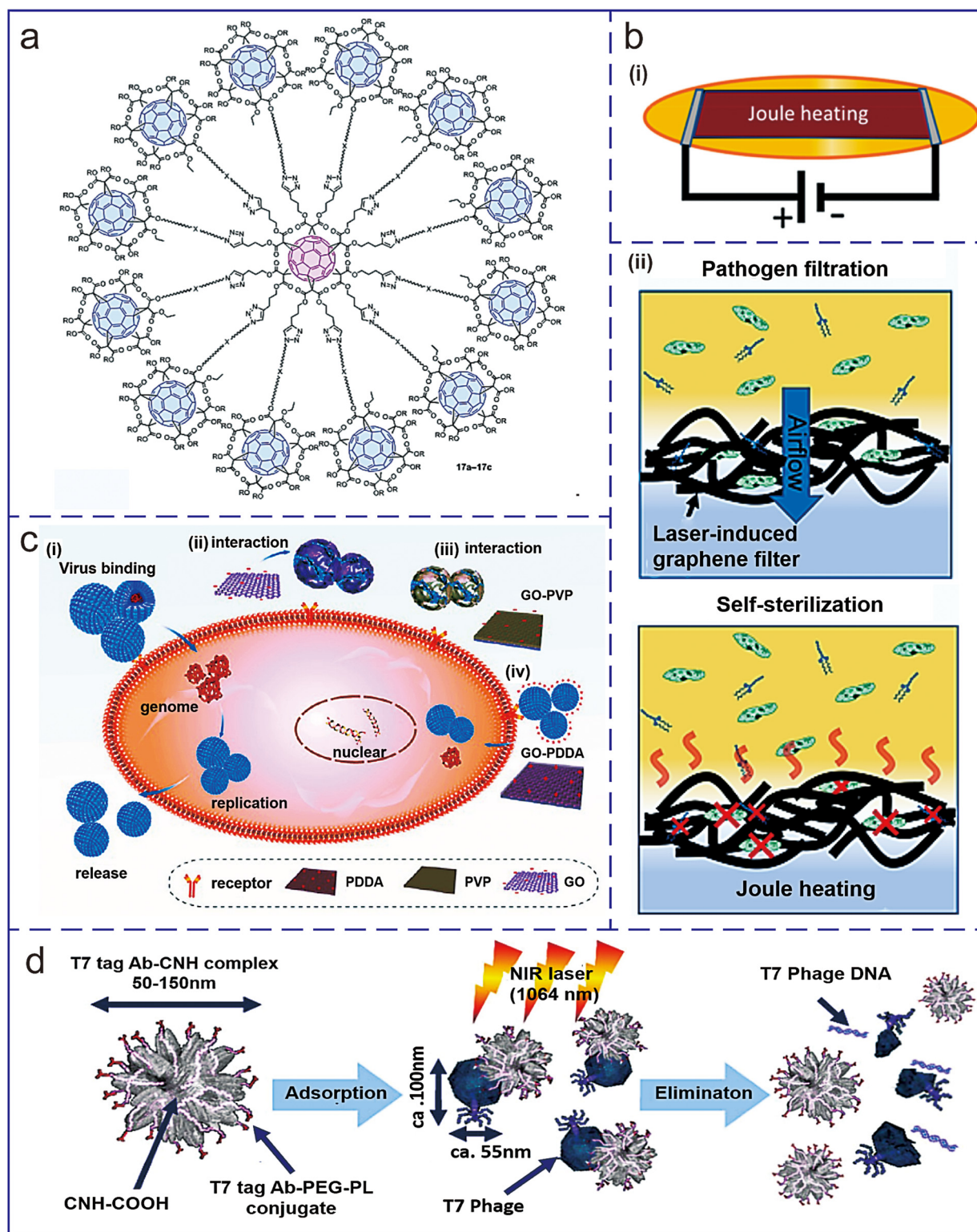
Graphene oxide (GO) is formed *via* oxidation of graphene, which creates more active properties than graphene owing to increased oxygen-containing functional groups. In addition, currently, it is the most studied class of antibacterial and antiviral graphene materials [46]. GO is under a unique two-dimensional surface chemical structure and sharp physical edge structure, which can adsorb and block viruses. Moreover, the structure of GO itself has an inhibitory effect on viral infection. Ye *et al.*

[47] found that GO can significantly inhibit the infection of the pseudorabies virus and porcine epidemic diarrhea virus. Both viruses can be inactivated through the destruction of their structure before the virus enters the cell, and the virus titer is reduced by 2 log TCID<sub>50</sub>. The potent antiviral activity of GO is attributed to its unique monolayer structure and negative charge. GO shows strong antiviral activity when combined with polyvinyl pyrrolidone (PVP, nonionic polymer), but not when combined with polydimethyl diallyl ammonium chloride (PDDA, cationic polymer). In addition, the antiviral activity of GO's precursor graphite and GO is much weaker than that of single-layer GO and reduced GO, indicating that the structure of nanoflakes is important to promote antiviral performance (Figure 4c).

The continuous development of biosensors has allowed researchers to create various types that detect and accurately locate viruses to prevent the virus from spreading further. Graphene has excellent electrochemical properties and can be used as a biosensor for virus monitoring. Kim *et al.* [49] prepared liquid coplanar gate graphene field-effect transistors on a flexible polyethylene terephthalate substrate for the detection of two typical viruses (HIV-1 and murine leukemia virus). In this case, the antibodies are used as probe molecules and modified on the graphene surface with 1-pyrene butyrate succinimidyl ester (PASE). When the solution containing the virus is dripped on the sensor, due to the electrostatic gating effect of the graphene in the antigen (namely, virus)-antibody complex, the Dirac point voltage moves downward (Figure 5a). Yang *et al.* [50] developed a new bandage-type wearable flexible microfluidics polymerase amplification sensor for visual detection of nucleic acids. The sensor is triggered by body temperature (30–37°C) and can be used for rapid, sensitive, intuitive, and highly portable nucleic acid detection. Kinnamon *et al.* [51] cross-linked influenza A-specific antibodies on the surface of GO to prepare a biosensor for virus monitoring. Wearable devices by high-risk groups allow virus detection before symptoms appear, as shown in Figure 5b.

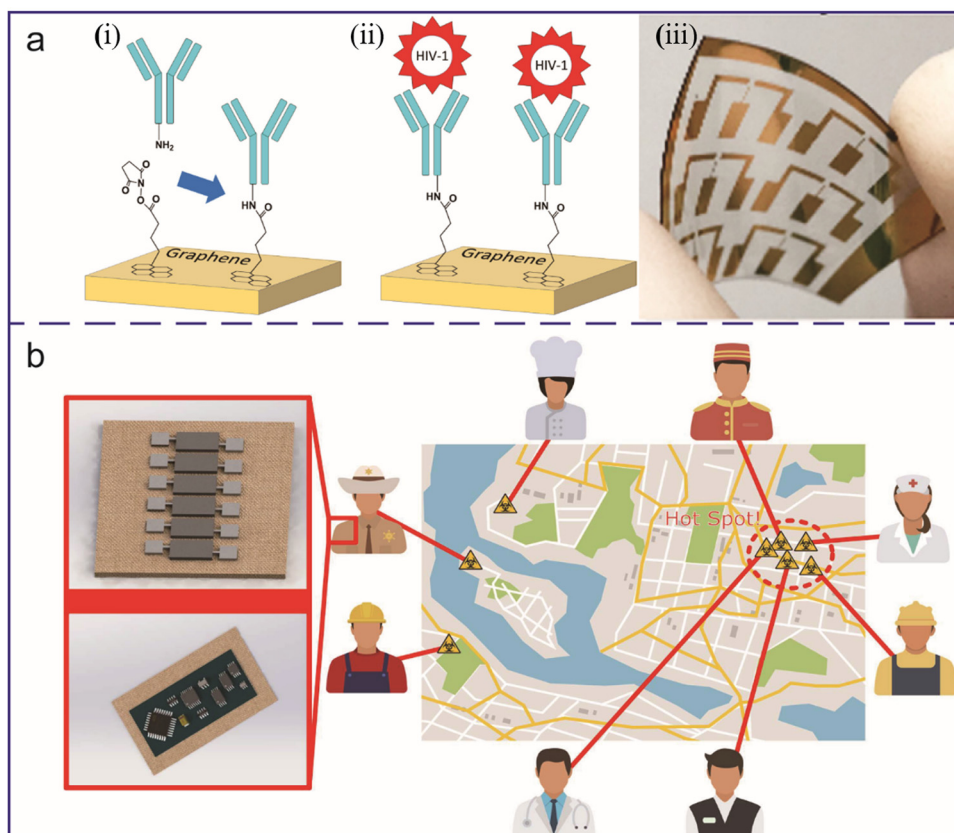
### 2.1.2.3 Carbon nanohorn (CNH)

CNH is a kind of “ox horn” carbon nanomaterial. Due to its unique structure, CNH has the characteristics of large specific surface area, strong thermal stability, and high porosity, making it ideal for the field of biological medicine. Miyako *et al.* [48] reported an antiviral approach



**Figure 4:** Antiviral mechanism of carbon-based materials. (a) Structure of the tridecafullerenes 17a–17c, the central C<sub>60</sub> core is covalently connected to 12 hexakis adducts of C<sub>60</sub>. Each peripheral fullerene is endowed with ten monosaccharides and so a total of 120 carbohydrates decorate the periphery of each molecule [41]. (b) Schematic of bacteria capture, along with subsequent sterilization and depyrogenation by Joule-heating. (i) Schematic of the Joule-heating setup in which a potential is applied across the filter for Joule heating. (ii) Schematic of filtration followed by sterilization and depyrogenation through Joule heating [42]. (c) Possible mechanisms of the antiviral activity of GO. (i) Normal viruses are absorbed into cells by interacting with cell receptors to initiate infection. (ii) Negatively charged GO has more chances to interact with the positively charged viruses, resulting in virus damage and infection suppression. (iii) Infection was blocked by GO conjugated with nonionic PVP. (iv) Conjugation of GO with cationic PDPA cannot prevent the virus from infecting cells [47]. (d) Method for the elimination of a virus by using CNH complexes and NIR laser irradiation [48].





**Figure 5:** Fabrication and application of graphene sensors. (a) (i) Binding schematic of the antibody to PASE/graphene by condensation covalent bonding. (ii) Detection schematic of virus sensors using the interaction between antibody/PASE/graphene and target HIV-1 virus. (iii) A camera image of a virus sensor [49]. (b) Schematic of envisioned application space for the GO screen printed flexible impedance biosensors. Sensors arrays mounted on textiles and interfaced with flexible electronics can report the location of positive cases and identify sources of the outbreak [51].

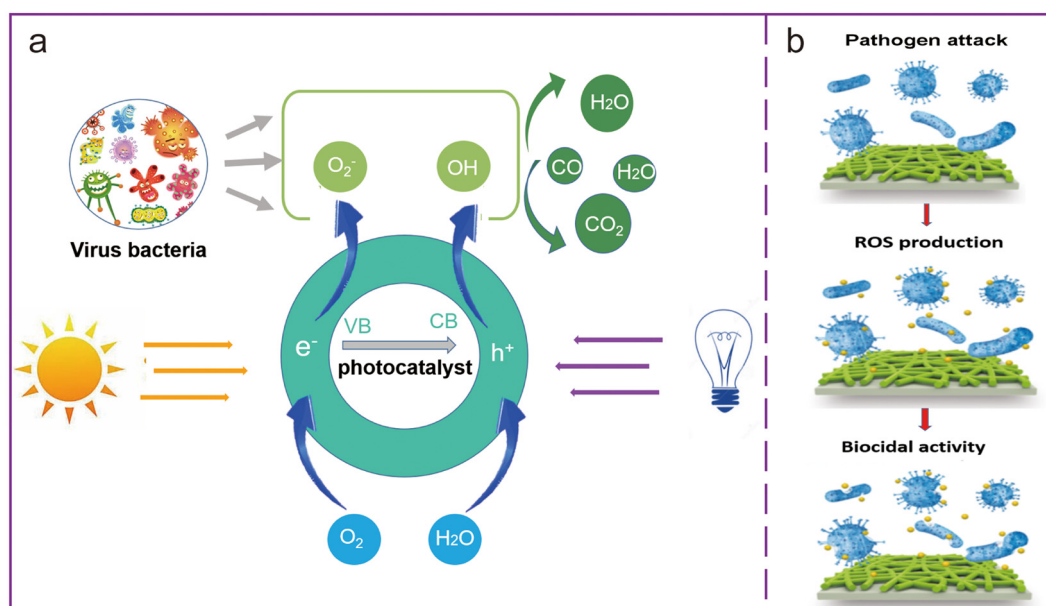
to carbon nanotubes driven by a near-infrared laser, successfully synthesizing complex T7Tag antibody-CN<sub>H</sub>, which selectively binds to T7 phages and effectively inactivates under near-infrared laser irradiation. Therefore, it is speculated that it can have a photothermal killing effect on harmful viruses (such as HIV, SARS, and avian influenza viruses), and this mechanism is shown in Figure 4d.

### 2.1.3 Photocatalytic materials

Under photo-irradiation conditions, photocatalytic antiviral materials can absorb light and generate singlet oxygen using surrounding oxygen, which can oxidize and destroy the protein membrane, thereby destroying the viral envelope and promoting deactivation (Figure 6a). The process of photocatalytic antiviral material's inactivation of microorganisms is shown in Figure 6b. This

kind of material has the advantages of being green, pollution free, and high durability.

Titanium dioxide (TiO<sub>2</sub>), a widely used photocatalytic material, can achieve antiviral effect through photocatalysis. Zan *et al.* [53] found that TiO<sub>2</sub> suspension and TiO<sub>2</sub>-coated ceramic plates destroy most hepatitis B surface antigens and affect the adhesion of hepatitis B virus on cells under weak ultraviolet light, weak sunlight, or indoor sunlight irradiation, which inhibit the viral activity. After 4 h of exposure to 0.6 mW/cm<sup>2</sup> mercury lamp, 97% of HBs can be destroyed in TiO<sub>2</sub> suspension. Mazurkova *et al.* [54] tested the inactivation effect of TiO<sub>2</sub> nanoparticles and TiO<sub>2</sub> powder on influenza virus, in which TiO<sub>2</sub> nanoparticles inactivate influenza viruses in the dark, while nonnanoparticles have no antiviral activity in the sun. Therefore, it is speculated that the main mechanism is that nanoparticles destroy the viral envelope, not just through photocatalysis. The degree of influenza virus inactivation depends on the concentration of nanoparticles



**Figure 6:** (a) Principle of photocatalysis. (b) Microbial inactivation process [52].

and contact time. Upon incubation of influenza virus with  $TiO_2$  nanoparticles, it is killed after 30 min, and the optimal concentration is 2 mg/mL. Hajkova *et al.* [55] prepared  $TiO_2$  films using titanium isopropanol as precursors by plasma chemical vapor deposition, which inactivate herpes simplex virus (HSV-1) and exhibit 100% antiviral effect after 6 h of light exposure.

After nanocrystallization, zinc oxide (ZnO) has the advantages of low toxicity, safety, odorless, and high efficiency. Under light, it can form ROS, which can destroy the binding of virus and host cells, as well as the surface proteins of the virus; hence, it displays good antiviral properties. The effect of ZnO on biological function depends on its morphological structure, particle size, exposure time, concentration, pH value, and biocompatibility [56]. López de Dicastillo *et al.* [57] prepared ZnO nanotubes with enhanced antimicrobial activity compared to ZnO nanoparticles (ZnO NPs). Ghaffari *et al.* [58] used A/H1N1 strain A/Puerto Rico/8/34 (PR8) as A (H1N1) virus model and evaluated ZnO NPs, as well as the addition of polyethylene glycol (PEG) (PEG-ZnO NPs) antiviral characteristics of H1N1 virus. Compared with the controls, the highest nontoxic concentrations of PEG-ZnO NPs and pure ZnO NPs (200 and 75  $\mu$ g/mL, respectively) after contact with the virus, the virus drops degree can be reduced by 2.8 and 1.2 log  $TCID_{50}$ , respectively. Li *et al.* produced ZIF-8 (zinc-imidazolate MOF) nanocrystalline film with good photocatalytic and antibacterial properties, which far exceeds the performance of

traditional semiconductors such as ZnO and  $TiO_2$  [9]. According to the indicated mechanism, the photoelectron captured by  $Zn^{+}$  center in ZIF-8 through ligand-metal charge transfer is the reason for the production of ROS related to oxygen reduction, which is the main disinfection mechanism. The inactivity of ZIF-8 against poliovirus and coronavirus is 99.99 and 99%, respectively.

## 2.2 Organic antiviral materials

Antiviral organic compounds have the characteristics of fast sterilization, easy synthesis, and high efficiency. They are often used to synthesize antiviral drugs and used in textile finishing to prepare antiviral textiles. Organic compounds can be polymerized and copolymerized with other comonomers to produce antiviral coatings or directly to produce antiviral fibers. Such compounds include quaternary ammonium salts, organic heterocyclic compounds, phenolic compounds, and organic metals.

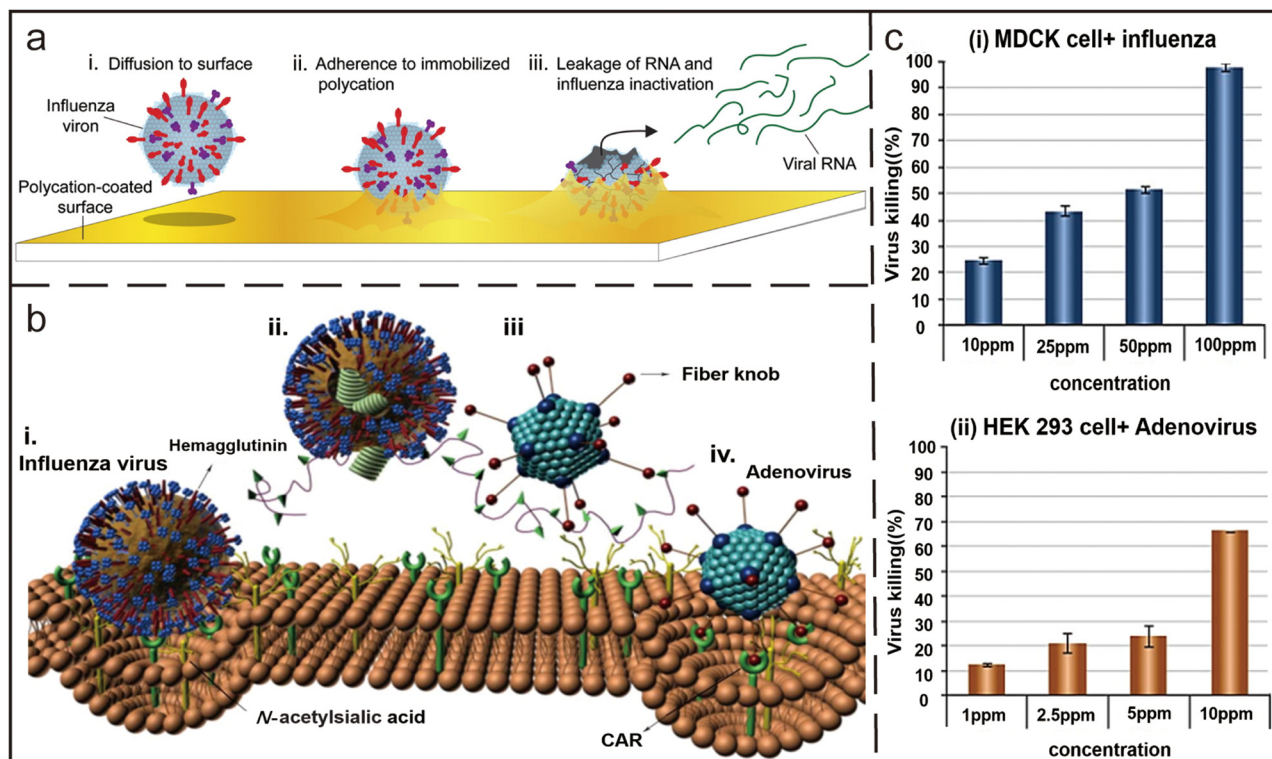
### 2.2.1 Quaternary ammonium salt polymer

Quaternary ammonium salts are the most commonly used quaternary ammonium compounds. Their structure, especially the length of the alkyl chain, plays an important role in its antimicrobial activity. The double-chain

quaternary ammonium salt has an inactivating effect on viruses. Their antiviral performance is also closely related to its concentration [59]. Hsu *et al.* [60] found that the dodecyl methyl polyethylene imine coating applied to the solid surface has a disinfecting effect on the influenza virus in the aqueous solution. Experiments based on scanning electron microscopy reveal that once in contact the influenza virus irreversibly adheres with the hydrophobic polycation coating, causing structural damage and inactivation, followed by the release of viral ribonucleic acid. The mechanism of its inactivation of influenza virus is shown in Figure 7a. Furthermore, monomer structure analogs of *N,N*-dodecyl, methyl-polyethyleneimine were analyzed, showing that the antiviral activity is inherent to the quaternary ammonium salt monomer unit and even remains in the form of polymer and surface fixation.

The structure of quaternary phosphonium salt (QPS) is similar to that of quaternary ammonium salt; however, its polarization is stronger, making it easier to adsorb bacteria and viruses and enhance antiviral performance.

Xue and Xiao [61] found that trimer poly(QPM-r-AM-r-ATC) (PQAA), which can be prepared from quaternary phosphate salts, has antiviral properties and can effectively inactivate enveloped viruses (influenza viruses) and nonenveloped viruses (adenoviruses). Different antiviral mechanisms lead to different antiviral effects of PQAA on enveloped and nonenveloped viruses. The lipids of enveloped viruses are susceptible to high-density positive charges [62,63], and PQAA can bind and destroy influenza virus lipid envelopes through strong charge interactions. Furthermore, the receptor binding site, the envelope glycoprotein hemagglutinin, is also destroyed. The destruction of the viral envelope and loss of the binding site contribute to the inactivation of influenza virus, as shown in Figure 7b(i) and (ii). The negatively charged fiber knob acts as a receptor-binding site for cell entry. For adenovirus, a nonenveloped virus, the polymer QPS can block the adenovirus fiber knob–receptor interaction, prevent the adenovirus from entering the cell, followed by its inactivation, as shown in Figure 7b(iii) and (iv). Plaque reduction experiments for influenza



**Figure 7:** (a) Mechanism of influenza virus inactivation by *N,N*-dodecyl, methyl-PEI coatings [60]. (b) PQAA antiviral mechanism: (i) binding of influenza virus to the *N*-acetylsialic acid receptor and engulfment by the cellular membrane, (ii) penetration of PQAA into the viral envelope followed by lipid destruction, (iii) inhibition of PQAA on ADV entry via blocking the association between CAR receptor and fiber protein, and (iv) binding of ADV to the CAR receptor mediated by the fiber protein and formation of clathrin pit. (c) Antiviral activity of PQAA against influenza virus (i) and adenovirus (ii) [61].



and adenovirus show that the highest virus-killing efficiency of PQAA is 97.9% at a polymer concentration of 100 ppm for influenza viruses (Figure 7c(i)). For adenovirus, the maximum virus-killing efficiency is 66.4% at 10 ppm (Figure 7c(ii)).

### 2.2.2 Organic heterocyclic compounds

Organic heterocyclic compounds, especially nitrogen-containing heterocyclic compounds, such as pyrazoles, pyrimidines, and pyrrole heterocyclic compounds, have been broadly used as antibacterial agents [64]. El-Sabbagh *et al.* [65] synthesized novel antiviral *N*-acetyl 4,5-dihydropyrazole 7, which inactivates vaccinia virus at subtoxic concentrations. Kim *et al.* [66] used the redox properties of polyaniline-copypyrrole polymerized nanotubes to synthesize polymerized nanotubes that regulate ROS levels. The activation of MEK (mitogen-activated protein kinase)/ERK (extracellular signal-regulated kinase) can be induced through the generation of ROS, thereby promoting cell survival and proliferation. They also confirmed that the three subtypes of influenza A virus (H1N1, H3N2, and H9N2) inhibit the spread of MDCK cells.

### 2.2.3 Others

In addition to the aforementioned two categories, organic antiviral materials also include biguanides, organotin, and so on. Park *et al.* [67] synthesized novel *N,N*-dodecyl methyl polyurethane (Quat-12-PU), which is easily processed into solutions, nanoparticles, and nanofibers. The surface of such materials has antiviral properties and inhibits influenza virus inactivation. Whether it is solution coating or nanocoating experiment, the material exhibits a strong inactivation effect on human influenza virus. It is speculated that hydrophobic Quat-12-PU coating destroys the lipid envelope of the virus, thereby promoting inactivation. However, Quat-12-PU coating cannot inactivate nonenveloped poliovirus. Rzaev and Sadykh-Zade [68] developed specific organotin polymers derived from trimethyltin and triethyltin ester, which show extraordinary antiviral activity due to the partial hydrolysis of organotin. Roner *et al.* [69] also verified that organotin polymers can inhibit virus replication.

Wang *et al.* [70] investigated the antiviral properties of other polymers by evaluating the virulent properties of poly(phenylacetylene)-based cationic conjugated polyelectrolytes (CPE) and oligophenylacetylene (OPE), which

are commonly used as antimicrobial agents. CPE and OPE are also excellent candidates for antiviral applications and display the same virus-killing mechanisms as antimicrobials. Under UV-visible light irradiation, chlorinated paraffins and oxidized paraffins can produce singlet oxygen due to the  $\pi$  bond system in the main chain of the compound and then form more corrosive reactive oxygen intermediates, showing significant virus-killing properties. CPEs and OPEs exhibit intermediate antiviral activity through partial decomposition of phage particle structures in the dark and by photochemical damage of phage capsid proteins under UV/visible light irradiation. Their structures and sizes can be chemically modified for specific antiviral needs.

## 2.3 Natural antiviral materials

Due to environmental protection and health and safety awareness in recent years, natural antiviral substances have been paid more attention. Natural antiviral materials have a series of advantages, such as wide availability, safety, and low toxicity. Commonly used natural antiviral materials can be divided into plants, animals, and microbial extracts.

### 2.3.1 Traditional Chinese medicine

Traditional Chinese medicine has a long history in antiviral therapeutics, in which its ingredients can be widely sourced and exhibit low toxicity. Certain Chinese herbal medicines are also effective against drug-resistant virus strains. Traditional Chinese medicines such as Huoxiang Zhengqi, Lianhua Qingwen, Shufeng Jiedu, and Xuebijing have been verified to have significant effects on new coronary pneumonia [71]. The key components of *Rhizobacteria sinensis*, such as kaolin, quercetin, auricin, glycyrrhetic acid, stigmasterol, and indigo, have a good binding ability with 3CL(Mpro) and ACE2 enzyme proteins of SARS-CoV-2 and can act on COVID-19 through multiple components, multiple targets, and multiple pathways. The main ingredients of Shufeng detoxification are *Polygonum cuspidatum*, *Forsythia suspensa*, *Isatis indigotica*, *Bupleurum*, *Corydalis*, *Verbena*, Reed root, and Licorice, which can inhibit virus proliferation and anti-inflammatory effects, as well as possessing certain immunomodulatory effects [71]. More and more Chinese herbal medicines with antiviral activity have obtained experimental or clinical evidence of efficacy. Table 1 lists some

antiviral traditional Chinese medicines and the corresponding viruses they can be effective against.

2.3.2 Propolis

As a natural medicine, propolis has a wide range of biological and pharmacological activities. Modern science has confirmed the antibacterial and antiviral effects of propolis [80]. The mechanism of antiviral properties of propolis is related to viral inhibition to a certain extent. It can promote reverse transcriptase and virus proliferation inhibition. Tait *et al.* [81] reported that natural and synthetic flavonoids may interfere with the replication of picornaviruses, prevent the shedding of viral particles and release intracellular RNA, or prevent the synthesis of viral RNA. Gekker *et al.* [82] confirmed that propolis has strong virus-inactivation activity against HIV-1 virus cultured in CD4 T lymphocytes and microglia cells, and propolis has a concentrate-dependent inhibitory effect on virus expression. A total of 66.6 µg/mL propolis can inhibit HIV-1 virus cultured in CD4 T lymphocytes and microglia cells by 85 and 98%, respectively. According to the research of Huleihel and Isanu [83], the antiviral activity of propolis may be related to the effect of flavonoids, which play a critical role in the antiviral process. Propolis has 50% inhibitory effect on HSV infection. Indirect results indicate that propolis has a strong interaction with the surface of Vero cells, but has no interaction with HSV particles, thereby inhibiting the cell–virus binding process.

2.3.3 Exopolysaccharides (EPSs)

EPSs are synthesized by eukaryotes and prokaryotes. Compared to other natural materials, the production time of EPSs is usually much shorter. Moreover, the extract method of EPSs is very simple, and it has been extensively used in textile finishing [84]. Effective inactivation of the virus is known to depend on the ability of the infected host to generate pro-inflammatory immune response and Th1 immunity, which limits viral replication [85]. In addition, reports have shown that probiotics and their metabolites can fight viral infection through enhancement of innate and adaptive antiviral immunity, thereby reducing the duration and frequency of disease, shedding the virus, normalizing intestinal permeability, and increasing the production of virus-specific antibodies [86]. *In vitro* studies have shown that EPSs (especially sulfated polysaccharides such as dextran) have antiviral effects against enveloped viruses [87], where they interfere with viral absorption and penetration into host cells, as well as inhibit the reverse transcriptase activity of various retroviruses. Arena *et al.* [85] studied the antiviral and immunomodulatory effects of EPS-1, a novel extracellular polysaccharide produced by heat-resistant *Bacillus teriformis* strain, against HSV-2, and found that EPS-1 inhibits HSV-2 replication in human peripheral blood mononuclear cells (PBMCs) by inducing a large number of Th1 cytokines (IFN-A, IFN-C, TNF-A, IL-12, and IL-18). The antiviral activity of 300 µg/mL EPS-1 reached 85%. Gugliandolo *et al.* [88] showed that a new extracellular polysaccharide (EPS1-T14) from a strain of *Bacillus*

Table 1: Partial list of traditional Chinese medicine names approved by the SFDA for the treatment of viral diseases

Traditional Chinese medicine name	Species of virus	Epidemic disease	References
<i>Radix bupleuri</i>	Influenza A (H1N1) virus	Influenza	[72,73]
	Human coronavirus 229E	Upper respiratory infection	
	Measles virus		
	Herpes simplex virus		
<i>Fructus forsythia</i>	14 Varicella zoster viruses		[74,75]
	Influenza A (H1N1) virus	Acute bronchitis, pneumonia influenza	
	Respiratory syncytial virus		
	Infectious bronchitis virus		
Honeysuckle	Influenza A (H1N1) virus	Influenza	[76,77]
<i>Scutellaria root</i>	Herpes simplex virus	Tonsillitis	
	Adenovirus	Pharyngitis	
	Respiratory syncytial virus	Upper respiratory infection	
Indigowoad root	Parainfluenza virus (PIV)		[78,79]
	Influenza A (H1N1) virus	Influenza	
	Herpes simplex virus	Acute tonsillitis	
	Hepatitis B virus	Mumps	

*licheniformis* T14 has an antiviral effect on HSV-2, with the inhibition rate reaching 77%. Kanmani *et al.* [89] showed that the extracellular polysaccharide of *Lactobacillus delbrueckii* OLL1073R-1 has the potential antiviral activity against enteroviruses such as rotavirus.

## 2.4 Composite antiviral material

In recent years, to improve the antiviral performance of various materials, many researchers have used the aforementioned three materials to create composite antiviral materials through various methods. These composite materials can often produce synergistic effects and greatly improve the antiviral efficiency. Currently, Ag is the most commonly used antiviral material in combination with other materials for antiviral synergy.

Chen *et al.* [90] prepared GO–Ag nanocomposites by growing silver on GO and identified the antiviral activity of GO and GO–Ag against coated feline coronavirus (FCoV) and uncoated infectious bursa virus (IBDV) using virus inhibition assay. They found that GO–Ag inhibits 25% of FCoV infection and 23% of IBDV infection at noncytotoxic concentrations, while GO inhibits only 16% of FCoV infection and exhibited no antiviral activity against IBDV infection. The unique structure of GO tablets benefits the inhibition of FCoV infection of lipid envelope and can enhance the antiviral effect of silver particles by supporting the uniform dispersion of silver particles and formation of nonaggregated spherical particles. The fixation of Ag NPs on GO tablets reduces cytotoxicity. Iyigundogdu *et al.* [91] applied sodium pentaborate and triclosan to fabrics to obtain antiviral properties. The cotton fabric finished with 3% sodium pentaborate, 0.03% triclosan, and 7% glucagon has a good inactivation effect toward adenovirus type 5 and poliovirus type 1. Textile materials can reduce the titer of both viruses by 60%. Mori *et al.* [92] prepared Ag NPs/chitosan flocculent powder composite material with antiviral activity. Ag NPs of varying diameters were embedded in the chitosan matrix, where the antiviral activity increases with increasing Ag NPs concentration. The smaller Ag NPs in the composite material projected stronger antiviral activity. Chitosan itself has no antiviral activity, but it is conducive to the combination of virus and nano-silver, thereby improving the antiviral activity. Li *et al.* [93] studied the antibacterial synergy of TiO<sub>2</sub> and Ag NPs. Ag NPs preferably break down the cell wall of the microorganism and attack the respiratory chain and cell division and ultimately lead to cell death. In addition, under

light, TiO<sub>2</sub> makes the surface of the fabric produce more active materials to ionize Ag. The ionized Ag is more active, can destroy the cell wall structure, and induces bacterial cell lysis. The NPs release Ag ions in the bacteria cell, which enhances the antibacterial activity. The synergistic antiviral mechanism of nanoparticles and photocatalysis is being further explored.

The aforementioned antiviral materials have been confirmed to have antiviral activity at a certain concentration, but these materials have their own advantages and disadvantages, as presented in Table 2. We can refer to these properties to prepare antiviral textiles for different purposes.

## 3 Preparation and detection method of antiviral textiles

To date, there are two main methods for the preparation of textiles that acquire antiviral functions. The first method is to mix the antiviral material with the polymer spinning solution and spin it. The second is through the finishing method, in which the antiviral material is added to the fabric finishing agent *via* impregnation or padding method to produce the fabric antiviral function. Table 3 summarizes the preparation methods of some antiviral textiles.

The most commonly used method to combine organic natural antiviral materials and certain metal nano antiviral materials with textiles involves impregnation and padding, as shown in Figure 8a. Nanoparticles can be integrated on various textile fibers through finishing methods [106]. Joshi and Roy [97] mixed AgNO<sub>3</sub> solution with various reducing agents, followed by immersion of fabric in the mixed solution to generate nanoparticles *in situ*, which was then dried to produce an antiviral fabric. Gabbay *et al.* [96] found that textiles impregnated with copper oxide solution have a strong inactivation effect on bacteria, fungi, and HIV virus. Borkow *et al.* [33] impregnated copper oxide solution on polypropylene fiber, which can effectively inactivate influenza virus. The antiviral material prepared by attaching silver, copper, zinc, and other metals or their ions to zeolite through physical adsorption and ion exchange can also prepare antiviral textiles by finishing. Imai *et al.* [38] used the structural components of zeolite as raw materials to synthesize (Na<sub>12</sub>((AlO<sub>2</sub>)<sub>12</sub>(SiO<sub>2</sub>)<sub>12</sub>)·27H<sub>2</sub>O) zeolite on cotton fabrics to produce CuZeo textile, which can be utilized in the medical and health fields. MOFs, as a good carrier of



Table 2: Advantages and disadvantages of various antiviral materials

Antiviral material	Advantage	Disadvantage
Inorganic antiviral material		
Metals and their compounds	Wide spectrum Long effective antiviral period Low toxicity Resistance to drug resistance	High cost Delayed effect Ease of oxidation
Carbon-based nanomaterials	Low cytotoxicity Specific antiviral activity	High cost Limited range of use
Photocatalytic material	Low cytotoxicity Good antiviral performance Environmentally friendly	High cost Poor antifungal effect
Organic antiviral material	Low cost Fast germicidal speed Easy to process Good color stability	Easy to produce drug resistance Toxic Poor heat resistance Pollution in the production process
Natural antiviral material	Safe and nontoxic Environmentally friendly	Difficulty in processing Poor durability Poor heat resistance Short service life Narrow application range
Composite antiviral material	Prolonged durability Broad spectrum Safe	The coordination mechanism is not clear

functional nanoparticles, can be combined with zinc, silver, and other antiviral materials, followed by impregnation or grafting adhesive finishing on the textile. Li *et al.* [9] reported that ZIF-8 MOF finishing on textiles has a strong adsorption ability to viruses and bacteria and inactivation ability to bacteria under the light. The finishing processing method is simple to operate, low in cost, and suitable for inorganic, organic, and natural antiviral materials. However, this method has a mass release in the initial stage, with low durability, which affects the comfort of the fabric. As a result, a series of spinning methods, such as wet spinning and melt spinning, have emerged. The spinning method can generate antiviral substances evenly dispersed in the fiber, hence, the antiviral effect of the fabric, high washable resistance and durability, and greatly improve the feel of the fabric.

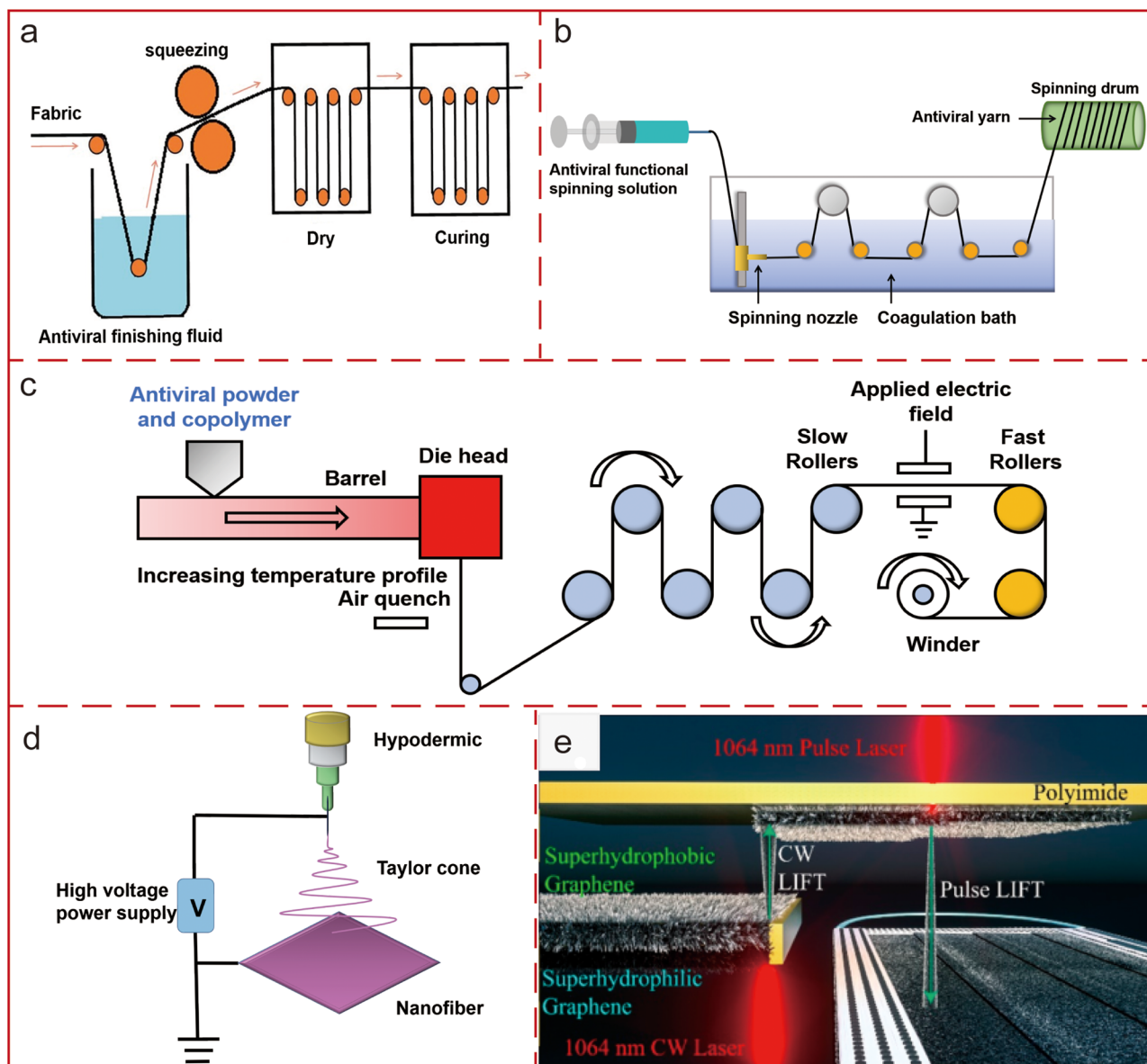
Wet spinning is a chemical fiber spinning method in which the polymer is dissolved in the solvent. A thin stream is ejected through a nozzle hole to enter a coagulation bath to form fibers. This method can produce fibers with a skin-core structure (Figure 8b). The fiber-forming polymer suitable for wet spinning can be dissolved in a suitable solvent and cannot decompose in the coagulation bath. Kwak *et al.* [101] used UV-visible light method to prepare Ag NPs and prepared antibacterial Ag NPs doped gelatin fibers by the wet spinning method. Water

and fructose can be employed as green solvents and cross-linking agents, allowing different amounts of Ag NPs to be embedded in gelatin fibers, and showed durable and effective antibacterial properties.

The melt spinning method involves the mixing of antiviral materials with various additives, which are uniformly combined with the fiber matrix resin. Finally, spinning under high-temperature conditions. Therefore, the material needs to be resistant to high temperature and has small particle size, good dispersibility, and compatibility. Compared with wet spinning, melt spinning draws more and produces finer fibers. In addition, it can be used to make antiviral yarns from most inorganic materials and some high temperature-resistant organic materials. The spinning device is shown in Figure 8c. Damerchely *et al.* [107] prepared 20 denier and 70 denier nylon 6/nanometer silver composite filaments *via* the melt spinning technique. The amount of nanometer silver added can reach 0.5–1 wt%. The yarn has good antibacterial properties and maintains excellent mechanical properties. Many studies have prepared antibacterial Lycell fibers *via* the addition of a variety of bioactive additives, including silver and chitosan derivatives, to *N*-methylmorpholine-*N*-oxide spinning solvent by physical blending. Silver zeolite and MOFs can also be blended and spun to produce antiviral fibers [108].

Table 3: Preparation schemes and advantages and disadvantages of some antiviral textiles

Method	Suitable material	Advantage	Disadvantage	References
Fabric finishing Microcapsule	Natural antiviral materials (especially Chinese herbal medicine)	Strong washing, resistance, slow- release function	Fabric feel and breathability deteriorate	[94,95]
	Inorganic organic natural	Simple operation, low cost, universal use	Reduce fabric softness and breathability	[91,96–100]
Spinning method				
Wet spinning	Inorganic and organic materials	Uniform structure Good quality	Low addition amount of antiviral materials, low efficiency, and high cost	[101]
Melt spinning	Inorganic organic materials with high heat resistance	Long-lasting antiviral effect Good flexibility	Agglomeration is easy to occur during the spinning process, and antiviral substances are not easily dispersed evenly	[102]
Gel spinning	Inorganic organic	Long-lasting antiviral effect, slow- release effect	Low output, low production efficiency	[103]
Electrostatic spinning	Inorganic organic	High specific surface area, high porosity, high antiviral activity	Low fiber strength and low production efficiency	[52,104]
Others				
Laser induction, radio frequency co-sputtering	Graphene	Simple operation, large-scale production	Cause damage to the structure of textiles, resulting in a decrease in mechanical properties	[105]



**Figure 8:** Methods of processing antiviral textiles. (a) Antivirus textile soaking and rolling process. (b) Preparation of antiviral textiles by wet spinning. (c) Antiviral textiles prepared by melt spinning. (d) Basic equipment for electrostatic spinning. (e) With CW-LIFT transfer of graphene onto a second polyimide and then pulse-LIFT transfer of graphene onto a temperature-sensitive mask [105].

Gel spinning involves the extrusion of polymer solution or plasticized gel with a high concentration from the fine hole of the spinneret head into a gas medium. The thin stream is cooled, followed by solvent evaporation and polymer solidification to obtain the desired fiber. The equipment is similar to melt spinning. This spinning method can produce yarn with high strength and high modulus. Similar to melt spinning, the antiviral materials used in the method are subjected to high temperatures. Ma *et al.* [103] proposed a new high-throughput method for mechanically exfoliating graphene (MEG) in natural media. MEG can be well dispersed in the polyvinyl alcohol

(PVA) matrix, where a certain amount of PVA and MEG are slowly added to mixed dimethyl sulfoxide (DMSO) solution in a specific ratio, and dispersed uniformly, and then passed through gel spinning and stretched 20 times to obtain PVA/MEG nanocomposite fiber. This nanocomposite fiber has high-strength characteristics and great antimicrobial, low cytotoxicity, and other properties.

However, there are some problems with these three approaches. The antiviral materials for the preparation of the antiviral fiber core layer cannot reach the fiber layer, which reduces the antiviral efficiency compared to the fabric finishing method. Therefore, electrospinning

technology, which can prepare nanoscale and highly effective antiviral fibers, has received more attention. The nanofibers prepared by electrospinning also have a slow-release effect, which further enhances the safety and durability of the antiviral fibers. Electrospinning is a special fiber manufacturing process in which a polymer solution or melt is sprayed into a strong electric field to produce polymer filaments with nanoscale diameters (Figure 8d) [109]. Most organic polymers can be mixed with antiviral materials to produce antiviral electrospinning nanofibers through the electrospinning process. López de Dicastillo *et al.* [57] obtained ZnO nanotubes by atomic layer deposition on electrospinning polyvinyl alcohol nanofibers and then removed the polymer by calcination to obtain antimicrobial nanostructures with high specific surface area. Wang *et al.* [110] modified polyacrylonitrile (PAN) by nitrile modification reaction and synthesized PAN-Ag<sup>+</sup> nanofiber membrane by the electrospinning method, which has high antibacterial activity and stability. Si *et al.* [52] used PVA-co-PE as a polymer precursor to fabricate a nanofiber web by electrospinning and finally dipped it in a photosensitizer to produce a daylight-driven antiviral nanofiber membrane. Many studies have improved the preparation method of electrospinning technology. Han *et al.* [111] used coaxial electrospinning technology to prepare nanofibers with high efficiency and a good slow-release effect. Dou *et al.* [112] introduced a high-speed thermal flow into the electrospinning, which can entangle the fibers and produce nanometer yarns with the tight arrangement. Some studies have also combined electrospinning and electrostatic spraying to spin nanofiber membranes with multilayer structures and functions [113]. Yu *et al.* [114] used a multi-needle conjugated electrospinning device to blend GO-polyethylenimine-silver composites with a PAN spinning solution to produce nanofiber yarn, which has high efficiency and durability, and enhanced strength compared to traditional electrospinning. Currently, the realization of large-scale production of electrospinning has also been further explored [115].

Laser-induced graphene is a new method for the preparation of graphene, using commercially available precursors (such as polyimide, SPEEK, and Bakelite) to produce functional graphene at a low cost. Zhong *et al.* [105] designed a double-membrane laser-induced forward transfer method as shown in Figure 8e, which can deposit multiple layers of graphene on a nonwoven mask with a low melting point. The surface of the fabric is superhydrophobic to prevent the infection of saliva soaking carrying the virus. Under the action of light, the temperature of the fabric can reach above 80°C, which can inactivate most viruses. Balagna *et al.* [116] used radio frequency (RF)

co-sputtering technique to deposit silver nanoclusters/silica composite coating on the surface of cotton fabrics. The results demonstrated that the silver nanocluster/silica composite coating is characterized by strong virucidal activity against RSV and influenza virus, and the nanostructured coating is able to reduce influenza virus of about two orders of magnitude, compared to the uncoated filters or the control.

## 4 Application of antiviral textiles

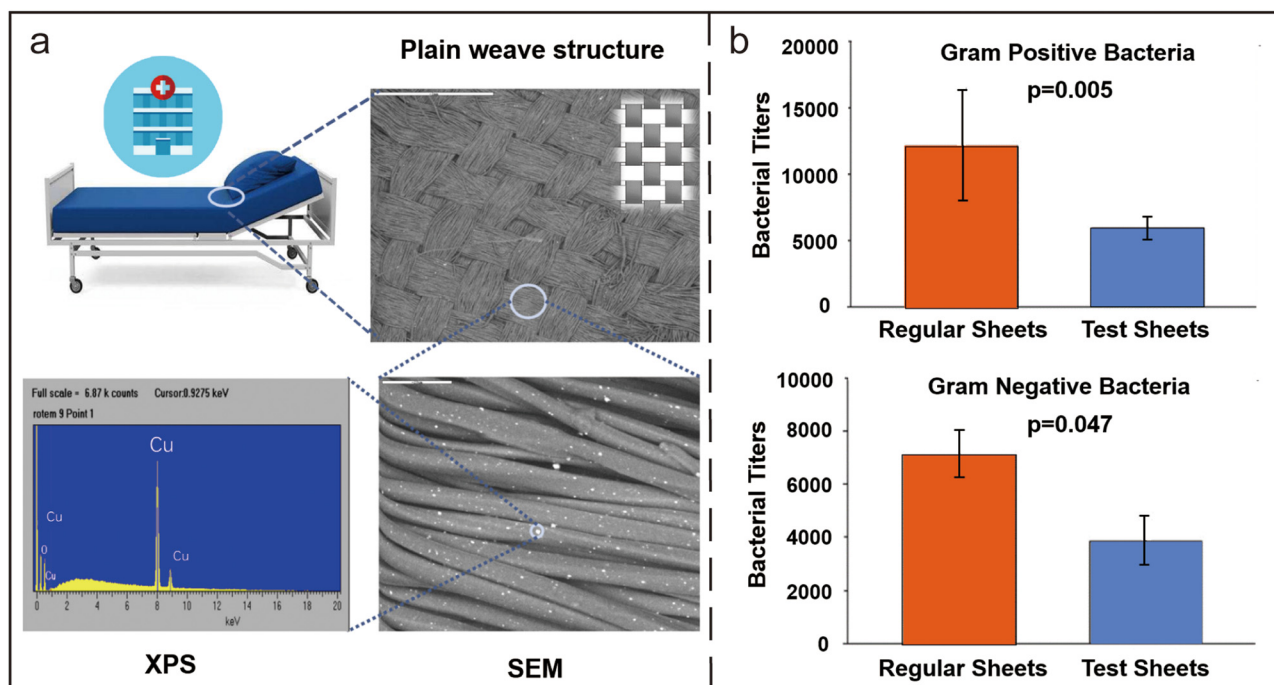
### 4.1 Applications in healthcare settings

Healthcare facilities are crowded with patients exhibiting a variety of diseases, in which hazardous bacteria are more common compared to elsewhere. In addition, healthcare workers are at high risk of contracting virus. For example, during Ebola outbreak, a total of 852 healthcare workers were diagnosed, of whom 492 died. Healthcare workers are at 100 times more higher risk than the general population [117]. Therefore, the use of antiviral textiles in healthcare settings is vital. Lazary *et al.* [118] compared the incidence of healthcare-associated infections in two similar patients in the head injury care ward during two parallel periods A and B. Phase A served as a control group without treatment. In the case of Phase B, all conventional nonantimicrobial linens and employee uniforms were replaced with antimicrobial products impregnated with copper oxide, as shown in Figure 9a. The results showed that compared with Phase A, the patient's infection index in Phase B decreases, the nosocomial infection index per 1,000 days of hospitalization reduces by 24%, the number of days of fever (>38.5°C) of patients reduces by 47%, and the total number of days of antibiotic administration reduces by 32.8%. Therefore, during Phase B, antibiotics, hospital infection-related treatments, X-rays, disposable supplies, labor, and laundry costs decrease by about 27% (Figure 9b). The filament prepared by the melt spinning of the nano additive and the spinning solution is prepared into anti-SARS masks for use by medical personnel [119].

### 4.2 Antiviral protective textile

COVID-19 epidemic is affecting more than 210 countries and regions, mainly through respiratory droplets. In



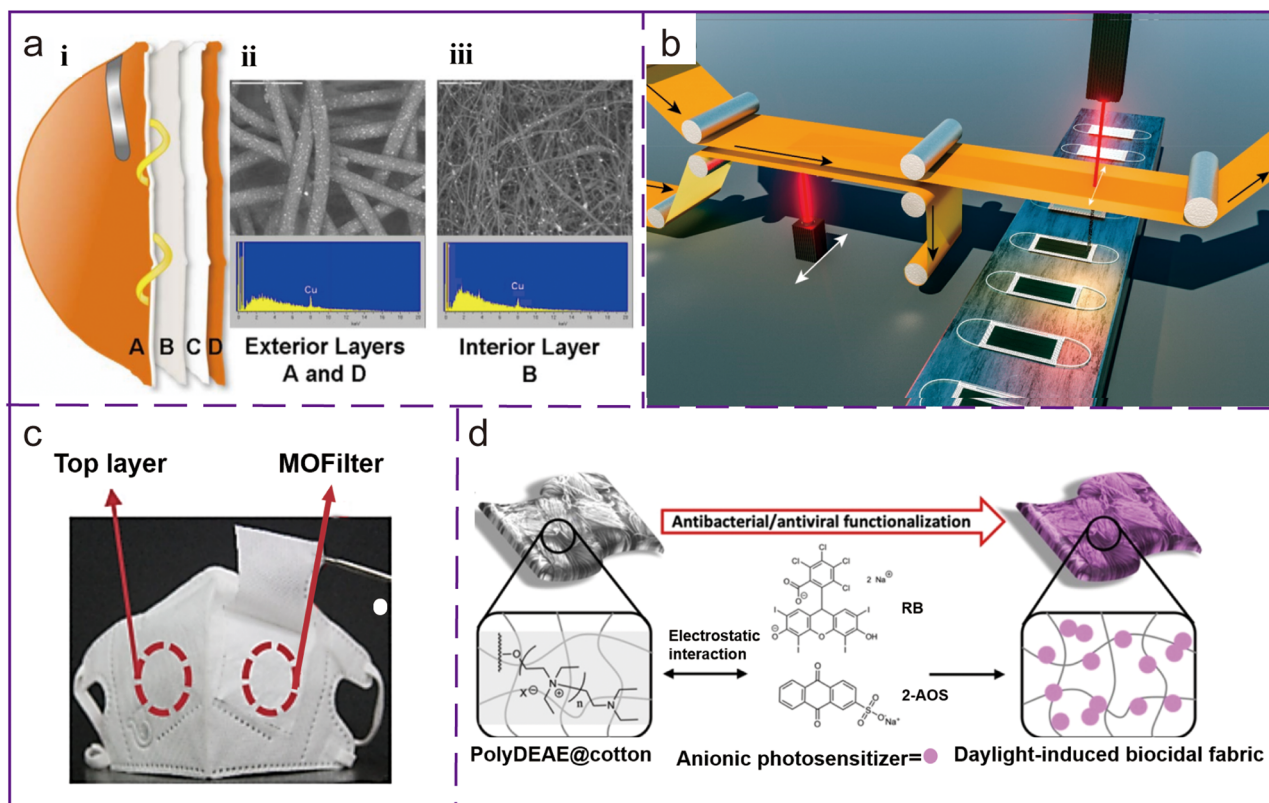


**Figure 9:** (a) Scanning electron microscope images of two representative pillowcases are shown. The white dots are copper oxide particles embedded in polyester fibers. (b) Bacterial loads were found in conventional and copper oxide impregnated sheets. Forty conventional sheets and Forty copper oxide impregnated sheets were swabbed immediately after being used by patients for 6–7 h. Swabs were taken from the area in contact with the patient's upper back [118].

high-risk areas, disposable surgical masks are commonly used by patients, doctors, and even the public. Masks can directly block the spread of droplets, and the protection of masks plays an important role in the health of people. In recent years, many researchers have developed antiviral masks. Borkow *et al.* [33] made an antiviral mask with copper intermediate layer, consisting of the following four layers (Figure 10a): The outer layer A consisted of spunbonded polyamide fabric containing 2.2% weight (w/w) copper particles; the inner layer B consisted of fused polypropylene fabric containing 2% (w/w) copper oxide particles and forms the barrier layer that provides the physical filtration performance of the mask; the inner layer C consisted of ordinary polyester and used to shape the mask; and the outer layer D was the same as layer A, but closer to the wearer's face when used. Respiratory masks were impregnated in copper oxide, giving them strong anti-influenza biocidal properties without changing their physical barrier properties. Zhong *et al.* [105] produced a layer of graphene on the surface of a common surgical mask by laser induction that kills virus with electrothermal properties (Figure 10b). Li *et al.* [9] used MOFilter as an intermediate layer, sandwiched between two layers of nonwoven fabric as a biological sterilization

layer. Compared with the control group (N95 masks), it has a strong sterilization performance and did not affect the adsorption (Figure 10c). Tang *et al.* [120] exploited the strong electrostatic interaction between cationic cotton fibers and anionic photosensitizers to develop durable and reusable sun-induced antibacterial/antiviral cotton fabrics that can be used in face masks and protective clothing (Figure 10d). Virus substitutes (T7 phages) possess a microbiome reduction rate of about 5–6 logs for up to 60 min of sun exposure. Antiviral materials can be added to the adsorption layer in the middle of the mask. The upper and lower layers are hydrophobic layer and hydrophilic layer, respectively. Materials with special wettability can make the mask have better moisture permeability and surface moisture resistance, so as to prepare a mask with both disease resistance toxicity and comfort [121].

In addition to the aforementioned two main applications, there is also a certain risk of infection in places such as public transportation, the catering industry, and public office learning. If seat fabrics, seat belts, interior textiles, tablecloths, carpets, towels, and other textiles have antiviral properties, the risk of cross-infection can be greatly reduced.



**Figure 10:** Design of antiviral mask. (a) Copper oxide impregnated test mask composition [33]. (b) Illustration of the compatibility of the dual-mode LIFT for roll-to-roll production of a grapheme-coated mask. The direction of rolling movement is a black arrow, and the direction of the laser movement is a white arrow [105]. (c) Antiviral mask made by adding MOFilter layer to two layers of nonwoven fabric [9]. (d) Schematic illustration of the fabrication of daylight-induced antibacterial and antiviral textiles [120].

## 5 Prospects for antiviral textiles

So far, most antiviral researches focus on medicinal applications. However, relatively few studies researched antiviral materials, especially textiles. The materials for the preparation of antiviral textiles are mainly inorganic metals such as silver, copper, and their compounds, most of which are combined with textiles through finishing methods. However, the combination of copper and silver in fabrics can easily change the material's color. Hence, the cost is high, and manufacturing is complex. After finishing the method, antiviral properties only exist on the fiber surface; it is not resistant to washing, initial dissolution is large, and there are safety problems in wearing the material. Hence, it is essential to develop green, safe and durable antiviral textiles.

In terms of materials, polypropylene fiber is the main component of mask melt-blown cloth. Its unique capillary structure provides a high surface area and electrostatic solid adsorption capacity. Therefore, viruses can be effectively intercepted and adsorbed by polypropylene

fiber. Graphene has higher surface energy, which makes it stronger than polypropylene melt-blown fabric for electrostatic adsorption. When air passes through, almost all dust and toxic droplets can be electrostatically adsorbed and added to the melt-blown cloth of the mask. Therefore, graphene and other antiviral materials can be mixed through electrospinning to create masks with an excellent blocking effect and excellent antiviral performance. In recent years, Chinese medicine has been used more frequently, especially when it has played a vital role in the new crown pneumonia epidemic. The application of nanotechnology in the research and development of Chinese medicine is one of the essential directions for the development of Chinese medicine. The application of nanotechnology can improve the water solubility of the effective ingredients of traditional Chinese medicine and increase the utilization rate of the medicine. Packaging the practical components of traditional Chinese medicine into nano-carriers can prevent the damage of pH and enzymes and maintain its stability. There are many ways to combine Chinese medicine with textiles, such

as Chinese medicine extract, padding, sol, and microcapsule. Nano-processing the active ingredients of traditional Chinese medicine, adding the spinning solution to blending or adding adhesive on the fabric's surface, can effectively improve the antiviral performance of the fabric. Composite antiviral materials have extensive application prospects. The combination of multiple antiviral materials can enhance spectral properties and antiviral activity. However, currently, only a few studies examine composite antiviral materials, and the research on its mechanism and ratio is still lacking. Therefore, researchers should explore antiviral textiles made of multiple materials.

In terms of technology, spinning to produce antiviral fibers has slow release and durability, which is an important trend in the development of antiviral textiles in the future. The antiviral material can be made into antiviral yarn or fiber through electrostatic spinning, blending spinning, and wet spinning methods, which can significantly improve antiviral fabrics' safety and washing durability. However, due to the limited number of antiviral substances added in the spinning process, researchers can further explore such materials and determine optimal concentration.

Bio-flexible sensors also play an important role in the epidemic outbreak. However, few such studies focus on sensors, which are mainly used for virus detection and the location of virus-infected persons. Researchers can use textiles as a substrate to create biosensors, combined with 5G wireless communication technology and equipment to control the spread of the epidemic.

Currently, there is an urgent need to develop low-cost, green, safe, high-efficiency, and industrially produced antiviral textiles. It is very necessary to cooperate in textile materials science, microbiology, and pharmacy to learn and develop together, realize industrialized production, and make antiviral textiles play an important role in the fields of medical protection and daily human protection.

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