A review on recent trends of antiviral nanoparticles and airborne filters: special insight on COVID-19 virus

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Abstract

Novel corona virus (COVID-19) pandemic in the last 4 months stimulates the international scientific community to search for vaccine of antiviral agents suitable for in activating the virus inside and outside the human body. More than 4 million people globally are infected by the virus and about 300,000 dead cases until this moment. The ventilation and airborne filters are also investigated aiming to develop an efficient antiviral filtration technology. Human secretion of the infected person as nasal or saliva droplets goes as airborne and distributes the virus everywhere around the person. N95 and N98 filters are the must use filters for capturing particles of sizes around 300 nm. The average size of the novel corona virus (COVID-19) is 100 nm and there is no standard or special filter suitable for this virus. The nanoparticle-coated airborne filter is a suitable technique in this regard. While the efficiency of this type of filters still needs to be enhanced, new developed nanofiber filters are proposed. Most recently, the charged nanofiber filters of sizes below 100 nm are developed and provide an efficient viral filtration and inactivation. The efficiency of filter must be kept at accepted level without increasing the pressure drop. The present review outlines the most efficient antiviral nanoparticles including the recent functional nanoparticles. The filtration theory, filtration modeling, filter testing, and different types of filter with special concentration on the charged nanofiber filter were discussed. The charged nanofiber filter able to capture novel corona virus (COVID-19) with 94% efficiency and a pressure drop less than 20 MPa.

Keywords COVID-19 · Nano-aerosols · Air filtration · Nanoparticles · Nanoparticle-coated air filter · Charged fibers

Introduction

The demand for the ventilator, respirator, facemask, and body protection has been surging dramatically during the COVID-19 pandemic. To the date of writing this paper, the number of infections is soared exponentially, reaching to more than 3.4 million patients around the world, and around 7% of them died. Novel coronavirus belongs to the coronavirus family which includes MERS and SARS. Under

scanning electron microscope, the coronavirus seems like crown having a size averaged between 60 and 140 nm. This profile has led to suggest the name for the virus (Zhu et al. 2020). Its height is 10 nm, which is less than the height of SARS and MERS for the values of 15 nm and 18.5 nm, respectively (Ather et al. 2020) (Konda et al. 2020). The spike protein nature with larger number of spikes makes the COVID-19 anchor and attacks the cells easily. The spikes help the virus to attach to droplets that come out of patients during influenza season (Huo et al. 2020) (R. Kumar et al. 2019). Accordingly, the spread aerosolize may transfer the virus to a long distances taking the advantage of small size for the virus (Zhu et al. 2020). The atmospheric aerosols can be divided relying on the size into less and greater than 100 nm. The National Institute for Occupational Safety and Health (NIOSH) advises to use N95 and N99 filters to capture 300-nm aerosol sizes with efficiencies of 95 and 99%, respectively, but there is no recommendation in case of aerosol size of less than 300 nm (Ge et al 2020). The National Institute for Occupational Safety and Health

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(NIOSH) limited the use of N95 and N99 to capture 300-nm aerosol sizes with efficiencies of 95 and 99%, respectively, but there is no standard for less than 300 nm. The common nonwoven microfiber filters can capture aerosols of sizes no less than 300 nm. The aerosols may be in different shapes and sizes depending on the source (Bau et al. 2020). The atmospheric aerosols are divided depending on the size into nano-aerosols of < 100 nm and larger (> 100 nm). The filtration efficiency is usually done based on the concentration of indoor and outdoor aerosols (Jeong et al. 2020). Very little number of studies has been done in order to fabricate air filters with the ability to work in continuous conditions of airflow and having a coating of antiviral activity (Liu et al. 2020) (Hirschmann et al. 2020). Charged nanofiber filter showed interesting filtration properties and the development studies on this type of antiviral filter by adding decorated graphene with nanoparticles may be the suitable target in the next step in fighting against novel corona virus (COVID-19). Many types of filters with nano-coating have been used for inactivating the viruses. In the current review, we are going to focus on recent antiviral nanoparticles used for coating on the surfaces of filters, method of preparation of nanoparticles, types of filters, woven, nonwoven, nanofiber, nanofiber electret filter, theory and modeling of filtration, testing of filter, and the mechanism of antivirus activities.

Aerosols

One of the most harmful pollutants for the air is the aerosol, especially the particulate matter of nanosize. The inhalation of PM causes a disorder in respiratory system, leading to difficulty in breathing (Matava et al. 2020). Nano-aerosols of size less than 100 nm, which are contaminating the lungs, can easily penetrate into the bloodstream near the lungs. Reaching contaminates the brain by blood circulation system which causes many damaging effects in human body (Thamboo et al. 2020). It has been reported that the road emissions of aerosols are around of 200 million per cubic meter (Leung and Chau 2019). The classical microfiber filters are inactive for capturing all these types of aerosols; here, we will present the progress in nanofibers to tackle this issue.

Viruses

Many diseases are caused by very small nonliving particles, which have an infectious pathogenic effect and able to damage organs, tissues, and cells of the mammals and humans and even led to death (UCSF 2020) (Gerba and Betancourt 2017). This leads to an increase in annual human death to reach 2 million around the world (Colpitts et al. 2016). Vaccines are the most useful way for

inactivation the viruses, but still, there are few of vaccines that have been explored. In 12th of March, the World Health Organization declared that the novel corona virus is a pandemic virus due to the speed of the virus spreading around the world. It is believed that the virus started from the animals in the city of Wuhan, China, in December 2019 and the infections continue to spread inside and outside China until reaching 3.4 million cases and the deaths of more than 240,000 in the globe until this moment (Huang et al. 2020). The evidences from Wuhan City proved that the novel coronavirus can spread from animal to human and from human to human in similar behavior with the SARS and MAERS which were declared for in 2003 and 2012, respectively (WHO 2019). It is believed that the infected person by novel corona virus can spread the infection to the other persons through the droplets by coughing and sneezing (Leung and Sun 2020). The size of droplets may be less or more than 50 nm in size (Cook 2020). In addition, the virus may be aerosolized during the vomiting and speech (Asadi et al. 2020). Consequently, the spread of the novel corona virus around the globe in this speedily manner may be explained depending on the above statements. Due to this pandemic, the need for efficient filtration increased strongly. TEM photos for novel coronal virus showed that the size of the virus around 100 nm and the conventional filtration technology cannot protect from this virus (Leung and Sun 2020). Figure 1 shows the

Fig. 1 Sketch showing the average size of the novel corona virus (COVID-19)

average size of the virus. The new efficient filtration technology for viruses will be outlined in this work.

Nanoparticles as antiviral agents

Nanoparticles of silver

The physicochemical and biological properties of Ag nanoparticles (NPs) have attracted the attention of researchers to employ it in different applications such as drug delivery and for products to heal the burns and wounds (Nakamura et al. 2019) (Kulathunga et al. 2020). However, using Ag NPs for viruses inactivation is still in the beginning (Augustine and Hasan 2020) (Choudhary et al. 2020). The Ag NPs have been investigated as antiviral agent for inactivating some viruses like HIV, H1N1, parainfluenza, HSV1, and hepatitis B (Kim et al. 2020). Moreover, a green preparation method for obtaining like spherical particles of Ag NPs has been tested by the researcher to be as an antiviral for the virus of H1N1, which inhibits H1N1 (Dung et al. 2019) (Moradi et al. 2017). Moreover, Ag NPs resist the ROS production and though inactivate the neuraminidase. The hydrogel of Ag NPs prepared by tannic acid shows an efficiency for inactivating HSV1 and HSV2 viruses as well (Szymańska et al. 2018) (Gherasim et al. 2020).

Nanoparticles of gold

Gold nanoparticles have been used in the nanomedical and diagnostic applications owing to their superior mechanical, optical, and electrical properties (Ambekar et al. 2020) (Sánchez-López et al. 2020). DNA and proteins were detected by Au NPs, and different methodologies are employed for preparing Au NPs (Rathore et al., 2020) (Chen and Liang 2020) (Slepička et al. 2020). Rosi and co-workers were first to prepare Au NPs for the biological and medicinal applications (Rosi and Mirkin 2005). In order to inhibit the HSV1 virus, the Au NPs were used, which were stabilized by gallic acid using ultrasonic technique and characterized using the plaque reduction neutralization test (Kim et al. 2020). Another study utilizes hyaluronic modified Au NPs for inactivation of hepatitis C virus (M. Y. Lee et al. 2012). Moreover, the gold nanoparticles have been utilized effectively in antiviral used for HIV, HSV1, and influenza (Milovanovic et al. 2017) (Ringe et al. 2019) (Senapathi et al. 2020). The activity of Au NPs is affected by the size of the particles concerning the size of the virus. The efficiency of nanoparticles will be higher as long as their size is larger than the size of the virus (Vonnemann et al. 2014).

Nanoparticles of graphene oxide

Geim and Novoselov have discovered graphene in 2004. Graphene is a material composed of carbon and having a hexagonal structure in two dimensions with an exceptional thick of single atom. Unique thermal, electrical, and mechanical properties for graphene and derived materials have drawn the attention for researchers to utilize it in different applications (Ghosal and Sarkar 2018) (Dave et al. 2016). Many researches have been done in biomedical field relying graphene oxide as antiviral (X. Wang et al. 2010). Graphene oxide was functionalized by curcumin for inactivating the RSV virus through the work of Huang et al. (Yang et al. 2017). The authors suggested three possible for antiviral mechanism: (1) direct inactivation, (2) prevent the host cell from virus attaching, and (3) disturb the replication of virus. Moreover, a nanomaterial of multifunctional modified graphene oxide was fabricated as an antiviral agent for HSV1 virus (Sametband et al. 2014). Quantum dots-graphene oxide have used as antiviral agent by a researches for inactivating the HIV virus (Iannazzo et al. 2018) (Yousaf et al. 2017).

Nanoparticles of mesoporous silicon

The antiviral drugs are failing in some situation, due to the problem in releasing the drug, and nanoparticles of mesoporous silicon were proposed as carrier for solving this limitation (De Clercq 2010) (Pan et al. 2014) (Ye et al. 2016) (Haimov et al. 2018). This type of antiviral agent was examined for inactivating the HSV1, HSV2, HIV, and VEEV viruses (Compton et al. 2017) (LaBauve et al. 2018). The advantage of mesoporous nanoparticles is that having low cytotoxicity and high stability compared to Au and Ag NPs (De Souza E Silva et al. 2016).

Nanoparticles of dendrimers and polymers

Nanoparticles of polymers have been used as an antiviral agents for their flexibility in molecular design (Dzhardimalieva et al. 2020) (K. J. Lee et al. 1999). A wide range of polymers reported as an efficient antiviral agents and one of these polymers is the organotin, which show excellent activity (Rzaev and Sadykh-Zade 1973) (Carragher and Roner 2014). Polymers may show antiviral activity even if the virus is not entering the cell (Y. Wang et al. 2011) (Chun et al. 2018). Many viruses like HCV and influenza A were inactivated efficiently using polymer NPs (Lancelot et al. 2017) (Jyothi et al. 2015). Moreover, sexual transmission of HCV was prevented using dendrimers (Sepúlveda-Crespo et al. 2015).

Nanoparticles of green metals

Nanoparticles were also prepared using green biotechnology methods from green sources like algae, fungi, bacteria, plants, and human cells used as antiviral agents (Zeedan et al. 2020) (Mohamed et al. 2020). The nanoparticles prepared by green sources are used as stabilizing and capping agents (Chandra et al. 2020) (Das and Karankar 2019). The most used nanoparticles in biomedical application, which are gold, and silver nanoparticles are prepared by the green route (Kuppusamy et al. 2015) (Salem and Fouda 2020). Using various plant extracts, mono-, di-, and tri-metallic nanoparticles were prepared but still have some limitations in the state of aggregation, stability, and crystal growth (Guimarães et al. 2020) (Gomathi et al. 2020).

Functionalized nanoparticles

Nanozymes were prepared as artificial nanoparticles for treating HCV virus using the mechanism of RNA mediation by RISC (X. Zhang et al. 2014) (Z. Wang et al. 2012). It is tested in mice and found there is no any interference or toxicity of nanozymes detected in the mouse cells while the antiviral activity against HCV virus was found excellent. Moreover, nanozyme preparation method is very simple and can be done in two steps. First, RNase is added to the NPs at pH of 9.6 using a buffer solution of carbonate. Second is the modification of NPs by antiviral agent of HCV (Pollock et al. 2010). Rare earth metal NPs have been used as antiviral agent for Zika virus (Ortega-Berlanga et al. 2020), while alumina modified with CuO NPs have been utilized as functional antiviral agent for HSV1 (Mazurkova et al. 2020) (Tavakoli and Hashemzadeh 2020). It has been suggested in Nabila et al. (2019) and Derbalah et al. (2019) that the NiO can be used for inactivating CMV. An antiviral for influenza has been prepared relying on ZrO₂, ZnO, and TiO₂

(Mazurkova et al. 2010). Recently, a recognized rising in the research for functionalized NPs as antiviral agents is seen.

The mechanism of antivirus activities

The antiviral activity of the nanoparticle agent acts on the virus membrane directly and decomposes it or by binding to the corona protein of the virus. Ag NPs activity on many viruses is explained in different studies and interpreted by the binding of agent with the glycoprotein of the virus membrane in the differentiation cluster 4 (CD4) in case of HIV-1 virus and HBV virus (Siadati et al. 2020). Moreover, the agents react with enzymes of the virus by binding to the imidazole, carboxyl, amino, phosphate, and sulfide groups (Borkow and Gabbay 2004). It has been reported recently that the mechanism of Ag NPs antiviral activity can be explained by the generation of reactive oxygen species (ROS) which create silver ions and reduce stress (Kora and Sashidhar 2018). Consequently, it is suitable materials for healthcare and filtration uses against virus infections (Clement 2012). The mechanism of inactivation the virus by Ag NPs is shown in Fig. 2 (Ishihara et al. 2015).

Nanoparticles preparation

Sol-gel technique

Sol-gel is a simple, low-temperature, and economic technique, which is suitable for nanoparticles synthesis. The procedure consists from the following subsequent steps: (1) production of metal hydroxide through the hydrolysis of metal, (2) 3D gel creation through the fast condensation step, (3) aerogel and xerogel production through the fast drying of gel (Owens et al. 2016). The sol-gel method is used to produce nanoparticles of homogeneous

Fig. 2 The mechanism of antiviral activity of the Ag

structure and high purity (Ahmed et al. 2020) (Pierre 2020). Figure 3 shows the steps of the sol–gel methods.

Polyol technique

Polyol technique depends on the polyol reaction using ethylene glycol or any other chemicals having polyol functional group. The polyol agents have many roles such as solvent, reducing, complexing with stabilizing agent, and medium for the preparation process (Ferdous and Nemmar 2020) (Iravani and Varma 2020). To obtain nanoparticles by this procedure, cheap metal salts are added to aqueous solution including polyol agent and specific amount of sulfuric acid. The mixture is then heated to the boiling point temperature until the reaction completion. After that, the solution is kept to cool down to room temperature, and the nanoparticles are separated by centrifugation; the nanoparticles are then washed thoroughly by ethanol and dried (Zeroual et al. 2020). Figure 4 displays a schematic diagram showing the steps of the polyol technique for Ag NPs production.

Micro-emulsion

Micro-emulsion is an inorganic technique to produce nanoparticles, which depends on a system composed of surfactant, nonpolar, and polar contents. Micro-emulsion solution is stable, homogeneous, and isotropic system (Malik et al. 2012) (H. Kumar et al. 2020). The reactant materials are mixed with the micro-emulsion material by the water droplet collision. Then, steps of precipitation, nucleation, and coagulation occur leading to produce of nanoparticles enclosed by water (Rane et al. 2018).

Hydrothermal synthesis

It is one of the favorable green methods which is used for the production of inorganic nanoparticles (Darr and Poliakov 1999) (Beyer et al. 2020). Hydrothermal technique gained attention as it is done in the liquid phase (water) (Bartkowiak et al. 2018) (Jaggessar and Yarlagaadda 2020). The process is done by preheating the water under a high-pressure stirred reactor; the metal salts are added continually, leading to the production of metal oxide nanoparticles (Darr and Poliakov 1999).

Fig. 3 The steps of the sol–gel method

Fig. 4 Schematic diagram of polyol steps process for Ag NPs production

Green synthesis routes of metal nanoparticles

Recently, the nanoparticles are produced using plant extracts and microbes (viruses, bacteria, and fungi); the procedure is ecofriendly, safe, and efficient (Gowramma et al. 2015) (Shah et al. 2015). However, many advantages are achieved by this procedure concerning microbial method, and it is easy to control the size and morphology of the nanoparticles in the later through temperature and pH of microbe cell (Iravani 2011) (Patil et al. 2011). Figure 5 shows the green methods used for metallic NPs production.

Fig. 5 The green methods used for metallic NPs production

Air filters

Nowadays, there is an urgent need for filters with high quality, due to the fast development in the viruses. The nano-sized virus (COVID-19) is very aggressive in attacking the human body, due to the nature of spikes on its surface and the tiny size. Therefore, the specifications are required for the novel filter to be able to filtrate aerosols of size less than the size of 100 nm and also able to inactivate the virus (Tian et al. 2018). Many types of filters are used for filtration; the different sizes of aerosols lick woven, nonwoven, nanoparticle-coated, nanofiber, and nanofiber electret filter (Feng and Cao 2019). The subsequence sections will discuss in details the most recent technologies, which are used for developing an efficient antiviral filters. Figure 6, the schematic diagram, shows the antiviral efficiency of filter.

Modeling of antiviral air filter activity

The following section discusses the theoretical base for the filter efficiency based on the number of fiber layers.

Filtration model for single fiber

The total efficiency of the filter (E) for single fiber type depends on the parameters of air velocity, fiber properties, and particle size. Davies (Davies 1983) presents the equation for the total efficiency for single fiber filter as follows (Eq. 1).

$$E = 1 - e^{-E_s S} \quad (1)$$

where E , S , and E_s are the total efficiency, dimensionless projected area of fiber (depend on the fiber diameter, packing density, and thickness of the filter), and fractional fiber efficiency, subsequently (Sambaer et al. 2012). The mechanism of filtration occurred according to the above equation consists of three steps (impaction, interception, and diffusion).

Fig. 6 Schematic diagram of the filter antiviral efficiency

When the inertia of particles is high, impaction occurs and this step is neglected for the most filter types, while the interception is dominated in this case for particles size more than 1 μm (Brown and Wake 1991) (Graham et al. 2002). The smaller particle of less than 0.1 μm is subjected to the diffusion process due to the Brownian motion effect (Davies 1983).

Filtration model for multi-fiber

For the fibers of diameters ranging from 0.65 to 6.5 μm , the total efficiency equation (Eq. 1) can be applied after changing the projection area. The projection area for multi-fiber filter can be calculated according to Eq. 2 as follows:

$$E_S S = \sum E_{si} S_i \quad (2)$$

where E_{si} is the single fiber efficiency.

Filter types

Nanoparticle-coated air filters

Antimicrobial agents of different nanoparticles have been investigated in the continuous flow mode as coating on the surface of filters (Huang et al. 2020). A researcher developed iodine-releasing filter as antiviral coating against MS2 virus aerosols (J. H. Lee et al. 2009). Moreover, TiO_2 , Ag–Cu, iodine-activated resin, and Enviz O_3 -Shield agents developed by another researcher as antiviral coatings on filters for inactivating MS2 virus (Rengasamy et al. 2010). Cellulosic filter with dialdehyde group coated with different nanoparticles agent shows a good efficiency against MS2 virus also (Rengasamy et al. 2010). SiO_2 -Ag NPs have been proposed as efficient antiviral agent for inactivating MS2 virus by dry coating on a commercial filter (D. H. Park et al. 2019).

CNTs and Ag NPs have been proved as a good antiviral agent for MS2 virus by coating on the surface of a fiber glass filter (K. T. Park and Hwang 2014). Moreover, magnetic particles are also investigated as antiviral agent. Magnetic silica decorated with Ag NPs showed an excellent antiviral activity if it is coated on the fiber filter (H. Z. Zhang et al. 2016). Magnetic silica particles were functionalized with aminopropyl as a dispersive agent in the liquid phase, and then were coated by Ag NPs to use as filter for antiviral activity (H. H. Park et al. 2013).

Nonwoven

Nonwoven filters are efficient antiviral filters which are adopted for industrial and personal usages (Stetzenbach et al. 2004). The mechanism of this filter depends on diffusion, which enables capture aerosols less than 100 nm, while the

interception is the mechanism for aerosols in the range of 100 nm to 1 μm .

Nanofiber

Filters were fabricated from nanofibers of diameter less than 1 μm and a high surface area was found to be suitable for facemask, due to the amount of nanofiber needed very small (less than 1 g/m^2) (Ahn et al. 2006). The pressure drop is high in the case of using nanofiber filters compared to microfiber filters according to Davis' equation (Davies 1953). The pressure drop may increase by 100 times that for the microfiber filter of the same weight.

Multilayer and multi-modules stack-up

As an effort for solving the problem of higher pressure in the nanofiber filter, multi-thin layer of nanofiber has been used on a macropore substrate (Leung and Sun 2020). The same filtration efficiency is obtained using multilayer filter compared to the single-layer filter with reducing the pressure drop (Leung et al. 2010).

Electret nanofiber filter

In the previous sections, we discuss the nanofiber filter of 200- to 600-nm fiber diameter that can be effective in capturing aerosols of size less than 100 nm (the diameter of COVID-19 virus), and it was found that this type of filter is suffering from the high pressure drop. A new technology for enhancing the efficiency of filtration without increasing the pressure drop is the charging of nanofibers with electrostatic charges. The challenging issue in this regard is the stability of nanofiber charges (Thakur et al. 2013). Recently, corona discharge method has been used for charging polyvinylidene fluoride (PVDF) and has been showed a stability for 3 months (Leung and Sun 2020) (L. Y. Wang et al. 2020). The efficiency of the charged nanofiber filter was found much efficient than the microfiber filter of 15- μm average diameter (Sun and Leung 2019).

Multilayer PVDF electret filter showed a promising filtration efficiency and reduction in pressure drop compared to the single-layer one (Sun and Leung 2019). The filter efficiency and pressure drop are continuously changed with increasing the aerosol loading (Leung and Sun 2020) (Sun and Leung 2020). This type of filter is considered more efficient from the viewpoint of energy consumption, health activity, and cost. Initially, the filtration efficiency of charged filter reduces with increasing the loading of aerosols and then increases due to the phenomena of electrostatic shielding by aerosol deposition and mechanical capture which form an effective surface media for the filter (Röhrig and Diebels 2019).

The mechanism of filtration for charged filters is summarized as follows: (i) initially, the aerosol capture done using the coulomb force of charged and induction of uncharged aerosols, (ii) the captured aerosols in the initial step then act as a trap for the next aerosols, which form a dendritic structure with continuing the filtration process. A cake of connected aerosols will cover the surface of the charged filter that reduces the electrostatic effect. Nevertheless, the mechanical collection of aerosols increases until the equilibrium is done between the mechanical capture efficiency and the electrostatic efficiency. A similar increasing behavior in the pressure drop is reported for the electret filter as compared to the normal filter (Schutz and Church 2011). Once the filter is clogged, it is working as surface filter. Researchers reported that some electret filter might have lower clogging rate due to the uniform distribution of deposited aerosols. Scanning electron microscopy (SEM) studies can support the above results (Schutz and Church 2011). The thickness of electret filter is high even for that of single-layer nanofiber filter and the deposition of the aerosols occurs at the face more than the backside of the filter (Leung et al. 2009).

The filtration efficiency can be controlled by stacking the multiple layers of nanofiber from thicker to thinner one (Sun and Leung 2020). Multi-thin layer nanofiber filter of the same weight may take a long time to be clogged by the aerosols as compared to the single-layer nanofiber filter due to the small thickness and porosity. This phenomena lead to uniform distribution of captured aerosols as seen in the images of SEM. From the above discussions, it is concluded that the charged multilayer nanofiber PVDF filter is a new emerging technology and can be modified in order to increase the filtration efficiency, decreasing the pressure drop. Moreover, coating charged nanofiber PVDF filter with antiviral nanoparticle agents like graphene may open up a new prospect for developing antiviral filters to fight the novel corona virus (COVID-19).

Testing of antiviral filters

The antiviral activity of the filters is measured using the logarithmic reduction value (LRV) for the titer of the virus, where LRV value provides evidence about the elimination of the virus and used as a safety factor. LRV values depend on less than 0.01% part of the virus collected in the filtrate and the rest of the virus are still in the filter and not detectable. The complete information on the virus holding in the filter cannot be obtained in this method. Therefore, techniques of artificial nanoparticle from gold or nanoparticle of fluorescent label have been used for better understanding the nanofiltration process (Yamaguchi et al. 2007). These techniques provide a precious method for detecting the virus in the filter and find the relation between the pore size distribution and

the virus detection using electron or fluorescence microscopy (Kosiol et al. 2017). Laser scanning microscopy (LSM) is another method used for detecting the virus in the filter (Bakhshayeshi et al. 2011). The above methods are reproducible and fast method for visualizing the particles using different dyes and provide understanding for the viral detection throughout the fouling and depressurizing actions (Jackson et al. 2014). MS2, PP7, and Φ X174 bacteriophages are the most useful substitute used for investigating the filter antiviral activity as it is of size similar to that of the parvovirus (Slocum et al. 2013).

Direct imaging is a good method for understanding the mechanism of virus retention in the filter but it is not providing a model reflecting the real phenomena in the membrane. The capsid of the virus surface usually interacted with the membrane of the antiviral agent and each virus have special interaction (Kosiol et al. 2019). Moreover, the filtrations conditions and filter material are also affecting the retention of the virus in the filter. From the above, we can conclude that the parvovirus model cannot be used every time. A few works provided an image for the parvovirus retention mechanism in the filter using immune detection and SEM for PPV and B19V (Adan-Kubo et al. 2019) (Hongo-Hirasaki et al. 2011). Moreover, TEM technique is also used for detecting the viral particles in the filter membrane. In a recent study, a method has been developed for detecting quantitatively virus retention phenomena in the filter to provide a good understand for the nanofiltration process (Leisi et al. 2020).

The most important test method for the filter is done by aerosolizing the MS2 virus using an atomizer for obtaining a uniform distribution of the virus on the surface of the filter by forced convection flow. At that point, the virus collected on the surface of the filter is removed to a liquid media containing *E. coli* C3000 by vibration method (shaking, sonication, or vortex). Afterward, plaque counting method is used for evaluation of the nanoparticle activity (Tellier 2006). Air filters used for indoor air cleaning system are important for healthcare places so that the air media test is more a useful one (Siegel et al. 2007). A recent study reported novel method for testing the antiviral activity of airborne filter. The testing method was done in a liquid media containing dispersion of H1N1 virus and then the plaque test is used for the liquid media. Also, a correlation equation is used for converting the plaque test data to air media data (D. H. Park et al. 2020). Finally, vulnerability is the best method for explaining the antiviral efficiency lick Ag and Cu NPs coating density on the filter (Yoon et al. 2007).

Conclusion

The concluded points from the present review are summarized as follows:

1. Nanoparticles as antiviral agents are widely investigated in addition to the field of biomedicine and biosensors.
2. Ag NPs, Au NPs, graphene oxide NPs, dendrimers NPs, and Si NPs are the most functional antiviral materials used in vivo and in vitro which form the future materials for fighting the viruses.
3. The biocompatibility of the functional nanoparticles is an important issue that has to be spotlighted and improved.
4. The effective techniques chosen for the preparation of functional nanoparticles can solve the limitation related to the biocompatibility issue.
5. The development of a suitable functional nanoparticle for a specified virus is a challenging job.
6. The conservation of the antiviral activity for the functional nanoparticles during the binding state with virus is another important job that has to be investigated.
7. The mechanism of inactivating the virus by the functional nanoparticles is still not well known and a new work in this field has to be done.
8. The in vivo delivery of the functional nanoparticles is another field that should be studied more.
9. The nanostructure of the functional nanoparticles should be developed carefully to consider the mutation of the virus also.
10. Stability and toxicity of the functional nanoparticles is a wide field for the researches on the developments of functional nanoparticles.
11. Nanoparticles preparation techniques are discussed in this review, and from these methods, it was found that the green one is a promising, and the future studies using this method are an emerging issue.
12. Phytometabolites are the plant extract useful for synthesis of nanoparticles in the green route.
13. Nanoparticles from biological sources are free from toxic materials.
14. Green methods have advantages of bio-functionality along with the physical and chemical functionalities.
15. The antiviral activity test of the airborne filter is investigated in the continuous airflow by eluting the virus into a liquid media.
16. Electret PVDF nanofiber filter has been used extensively and showed a stability of the charge using the corona discharge method.
17. Single- and multilayer electret filters have been tested for the antiviral activity.
18. Simulated sodium aerosols were used for testing the filter activity against novel corona virus (COVID-19).
19. Nanofiber filter of small fiber size has higher mechanical ability to capture the aerosols by interception and diffusion due to the increase of the surface area of the nanofiber.
20. Diffusion is the main mechanism for capturing aerosols less than 100 nm (size of the COVID-19 virus) in the nanofiber filter.
21. Charging the nanofiber filter with electrostatic charge enhances the capture of nano-aerosols.
22. Using multilayer of nanofibers in the filter may reduce the pressure drop by adding a macropore.
23. Charging small diameter fiber filter may increase the interference of electrical charge with other fibers in the same layer.
24. Increasing the basis weight for large diameter fiber increases the electrostatic capture efficiency and did not increase the pressure drop.
25. The pressure drop proportioned inversely with the fiber diameter.
26. For increasing the efficiency of the charged multilayer nanofiber filter without increasing the pressure drop, the suitable strategy used in this regard is to decrease the basis weight for each layer.
27. The target of the recent studies for developing the electret nanofiber filter is the capturing of aerosols less than 100 nm (size of COVID-19 virus) with efficiency of 90% and a pressure drop no more than 30 Pa.
28. Stacking multilayer of fine nanofiber using small basis weight reduces the pressure drop to the target of 30 Pa.
29. Using high basis weight and large nanofiber diameter or vice versa for the charged multilayer nanofiber filter gave high efficiency of 90% in capturing simulated novel corona virus 100-nm sodium chloride aerosols.
30. Engineered charged nanofiber filter for obtaining a high filtration efficiency for capturing aerosols of corona viruses especially COVID-19 virus without increasing the pressure drop of more than 30 Pa is the recommended target for new researches in this field.

Recommendation

1. Graphene with single atom thickness is promising material to be used as antiviral for virus of nanosize; despite there are rare researches in this area, many parameters are need to be covered.
2. It has been reported that some materials such as Ag and Au can be used effectively as antiviral decoration graphene nanoparticles by these materials as agent against COVID 19 has not done yet.
3. CNTs have been used in filters fabrication, and testing these filters against crown viruses is still in the beginning.
4. Using special alignment for carbonaceous nanomaterials in filters may raise the efficiency of filtration against crown viruses.

5. Charged nanofiber filter showed interesting filtration properties and the development studies on this type of antiviral filter by adding decorated graphene with nanoparticles may be the suitable target in the next step in fighting against novel corona virus (COVID-19).

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Data availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interests The authors declare competing interests.

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