

RECENT ADVANCES IN PERSONAL PROTECTIVE EQUIPMENT USING NANOTECHNOLOGY AS A SHIELD AGAINST SARS-COV-2¹

AVANÇOS RECENTES EM EQUIPAMENTOS DE PROTEÇÃO INDIVIDUAL USANDO NANOTECNOLOGIA COMO UM PROTETOR CONTRA SARS-COV-2

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ABSTRACT

COVID-19 is a disease caused by the SARS-CoV-2 coronavirus, and the use of personal protective equipment (PPE) has become essential against pandemics. This has led to many advances in facial masks and other types of PPE, using nanotechnology to improve antiviral properties and filterability. In this context, this study aimed at carrying out an integrative review regarding advances in personal protective equipment using nanotechnology to improve antiviral properties against SARS-CoV-2. Thus, 34 articles were retrieved from the Web of Science, Scopus, and PubMed databases, published until August 22, 2021. The main nanostructures used were nanofibers, carbon nanotubes, metallic nanoparticles, nanorods, nanowires, graphene, and C-dots, in the use of facial masks, air filters, and antiviral surfaces with functions such as antiviral/antimicrobial, reuse of personal protective equipment (PPE), self-feeding, whether by mechanical or solar action, hydrophobicity, and filtration efficiency, adjustable to the physical biotype of each individual and high breathability.

Keywords: Air filter, Antiviral, COVID-19, Mask, Nanostructure.

RESUMO

A COVID-19 é uma doença causada pelo coronavírus SARS-CoV-2, e o uso de equipamentos de proteção individual (EPI) tornou-se essencial contra as pandemias. Isso levou a muitos avanços em máscaras faciais e outros tipos de EPI, usando nanotecnologia para melhorar as propriedades antivirais e a filtrabilidade. Nesse contexto, o objetivo deste estudo foi realizar uma revisão integrativa a respeito dos avanços em equipamentos de proteção individual utilizando nanotecnologia para melhorar as propriedades antivirais contra SARS-CoV-2. Assim, foram recuperados 34 artigos das bases de dados Web of Science, Scopus e PubMed, publicados até 22 de agosto de 2021. As principais nanoestruturas utilizadas foram nanofibras, nanotubos de carbono, nanopartículas metálicas, nanobastões, nanofios, grafeno e pontos C, em uso de máscaras faciais, filtros de ar e superfícies antivirais com funções como antiviral / antimicrobiano, reaproveitamento de equipamentos de proteção individual (EPI), autoalimentação, seja por ação mecânica ou solar, hidrofobicidade e eficiência de filtração, ajustável ao biótipo físico de cada indivíduo e alta respirabilidade.

Palavras-chave: Antiviral, COVID-19, Filtro de ar, Máscara, Nanoestrutura.

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INTRODUCTION

Viral infections are one of the main causes of morbidity and mortality and also of significant economic losses worldwide. Standard treatment approaches are mainly based on vaccination and therapy derived from key processes in the virus life cycle (WEISS *et al.*, 2020). The newly emerged COVID-19 disease is a highly transmissible viral infection caused by another new zoonotic coronavirus called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), first reported in December 2019 in a local seafood market in Wuhan, Hubei Province, China (KHAN *et al.*, 2020).

SARS-CoV-2 is a large, positive-stranded, enveloped RNA virus with nucleocapsid and structure similar to SARS-CoV-1, its diameter size ranging from 80 to 140 nm. This virus has become a leading cause of emerging respiratory diseases and has spread rapidly around the world, affecting billions of people and triggering unexpected changes in the healthcare system, global economy, and interactions in societies around the world (VAZQUEZ-MUNOZ; LOPEZ-RIBOT, 2020).

The World Health Organization (WHO) globally has reported as of September 23, 2021, more than 229 million confirmed cases of COVID-19 and 4.705.111 deaths (WHO, 2021). The costs related to this communicable disease are estimated to be in trillions of dollars globally, but the real cost cannot be estimated. Several measures have been implemented to control COVID-19, from campaigns aimed at improving personal hygiene practices to community approaches such as social distancing and quarantines (CARVALHO; CONTE-JUNIOR, 2021). As a result, there has been a great demand for designing tools to improve antiviral strategies to control the spread of COVID-19, such as advances in the design of facial masks, and other types of personal protective equipment (PPE) such as gloves, lab coats and clothing. The COVID-19 outbreak has clearly shown the need for substantial PPE development using multifunctional materials with antiviral properties (KARAGOZ *et al.*, 2021).

Viruses are considered naturally occurring nanoparticles due to their nanometric size. Thus, because of the small size and adjustable surface charge, nanoscale materials have great potential to interact with the peak protein to block the onset of viral infection (CARVALHO; CONTE-JUNIOR, 2021). Nanomaterials are single structures, free or in a compound, with size within the nanometer range, usually less than 100 nm in at least one of its three dimensions. Within the nanometer range, the physicochemical properties of materials exhibit significant changes that contrast with their counterparts at larger scales, as quantum effects determine their new properties (VAZQUEZ-MUNOZ; LOPEZ-RIBOT, 2020).

Nanomaterials are widely used in different health-related applications, such as disinfectants, imaging tools, dressings, wearable devices, anticancer therapies, pharmaceuticals, drug delivery, vaccines, diagnostic techniques, and implants, among others (TOLEDO *et al.*, 2020). Nanotechnology-based approaches should leverage the fight against COVID-19, as well as any future pandemics, in a

variety of ways, including new vaccines, and drugs. Highly specific, rapid and sensitive tests to detect infection or to detect immunity (serological tests). Super thin filters for facial masks or blood filtration, new surfaces, or surface coatings that are resistant to viral adhesion and can inactivate the virus (WEISS *et al.*, 2020).

In this context, the present study aimed to conduct a literature review on the advances in the design of personal protective equipment using nanotechnology to improve the antiviral properties and filtration capacity of the SARS-CoV-2.

METHODOLOGY

This study was characterized as an exploratory and integrative literature review type. This review retrieved and evaluated data available in databases on advances in personal protective equipment using nanotechnology to improve the antiviral properties and filtration capacity of the SARS-CoV-2.

DATABASES AND STRING DEFINITION

The research strategy used search strings built and adapted for three electronic databases: Web of Science, Scopus and PubMed. The string was based on predetermined groups of keywords related to nanotechnology, the SARS-CoV-2 virus and personal protective equipment, accordingly:

- Searching Component 1: nano*
- Searching Component 2: PPE OR mask OR coat OR glove OR clothes OR respirator OR filter OR fabric
- Searching Component 3: COVID-19 OR SARS-CoV-2

RESEARCH STRATEGY, SELECTION PROCESS, AND STUDY SELECTION CRITERIA

The advanced research in the databases was performed by pairs, considering research articles published until August 22, 2021, in which the authors conducted the preliminary selection and data extraction independently, in the identification stage and then proceeded to the stages of screening and inclusion, taking into account the inclusion and exclusion criteria, as described in Table 1.

Table 1 - Inclusion and exclusion criteria in the review construction stages.

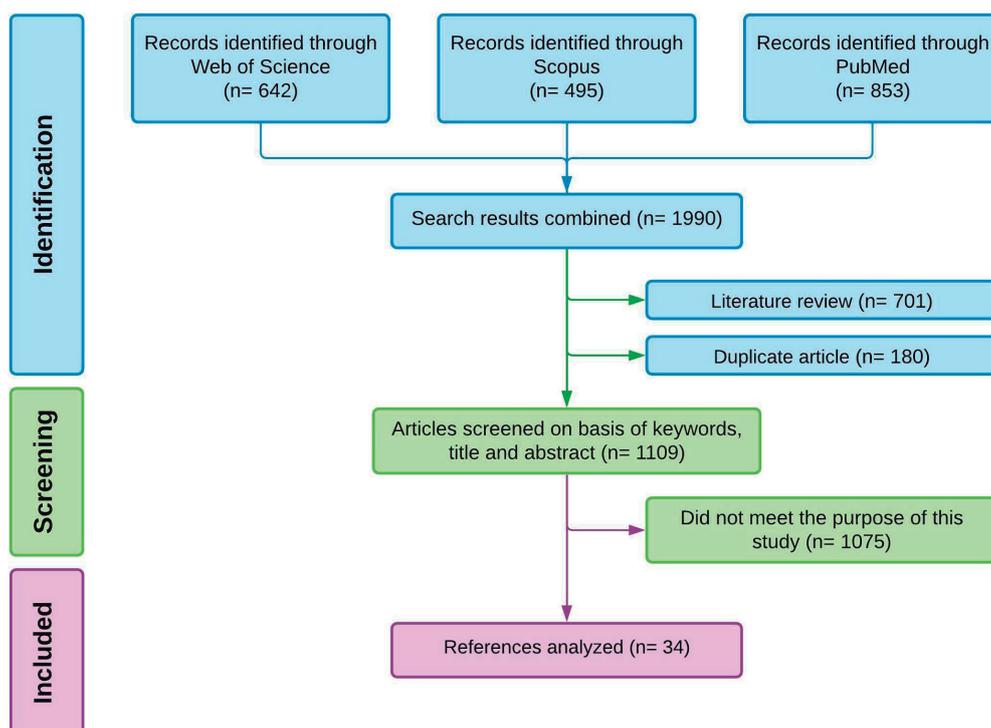
Step	Inclusion criteria	Exclusion criteria	Based on
Identification	Studies published in English	Reviews, letters to the editor, notes, duplicate articles	Title, keywords and abstracts
Screening	PPE studies with antiviral activities At least one nanomaterial or nanoparticle has been studied	No activity test was performed No nanoscale materials strategy was presented	Title, keywords and abstracts
	Has a PPE or PPE material been developed	No PPE or component development studies have been portrayed	
Eligibility	-	Studies do not match study objectives	Reading full texts

Source: Authors' construction.

To extract data from the articles included in this study, the authors independently extracted and summarized the following information: product developed, type of nanomaterial used, potential application, functions and reference.

RESULTS AND DISCUSSION

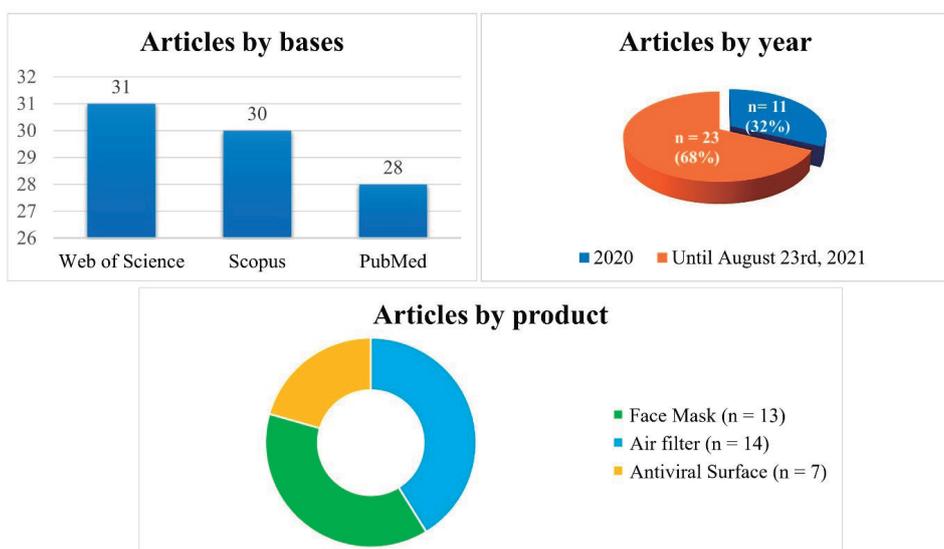
The research in the databases resulted in the collection of 1990 articles, 642 in Web of Science, 495 in Scopus and 853 in PubMed. Of these, 34 adequately met the inclusion criteria and were selected for this data collection. Figure 1 shows the flowchart with the strategy for the selection of the articles included.

Figure 1 - Flowchart with the articles selection strategy.

Source: Authors' construction.

The studies that built up this review were published in 2020 (32 %) and until August 2021 (68 %), with an increase in publications involving antiviral PPE with nanotechnology, in the second year of the COVID-19 pandemic. The Web of Science database sought 91 % of the studies selected for this review, followed by Scopus (88 %), and PubMed (82 %). As no base showed 100 % of the studies, it was essential to complement the bases for a more complete study. Of the 34 articles included in the study, 38 % developed facial masks with antiviral or antimicrobial properties, 41 % developed air filters for mask and respirator applications, and 21 % developed antiviral surfaces for general PPE applications. These data make up Figure 2.

Figure 2 - Articles included by bases, year of publication, and developed products.



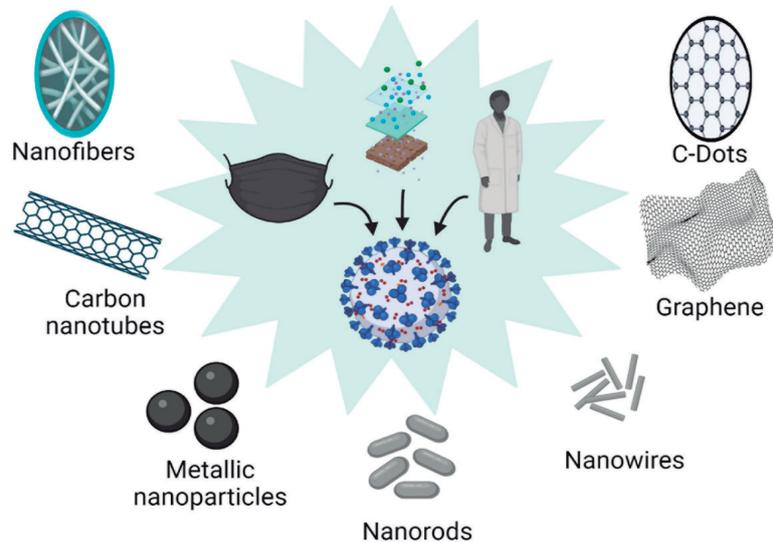
Source: Authors' construction.

Several nanostructures have been described and used in the development of PPE with antiviral and antimicrobial (antiviral + antibacterial) functions. They are copper nanoparticle and graphene oxide nanosheets (AHMED; AFIFI; USKOKOVIĆ, 2020), electrospun nanofibers and plasmonic gold nanoparticles (DE SIO *et al.*, 2021), copper nanowires (KUMAR, A. *et al.*, 2021), graphene nanosheet (LIN *et al.*, 2021; PAL *et al.*, 2021), C-dot (SINGH *et al.*, 2021). They are also: thermoplastic polyurethane nanofibers (CHEN *et al.*, 2021), titanium dioxide nanowires (HORVÁTH *et al.*, 2020), polyacrylonitrile nanofiber containing zinc oxide nanoparticles (PARDO-FIGUEREZ *et al.*, 2021), carbon nanotubes decorated with metals (AASI *et al.*, 2020), zinc oxide nanorods and silver nanoparticles (KARAGOZ *et al.*, 2021), *Aloe vera* nanofibers and polyvinyl alcohol (KHANZADA *et al.*, 2020), among others. The main nanostructures used for the development of PPE with antiviral properties are shown in Figure 3.

In the development of nanostructured systems for application in PPE, important characteristics such as antiviral properties combined with mechanical or photoelectric properties, to eliminate the virus (XIE *et al.*, 2020; KUMAR *et al.*, 2021b), have been sought, in addition

to characteristics such as biocompatibility (XIE *et al.*, 2020), hydrophobicity (KUMAR *et al.*, 2021b) and biodegradability (MÜLLER *et al.*, 2021).

Figure 3 - Main types of nanostructures with antiviral properties used in the development of PPE.



Source: Authors' construction.

Regarding the development of facial masks, 13 different studies were found using nanostructures with antiviral activity, which can be used to protect against SARS-CoV-2. The product developed, the type of nanostructure, and the functions of each study are shown in Table 2.

Table 2 - Nanostructures used in the development of antiviral facial masks.

Developed Product	Type of Nanostructure	Function	Ref.
Recyclable reusable facial mask	Cu oxide nanoparticle and graphene oxide nanosheets	Antimicrobial by virus and bacteria deactivation	AHMED <i>et al.</i> , 2020
Recyclable reusable facial mask	PVA nanofibrous membrane and licorice root extract	Antiviral by virus deactivation	CHOWDHURY <i>et al.</i> , 2021
Reusable facial mask	Electrotrophied nanofibers, plasmonic gold nanoparticles	Antimicrobial by light activation, humidity control, and effective filtration	DE SIO <i>et al.</i> , 2021
Self-powered facial mask	Simple triboelectric nanogenerator (TENG)	Virus deactivation by mechanical energy capture	GHATAK <i>et al.</i> , 2021
3D mask with filter	Functionalized graphene	Antimicrobial	GOSWAMI <i>et al.</i> , 2021
Reusable facial mask	Cu nanowires	Antimicrobial by functionalization with nanowires	KUMAR <i>et al.</i> , 2021a
Self-cleaning and reusable mask	Shellac Nanocomposites and Cu Nanoparticles	Surface hydrophobicity and photothermal properties for antimicrobial action	KUMAR, <i>et al.</i> , 2021b
Facial mask	Amorphous calcium polyP nanoparticles	Antiviral, Biodegradable, Moisture Resistant, Breathable	MÜLLER <i>et al.</i> , 2021
Reusable facial mask	Graphene nanosheet	Antimicrobial through photo sterilization by sunlight	LIN <i>et al.</i> , 2021
Recyclable facial mask	Graphene nanosheet	Antimicrobial through photo sterilization by sunlight	PAL <i>et al.</i> , 2021

Biodegradable facial mask	Nano-fibrous PLA functionalized with Indian herbal extract	Antimicrobial, high breathability, splash resistance, and filtration efficiency	PATIL <i>et al.</i> , 2021
Mask with Nanoporous membrane	C-dot	Antimicrobial, self sterilized by sunlight induction, hydrophobic	SINGH <i>et al.</i> , 2021
Facial mask with self-decontamination	Graphene and Silver Nanoparticles	Antimicrobial with photothermal decontamination and super-hydrophobic	ZHONG <i>et al.</i> , 2020

Source: Authors' construction.

Ahmed *et al.* (2020) developed a protocol for a reusable, recyclable, and antimicrobial facial mask, with copper oxide nanoparticles (CuONP) and graphene oxide (GO) nanosheets that deactivate viruses, and bacteria. CuO nanoparticles have a narrow energy gap (ALAYANDE; OBAID; KIM, 2020). Because of this, they have been used to inhibit fungi, bacteria, and viruses (VARAPRASAD *et al.*, 2020). GO exhibits excellent mechanical properties, including high tenacity, as well as high electrical conductivity and biocompatibility (XIE *et al.*, 2020). In the study published by Chowdhury *et al.* (2021), the polyvinyl alcohol (PVA) nanofibrous membrane and licorice root extract were used in the production of a reusable, recyclable facial mask with antiviral properties due to licorice root, a herb traditionally used in the Asian region, which it has antiviral properties and the potential to weaken virus activity (CHIRUMBOLO, 2016).

De Sio *et al.* (2021) produced a reusable facial mask using electrospun nanofibers and plasmonic gold nanoparticles, with antimicrobial activity by light activation, and also achieved effective moisture control and filtration. The possibility of light-assisted photothermal disinfection is due to the photothermal sensitivity of plasmonic nanoparticles, such as gold (AMENDOLA *et al.*, 2017). Owing to this nanotechnology-assisted disinfection and the mechanical strength of nanofibers, masks can be continuously sterilized and can be used several times (DE SIO *et al.*, 2021). In the study by Ghatak *et al.* (2021), the authors describe a self-powered facial mask, in which a simple triboelectric nanogenerator (TENG) with an electrocution layer that works as filtration and deactivation of SARS-CoV-2, in which viral particles suffer a mild shock due to electric field produced between the electrocution layers by contact electrification, thus being deactivated.

In the study developed by Kumar *et al.* (2021a), Cu nanowires were used with antimicrobial function in reusable facial masks. Inorganic nanomaterials such as copper have attracted interest for their antimicrobial activity, as they release copper ions that are responsible for the generation of reactive oxygen species, which damage RNA and cause lipid peroxidation, destroying viruses and bacteria (SLAVIN *et al.*, 2017). Kumar *et al.* (2021b) also used copper due to its antimicrobial property, where they applied a hybrid of shellac nanocomposites and Cu nanoparticles in a surgical mask, thus increasing surface hydrophobicity and repelling aqueous particles, and also conferred reusability and self-sterilization under solar lighting.

Goswami *et al.* (GOSWAMI *et al.*, 2021), Lin *et al.* (LIN *et al.*, 2021) and Pal *et al.* (PAL *et al.*, 2021) used graphene nanosheets in the development of reusable antimicrobial facial masks, with hydrophobic characteristics and photo sterilization in sunlight, due to the properties of graphene. The graphene layer used inhibits both airborne transmissions, preventing atomization and inhalation of virus-carrying aerosols, and direct communication, preventing the spread of viruses and droplets (CHUA *et al.*, 2020). Zhong *et al.* (2020) also made use of graphene in the development of photo-thermal and super-hydrophobic respirators. In addition to graphene, they used silver nanoparticles (AgNP) that can provide additional protection through disinfection with silver ions. This synergism between graphene and AgNP provides the respirator with better protection when fighting the COVID-19 pandemic (ZHONG *et al.*, 2020).

In the study published by Müller *et al.* (2021) amorphous calcium inorganic polyphosphate nanoparticles (Ca-polyP-NP) were used in the production of an anti-COVID-19 facial mask responsive to stimuli and virus inactivation. Polyphosphate is a biocompatible, biodegradable, and antiviral active physiological polymer, and with nanoparticles are used as a transporter of tretinoin (all-trans-retinoic acid) that blocks the function of the SARS-CoV-2 protein (MÜLLER *et al.*, 2021). In the study by Patil *et al.* (2021) a biodegradable antimicrobial facial mask was developed from nano-fibrous polylactic acid (PLA) functionalized with extract of Indian herbs (*Azadirachta Indica* and *Eucalyptus Citriodora*). The incorporation of an electrospun nano-fibrous layer in the mask improved the filtering ability and the addition of Indian herbs demonstrated effective performance in neutralizing viruses and bacteria. Singh *et al.* (2021) used nanoporous membranes comprising carbon dots (C-dots) and poly (vinylidene fluoride) (PVDF) in antimicrobial, hydrophobic, and self-sterilized masks by sunlight induction. The C-dots were used for their excellent photothermal properties, so the heat dissipated by the collection of sunlight by the C-dots can lead to the destruction of viral particles, without the need for external sterilization procedures.

Facial masks are considered the most effective means of preventing infections and dissemination of viral particles, such as the COVID-19 virus, but their production and disposal consume substantial resources, causing serious environmental damage, due to the increase in use by the world population. This review showed that studies have been concerned with developing reusable antimicrobial or antiviral masks to reduce environmental damage, combined with other functions such as biodegradability, self-feeding, self-decontamination, hydrophobicity, and increased filtration and breathability. For this purpose, nanostructures such as CuONP, graphene and GO, nanofibers, AuNP, CuNP, and AgNP were applied to deactivate SARS-CoV-2 through the virus protein denaturation, be that by capturing solar or mechanical energy.

According to the WHO (2020), the masks can be composed of several arrangements of fabrics, different sequences of layers, dividing the mask into three layers, the innermost being composed of hydrophilic fibers, while the intermediate and external layers need to have hydrophobic fibers. Thus,

masks can be hierarchically designed according to porosity and hydrophobicity, where the outer layer has greater porosity and extreme water resistance than the innermost layer (RAWAL, 2020).

When researched on nanostructures used in the development of antiviral air filters and their potential uses, 14 different studies were found using nanostructures with antimicrobial and antiviral activity, which can be used to protect against SARS-CoV-2. The product developed, the type of nanostructure, and the functions of each study are shown in Table 3.

Table 3 - Nanostructures used in the development of antiviral air filters and their potential uses.

Developed Product	Type of Nanostructure	Function	Potential application	Ref.
Biodegradable air filter medium	Cellulose acetate nanofibers and cationic surfactant cetyl pyridinium bromide	Antimicrobial	Facial masks	ALMEIDA <i>et al.</i> , 2020
Nanofibrous membrane	PVA and TPU nanofiber membranes with Ag nanoparticles	Antimicrobial	PEE	ALSHABANAH <i>et al.</i> , 2021
Filter	Electrotrophied nanofibers of PVA doped with AgNPs	Antimicrobial	Facial masks	BLOSI <i>et al.</i> , 2021
Air filter	Thermoplastic polyurethane nanofibers	Antiviral	Facial masks	CHEN <i>et al.</i> , 2021
Filter	Electrotrophied nanofibers	Antimicrobial	Facial masks	CHOI, S. <i>et al.</i> , 2021a
Air filter	Nanocapsule LAP-Cu ²⁺	Antimicrobial	Facial masks	CHOI, D. <i>et al.</i> , 2021b
Porous membrane	Nanoporous mold based on silicon oxide	Antiviral	Fixed on N95 mask	EL-ATAB <i>et al.</i> , 2020
Air filter	Titanium Dioxide Nanowires	Antiviral	Facial masks	HORVÁTH <i>et al.</i> , 2020
Air filter	Polyvinylidene Fluoride Nanofibers	Antiviral	Respirators, facial masks	(LEUNG; SUN, 2020a)
Air filter	Polyvinylidene Fluoride Nanofibers	Antiviral	Facial masks	LEUNG; SUN, 2020b
Nanofibrous membrane	Nanofibrous membrane loaded with active luminogen	Antimicrobial	Reusable bioprotective PPE	LI <i>et al.</i> , 2021
Filters	Polyacrylonitrile nanofiber containing zinc oxide nanoparticles	Antimicrobial	Respirators	PARDO-FIGUEREA <i>et al.</i> , 2021
Air filter	Electrotrophied PVDF Nanofibers	Antiviral	Facial masks	SHEN <i>et al.</i> , 2021
Nanofibrous membrane	Polystyrene nanofibers grafted by 5,5-dimethylhydantoin and trimethylamine	Antimicrobial	Facial masks	TIAN <i>et al.</i> , 2021

Source: Authors' construction.

Almeida *et al.* (2020) developed in their study biodegradable nanofibers of cellulose acetate and cationic surfactant cetyl pyridinium bromide (CA/CPB), produced by electrospinning technique to efficiently retain the airborne nanoparticles. Thus, the authors developed electrotrophied nanofibers with an average particle diameter of 239 nm, ranging from 113 to 398 nm. From the results obtained in this research, it was possible to conclude that CA / CEC can be applied to capture nanometric particles, smaller than 300 nm, with a high filtration rate, including the new 2019 coronavirus. This research provided information for future air filter projects internal and filter media for facial masks with renewable characteristics, biodegradable non-toxic, and antibacterial potential.

Alshabanah *et al.* (2021) nanofibrous hybrids are manufactured, characterized, and assessed as active antiviral and antibacterial membranes. In more detail, both polyvinyl alcohol (PVA developed an antiviral/antibacterial membrane from synthetic and biodegradable electrospun nanofibers that can be used as a promising functional layer in personal protective equipment (PPE), such as lab coats and other hospital equipment. The developed nanofibers, thermoplastic polyurethane (TPU), and polyvinyl alcohol (PVA) loaded with silver nanoparticles (AgNPs) were characterized and investigated for their potential antiviral and antibacterial activities as well. The results showed that TPU-Ag was more effective than PVA-Ag as an antiviral HIV-1 nanohybrid, as well as in deactivating SARS-CoV-2 peak proteins. The TPU-Ag and PVA-Ag nanofibrous membranes demonstrated superior antimicrobial performance, increasing the Ag concentration from 2 to 4% by weight. Furthermore, the developed membranes showed acceptable physical and mechanical properties, along with antiviral and antibacterial activities, which may allow them to be used as a promising functional layer in Personal Protective Equipment (PPE).

Blosi *et al.* (2021) we designed a new class of high performance filter media suitable to advance the facemask technology and provide new efficient widespread solutions against virus propagation. By means of the electrospinning technology we developed filter media based on polyvinyl alcohol (PVA developed filter media based on polyvinyl alcohol (PVA) nanofibers doped with silver nanoparticles (AgNPs) combining requirements for high performance, they being high air filtration efficiency to capture nano-sized particles, low airflow resistance essential for ensuring breathability and antimicrobial activity to inactivate aerosolized microorganisms. They achieved filter media characterized by exceptional performance requirements for masking purposes, such as high air filtration efficiency and low-pressure drop expressed by QF values comparable to or better than commercial filter media. In addition, they evaluated a total bacterial depletion associated with a filtration efficiency for nano-aerosolized particles of 97.7% greater than that required by the EN149 standard and a pressure drop in line with the FFP1 and FFP2 masks, even at the highest filtration speed.

Chen *et al.* (2021) developed thermoplastic polyurethane nanofiber membrane-based air filters for efficient removal of $PM_{0.1}$ ultra-fine particulate matter. Cast or electrospun nanofibers are considered ideal for resistance to aerosol particles containing viruses, eliminating air pollution by particulate matter, and protecting public health. The air filter developed by the authors demonstrated the attributes of high $PM_{0.1}$ removal efficiency of up to 97.08%, a pressure drop of ~58 Pa, the quality factor of $0.061 Pa^{-1}$ and good optical transparency with only $6 g.m^{-2}$ basis weight. This is innovative compared to existing air filters based on micro/nanofiber membrane for ultra-fine particle filtration and can be used in face masks, filtering aerosol particles containing viruses, including the COVID-19 virus.

Choi *et al.* (2021) developed a biodegradable, moisture-resistant, highly breathable, high-performance fibrous mask filter based on poly(butylene succinate) (PBS) and chitosan nanowhiskers (CsW). The filter developed was as efficient as the commercial N95 filter and removes 98.3% of $2.5\mu m$ of particulate matter (PM). The nanofiber sieve physically fine PM and the microfiber provides a

low-pressure differential of 59 Pa, which is comfortable to breathe and has not significantly lost filtering when exposed to moisture, unlike the N95 filter, which loses performance. Therefore, the new filter is multifunctional because chitosan's permanent dipoles adsorb ultra-fine PM (e.g. nitrogen and sulfur oxides). Furthermore, unlike commercial disposable facial masks, the developed filter is sustainable; it fully biodegrades in 1 month in composted soil.

Choi *et al.* (2021) the indoor environment provides a unique exposure situation to induce infection through airborne transmission like SARS-CoV-2. To prevent the infection from spreading, personal protective equipment or indoor air purification is necessary. However, it has been discovered that the conventional filter can become contaminated by pathogen-containing aerosols, meaning that advanced filtering and self-sterilization systems are required. Here, we fabricate a multilayered nanocoating around the fabric using laponite (LAP fabricated a multilayer nano-coating around the fabric using Laponite (LAP) with Cu^{2+} ions (LAP- Cu^{2+} nano-coating) two contradictory functions in a system: entrapment of protein pathogens and antibacterial effect. Due to the strong LAP-protein interaction, albumin and the spike protein (protein S) are trapped in the tissue when the proteins are sprayed using a nebulizer. The protein blocking performance of the nano-coated fabric is 9.55 times that of normal fabric. These trapping capabilities are maintained after repeated rinsing and adsorption cycles, showing reproducibility for air filtration. Even though protein binding has occurred, LAP- Cu^{2+} tissue indicates an antibacterial effect. The LAP- Cu^{2+} tissue has a transmission rate of air and water equivalent to that of the naked tissue, with stability in a physiological environment. Therefore, due to its excellent "spear and shield" functions, the proposed LAP- Cu^{2+} fabric has great potential for use in filters and masks during the viral pandemic.

In the study developed by El-Atab *et al.* (2020), they performed the synthesis of a flexible nanoporous mold for the design and development of reusable hydrophobic anti-COVID-19 facial masks. The development of a nanoporous membrane attachable to a reusable N95 mask and replaceable after each use has been demonstrated. The porous membrane is based on a naturally hydrophobic polymer, so the droplets that come into contact with the mask will roll and slide over the mask due to the large angle of inclination of the membrane when used in the full facial mask. The results showed nanopores with sizes below 5 nm and theoretical calculations to assess the breathability of the obtained membrane showed airflow rates above 85 L min^{-1} . As such, the flexible membrane can be used in a reusable N95 mask to increase its filtering efficiency against particles below 300 nm, including the COVID-19 virus.

Horvath *et al.* (2020) developed an air filter based on TiO_2 photocatalytic nanowires (TiO_2 NWs) for personal protection equipment, as well as for a new generation of air conditioners and air purifiers. The immediate importance of such a filter is represented by the urgency of the Covid-19 crisis, which quickly spread to a pandemic. As a result, the authors obtained TiO_2 NWs that can be processed into films by scraping, screen printing, filtering, dip-coating, and spin-coating with a thickness of fewer than $2 \mu\text{m}$.

Leung and Sun (2020a) developed electrostatically charged multilayer/multimodule nanofiber (PVDF) filters for filtering new simulated airborne coronaviruses (COVID-19) using environmental nanoaerosols. The results demonstrate that electrostatically charged multilayer/multimodule (PVDF) nanofiber filters are potent candidates for facial masks, which can be used to protect against SARS-CoV-2. Another study by Leung and Sun (2020b) demonstrated the development of an electrostatically charged nanofiber filter to filter out new airborne coronaviruses (COVID-19) and nanoaerosols. With the multilayer/multimodule approach using small diameter nanofibers with small basis weight in modules, or large diameter nanofibers with large basis weight in modules, high-performance loaded nanofiber filters have been developed that achieve capture of more than 90% COVID-19 airborne simulated by 100 nm sodium chloride aerosols. Thus, the filters developed are excellent in capturing viruses, especially SARS-CoV-2, which has a size range of 60-140 nm with an average size of 100 nm.

Li *et al.* (2021) the inappropriate disposal and sterilization of PPE may result in a high risk of cross-contamination. Therefore, the exploration of antimicrobial materials possessing both microbe interception and self-decontamination effects to develop reusable and easy-to-sterilize PPE is of great importance. Herein, an aggregation-induced emission (AIE) used the electrospinning technique to develop a nanofibrous membrane loaded with aggregation-induced emission (AIE) active luminogenic (TTVB @ NM) sharing photodynamic/photothermal antipathogen functions triggered by sunlight. After irradiation with sunlight, TTVB @ NM can generate massive ROS, which plays a dominant role for the microbicide effect, and exhibits a moderate photothermal conversion performance that plays an adjuvant role for the inhibition of microbes, synergistically providing its effective application for sunlight-triggered inactivation of various microbes, including bacteria, fungi, and viruses. A series of antimicrobial evaluations revealed that TTVB @ NM can effectively inactivate pathogenic aerosols containing bacteria (inhibition rate: >99%), fungi (~88%), and viruses (>99%) in just 10 minutes of solar irradiation.

Pardo-Figuerez *et al.* (2021) developed antimicrobial filters based on polyacrylonitrile nanofibers (PAN) for high filtration efficiency respirators. The fibers were deposited onto polypropylene non-woven material in rolled form (SPP). The results suggested that a symmetric structure based on SPP / PAN / PAN / SPP was the ideal structure, as it has maintained the filtration efficiency of the FFP2 mask type, as well as reduced respiratory resistance, especially at high airflow rates such as the FFP2. Furthermore, the incorporation of zinc oxide (ZnO) nanoparticles in electrospun nanofibers in the form of nanocomposites maintained the high filtration characteristics of the unfilled filter, although exhibiting a strong bactericidal capacity, even after short contact times. This study expresses the possibility of producing a high filtration efficiency filter medium with antimicrobial properties.

Shen *et al.* (2021) used coronavirus aerosols to challenge air filters and facial masks and to assess their efficiency. They have developed electrospun nanofibrous air filters with a reduced

pore size that can effectively capture viral aerosols. Due to the ultra-fine (~300 nm) nanofibers, the electrospun air filters had a much smaller pore size compared to the surgical mask and tissue masks (a few micrometers versus tens to hundreds of micrometers). Electrospun air filters have shown excellent performance, capturing up to 99.9% of coronavirus aerosols, outperforming many commercial facial masks.

To complete the studies found on nanostructures used in the development of antiviral air filters and their potential uses, Tian *et al.* (2021) synthesized antibacterial and antiviral N-halamine nanofiber membranes with a nanonet structure for bioprotective applications. They designed membranes that exhibited integrated properties of high fine particle interception (96.7%) and low-pressure drop (95.4 Pa). Furthermore, the nanofiber membranes exhibited superior bactericidal (> 99.99%) and virucidal (> 99.99%) efficiency in a short time (2 min), which allows the nanofibers to be used as a filtration material, providing interception bacterial (99.77%) and death by contact against pathogens.

Conventional filters, used in masks, are disposable and are not biodegradable and recyclable, generating a high amount of waste in the environment, as seen in masks without nanotechnology, in addition to losing their effectiveness in humid conditions. Another problem with conventional filters is their use in valves or one-way mask openings, where the virus spreads through released respiratory droplets. To overcome these adversities, studies have resorted to nanotechnology, such as the use of electrospun nanofibers, to which Electrospinning is an emerging technology to synthesize non-woven nanofiber membranes that are ideal for air filtration (AGARWAL, WENDORFF e GREINER, 2008).

In addition to the use of SiO₂, TiO₂, ZnO, AgNPs, and LAP-Cu²⁺ nanocapsules, to control the transmission of SARS-CoV-2, and thus use these filters in different types of PPE. These nanostructures can add characteristics of biodegradability, nontoxicity, hydrophobicity, and reuse of filters, which, together with the antiviral properties of nanomaterials, become good alternatives for controlling the proliferation of SARS-CoV-2.

Further to the articles described above, data described in Table 4 demonstrate that we found 7 different studies on nanostructures used in the development of antiviral surfaces and their potential uses in protection against SARS-CoV-2.

Table 4 - Nanostructures used in the development of antiviral surfaces and their potential uses.

Developed Product	Type of Nanostructure	Function	Potential application	Ref.
Antiviral surface	Carbon nanotubes decorated with metals (Pt and Cu)	Antiviral	PPE	AASI <i>et al.</i> , 2020
Nanocetical cotton fabric	ZnO nanoflowers	Antimicrobial	Facial mask and Clothes	ADHIKARI <i>et al.</i> , 2021
Multifunctional nanofibers	ZnO Nanofibers and Ag Nanoparticles	Antimicrobial	Protective clothing	KARAGOZ <i>et al.</i> , 2021
Antimicrobial nanofibers	Aloe Vera and PVA Nanofibers	Antimicrobial	Protective clothing	KHANZADA <i>et al.</i> , 2020

Superhydrophobic surface	Cu nanoparticles	Antimicrobial	Fomites	MEGUID; ELZAABALAWY, 2020
Antimicrobial coating	Ag, CuO, and ZnO nanoparticles	Antimicrobial	Fomites	MERKL <i>et al.</i> , 2021
Biocidal nanofibers	Nanofibers	Antimicrobial	Clothes and Facial Masks	WU <i>et al.</i> , 2021

Source: Authors' construction.

Surfaces capable of detecting, inactivating, and removing viruses from the air or fomites are vital to prevent viral transmission, especially in pandemics such as the ones caused by SARS-CoV-2. Reactive oxygen species (ROS) promoting molecules such as peroxides are harmful to many viruses, including coronaviruses. In the article published by Aasi *et al.* (2020), metal-decorated single-wall carbon nanotubes (SWCNTs) were evaluated for the adsorption of hydrogen peroxide (H₂O₂) for potential use in the design of viral inactivation surfaces such as filter nanomaterials, PPE, and virus detection devices. SWCNT has shown potential as a largely unexplored substrate for capturing, inactivating, and controlling viral infectious diseases. Adhikari *et al.* (2021) used zinc oxide nanoflowers (ZnO NFs) in the development of a nanoceutical cotton fabric with antimicrobial activity. This fabric was developed for use in clothing and face masks to increase breathing comfort and deactivate SARS-CoV-2 viruses through Spike protein denaturation.

Karagoz *et al.* (2021), investigated the potential of using multifunctional poly(methyl methacrylate) nanofibers decorated with ZnO nanorods and Ag nanoparticles in protective mats. The new material showed high performance, featuring four functionalities (I) antibacterial agent, (II) antiviral agent to inhibit corona and influenza viruses, (III) photocatalyst for degradation of organic pollutants, allowing a self-cleaning protective mat, and (IV) Raman scattering substrate, with an improved reusable surface for quantitative analysis of trace pollutants on nanofiber. The multifunctional material also showed high potential for use in the application of protective clothing. Khanzada *et al.* (2020) also manufactured nanofibers in their studies but using Aloe Vera and Polyvinyl Alcohol (AV/PVA). The antimicrobial activity of the AV/PVA electrospun nanofibers was excellent and therefore these fibers are more suitable for the preparation of protective clothing (lab coats, face masks, etc.) used against COVID-19.

Literature indicates that copper (Cu) may play a crucial role in further eliminating the risk of the virus. Copper fomites have been found to have antiviral properties against Influenza A virus particles and are also the fastest to eliminate SARS-CoV-2 virus particles when compared to other materials. Therefore, Meguid and Alzaabalawy (2020) studied the potential of implementing superhydrophobic surfaces incorporated with Cu nanoparticles to reduce virus transmission. They were able to manufacture nanocomposites with antibacterial and antiviral activities, which can repel contaminated particles, providing improved protection on surfaces used in public and healthcare facilities. These nanocomposites can be applied to coating surfaces or synthesized in masse into super-hydrophobic monoliths.

Coatings of Ag, CuO, and ZnO on flat solid substrates (glass) and also on porous filter media (fiberglass filters and FFP3 filters) were produced by Merkl *et al.* (2021), to study its antiviral activity against SARS-CoV-2. Among the three nanomaterials studied, nanosilver exhibited the highest antiviral activity against SARS-CoV-2. After 5 minutes, the viral load was reduced by 75% and, after 120 minutes, by 98%. During the incubation of the nano-coatings with the drop containing the virus, the virus particles could be inactivated both by their direct interaction with the surface and by their interaction with the released ions (Ag^+ , Cu^{2+} e Zn^{2+}). The results of this research provide the necessary guidance for the healthcare industry to use antiviral coatings on solid surfaces against fomite transmission, leading to super scattering events, as well as to mitigate aerosol transmission by using air filtration units to nanosilver basis for the current COVID-19 pandemic and any future pandemics caused by similar pathogens.

Wu *et al.* (2021) presented green nanofibers with effective antibacterial and antiviral activities that can provide sustainable bioprotection through the continuous production of reactive oxygen species (ROS). The design's superiority is that nanofibers can absorb and store visible light energy and maintain activity in a light or dark environment. Furthermore, nanofibers can release ROS uninterruptedly in the absence of an external hydrogen donor, acting as a biocide in all weather conditions. The PPE modified with nanofibers exhibit stable ROS production, excellent long-term durability, and high bactericidal (>99.9%) and virucidal (>99.999%) activity.

With the world pandemic decree, the demand for PPE increased, but most tissues used in the manufacture of this PPE do not have or are deficient in biocidal properties. Because of this, several studies have proposed the addition of nanostructures to surfaces, making them antiviral or even antimicrobial, examples of nanostructures found in this integrative review are: carbon nanotubes decorated with metals, ZnO and AgNP nanofibers, Aloe Vera nanofibers, and nanoparticles of Cu, Ag, CuO and ZnO. With the use of nanotechnology, the surfaces, in addition to blocking the virus, manage to deactivate it and can be used in facial masks, protective clothing, fomites, and PPE in general.

CONCLUSION

Nanomaterials have a wide spectrum of interesting properties that make them useful as potential nanomedicine and prophylactic tools against COVID-19. In this integrative literature review, the articles analyzed to show that different nanostructures have been used to develop facial masks, air filters, and surfaces with antiviral properties, to deactivate the SARS-CoV-2 virus through these PPEs. Understanding the interface between the studied nanomaterials and coronaviruses is essential for designing target antivirals for COVID-19 infection.

Through this review, it can be concluded that the main nanostructures used in the development of face masks, filters, and antiviral surfaces are nanofibers, carbon nanotubes, metallic nanoparticles,

nanorods, nanowires, graphene, and C-dots, e when compared to traditional PPE, PPE manufactured using nanoparticles exhibited advantages as prophylactic tools against COVID-19: i) NPs increase surface hydrophobicity by repelling aqueous particles; ii) the NPs provide reusability and self-sterilization under sunlight; iii) NPs have antimicrobial and viricidal activity with the ability to cause death or viral inactivation of pathogens by contact. Although promising results have been found in the different articles, there are still some challenges (for example, how to optimize the production of these PPE and nanoparticles, what are the possible effects of disposing of these PPE containing nanoparticles in the environment). Therefore, future studies on PPE containing nanoparticles should pay more attention to these issues. Overall, these new PPE are expected to make major contributions to decreasing the spread and spread of COVID-19 and other diseases transmitted by viruses and bacteria.

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