



# Nanocellulose-based membrane as a potential material for high performance biodegradable aerosol respirators for SARS-CoV-2 prevention: a review

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**Abstract** The controversy surrounding the transmission of COVID-19 in 2020 has revealed the need to better understand the airborne transmission route of respiratory viruses to establish appropriate strategies to limit their transmission. The effectiveness in protecting against COVID-19 has led to a high demand for face masks. This includes the single-use of non-degradable masks and Filtering Facepiece Respirators by a large proportion of the public, leading to environmental concerns related to waste management. Thus, nanocellulose-based membranes are a promising environmental solution for aerosol filtration due to their biodegradability, renewability, biocompatibility, high specific surface area, non-toxicity, ease of functionalization and worldwide availability. Although the technology for producing high-performance aerosol

filter membranes from cellulose-based materials is still in its initial stage, several promising results show the prospects of the use of this kind of materials. This review focuses on the overview of nanocellulose-based filter media, including its processing, desirable characteristics and recent developments regarding filtration, functionalization, biodegradability, and mechanical behavior. The porosity control, surface wettability and surface functional groups resulting from the silylation treatment to improve the filtration capacity of the nanocellulose-based membrane is discussed. Future research trends in this area are planned to develop the air filter media by reinforcing the filter membrane structure of CNF with CNCs. In addition, the integration of sol–gel technology into the production of an air filter can tailor the pore size of the membrane for a viable physical screening solution in future studies.

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## Introduction

Protection against airborne pathogens has been a major human health challenge since the emergence of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in 2020 (Cheng et al. 2021). The

main vector for community transmission of SARS-CoV-2 is respiratory droplets when an infected or asymptomatic patient sneezes, coughs or communicates with others (Konda et al. 2020). As a result, the use of face masks (medical grade or cloth) is becoming ubiquitous worldwide to act as barriers to prevent or limit the transmission of virus-containing droplets from an infected person to others in public spaces (Benson et al. 2021; Cheng et al. 2021). For example, several countries around the world have passed laws mandating the use of medical grade masks or cloth masks in public places and in the workplace to reduce the spread of viruses (Benson et al. 2021). This pandemic makes the face mask a national commodity. Worldwide, 129 billion masks are used each month, which corresponds to about 3 million masks used per minute (Prata et al. 2020; Wang et al. 2022). This growing demand for face masks due to the covid-19 pandemic is resulting in a large amount of waste, estimated at 3.4 million per day, leading to widespread contamination of the environment, (Benson et al. 2021) which can turn into a major wastes management problem (Binda et al. 2021; Fadare and Okoffo 2020). Despite the resulting non-biodegradability and high carbon footprint of petroleum-derived fibres, the filter layer of disposable masks is usually made of a melt-blown polypropylene (PP) nonwoven (Garcia et al. 2006). Furthermore, these synthetic fibre masks could take 450 years to fully decompose, slowly turning into microplastics while having a negative impact on marine life and even entering human food chains (Aragaw 2020; Fadare and Okoffo 2020; Ragusa et al. 2021; Wang et al. 2022). In the context of the crisis caused by the Covid-19 pandemic, nanocellulose-based materials from paper companies and agricultural waste can play a major role in providing a wide variety of cellulose-based products for the general public and healthcare workers (Garcia et al. 2006). This could at the same time limit the risk of shortages of personal protective equipment (PPE) due to the abundance and worldwide availability of cellulose sources.

Several studies have been performed on the development of a novel technology to improve the commercial availability and reduce the environmental concerns of the face mask and FFRs using filter membrane from cellulose-based materials produced via electrospinning technique (Bortolassi et al. 2019; Naragund and Panda 2020; Santos et al. 2020;

Wibisono et al. 2020; Xie et al. 2021) and freeze-drying method (Liu et al. 2021a, b; Lu et al. 2018; Sim and Youn 2016; Ukkola et al. 2021; Xiong et al. 2021). Nanocellulose-based filter membranes are potential materials for trapping air pollutants due to their biocompatibility, high specific surface area, renewable nature, biodegradability, worldwide availability and ease of functionalization (Liu et al. 2021a, b; Ukkola et al. 2021). In addition, fibrous filters made of cellulose nanofibrils (CNF) are very effective in removing particulate matter from the air; however, their use remains a challenge due to the lack of studies evaluating moisture resistance treatment, mechanical behaviour as well as filtration performance (Bortolassi et al. 2019). Compared to the conventional non-woven microfibre filter (temporarily charged to allow electrostatic interaction with viruses/bacteria), the cellulose nanofibrils filter is now considered the most effective and durable physical filtering method for protection against air pollutants, due to its small pore size (Givehchi and Tan 2015), but its hydrophilicity and resulting high pressure drop remain a challenge. In addition, the requirement for low airflow resistance (pressure drop < 350 Pa for the N95 respirator) minimises energy consumption and avoids inward leakage of air during breathing, thus eliminating protection against pathogen entry into the airways (Wang et al. 2021). Therefore, significant efforts are needed to develop viable air filtration and purification technologies on nanocellulose-based materials, to tailor the pore size of the filter as well as to modify the functionality of the membrane surface to achieving high hydrophobicity and antibacterial/antiviral resistance.

This study presents a review of potential methods to develop a high performance, moisture resistant, highly breathable and biodegradable nanocellulose (combination of CNF and CNC) air filter membrane to replace the current synthetic non-woven air filter, thereby promoting cleaner production. Information on aerosol transmission of respiratory viruses, with a focus on SARS-CoV-2, will be presented. Then the structure, processing, classification and standard of commercial disposable masks will be discussed. The preparation, functionalization and performance of biodegradable cellulose and nanocellulose filter membranes are highlighted for their potential application in masks and FFRs.

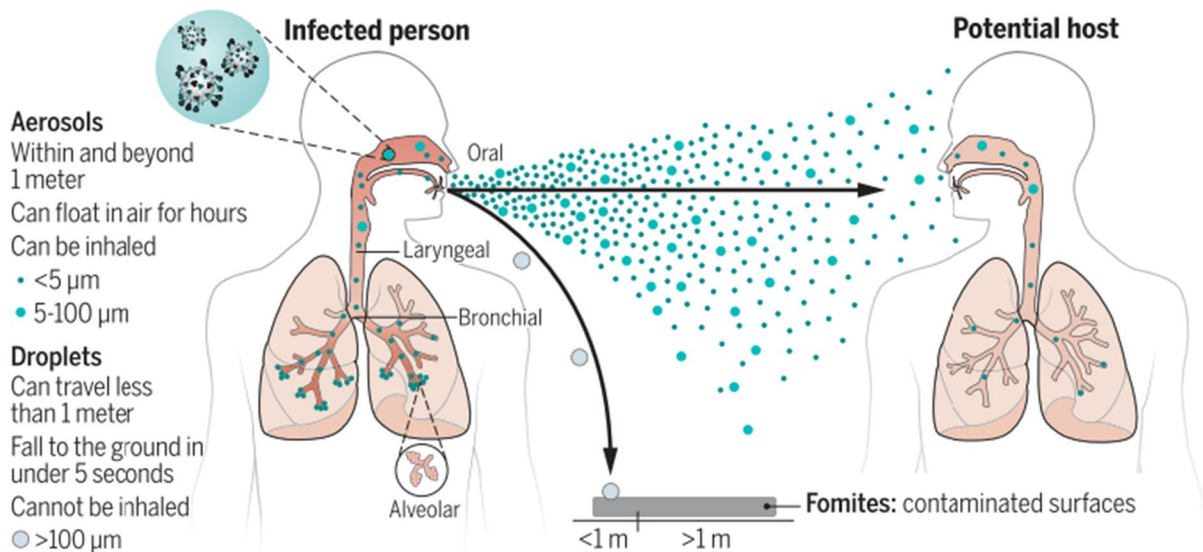
## Airborne transmission of respiratory viruses

Due to the high frequency of SARS-CoV-2 spread events in 2020, the controversy surrounding the transmission of COVID-19 has revealed the need to better understand the airborne transmission route of respiratory viruses (Cheng et al. 2021). This helps to establish appropriate strategies to limit the transmission of infections. Therefore, assessing the airborne behaviour of aerosols requires understanding their transmission mechanism. Traditionally, airborne transmission is defined as the inhalation of contagious aerosols smaller than  $5\ \mu\text{m}$  and primarily at a distance greater than 1 to 2 m from the patient as shown in Fig. 1 (Wang et al. 2021). Figure 1 shows that several parameters such as environmental factors (temperature, relative humidity, ultraviolet radiation, airflow and ventilation) and physico-chemical properties of aerosols including viral load, physical size, infectivity, pH, electrostatic charge, and air–liquid interfacial properties can affect the transport of virus-laden aerosols. Gravitational forces are applied to droplets ( $>100\ \mu\text{m}$ ), which typically fall within a few meters of the infected person and are quickly cleared from the air, while aerosols remain airborne longer and can travel much further (Moschovis et al. 2021; Santos et al. 2022). After inhalation, the large virus-laden aerosols ( $5\text{--}100\ \mu\text{m}$ ) settle in the upper respiratory tract, while the smaller ones ( $<5\ \mu\text{m}$ ) settle in both

upper respiratory tracts and penetrate deep into the alveolar region of the lungs. The main mode of transmission of the SARS-CoV-2 virus responsible for the spread of COVID-19 has been identified as the inhalation of virus-laden aerosols by the World Health Organization (WHO) and the U.S. Center for Disease Control and Disease Prevention (CDC).

Studies on the particle size distribution of aerosol exhaled during coughing estimate particle sizes ranging from  $0.1$  to  $900\ \mu\text{m}$ , of which about 97% of the measured aerosols are smaller than  $1\ \mu\text{m}$  (Zayas et al. 2012). Fabian et al. (2011) demonstrated that an individual infected with the human rhinovirus (HRV) while breathing can exhale up to 7200 aerosol particles per liter of air. As the diameter of SARS-CoV-2 is estimated at  $80\text{--}150\ \text{nm}$  (Essa et al. 2021), an aerosol can potentially contain several virus particles and can remain suspended in the air for several hours. Furthermore, analysis of the spread SARS-CoV-2 shows that it can remain in breath-sized aerosols for more than 16 h while maintaining its structural integrity (Fears et al. 2020).

The first reason for surgical masks in hospitals was to prevent contamination of the wound by surgeons (the wearer) during surgery. Later, with the advent of respiratory infections, they were adopted to protect health care workers from contaminating patients. Leung et al. (2020) evaluated the effectiveness of the surgical mask in preventing contamination from



**Fig. 1** Phases involved in airborne transmission of respiratory viruses (Wang et al. 2021)

respiratory droplets and aerosols with a particular focus on coronaviruses, influenza viruses and rhinoviruses on volunteers. The results show that the respiratory droplets and aerosols of individuals infected with the coronavirus were 30% and 40% higher, respectively, when the individuals did not use a mask. While wearing the surgical mask eliminates the presence of coronavirus in their respiratory aerosols or droplets (Fig. 2). This experimental method for evaluating the collection efficiency of surgical masks demonstrated the mask's ability to reduce human-to-human coronavirus contamination (World Health Organization 2020a). However, further testing protocols regarding the number of volunteers and the SARS-CoV-2 virus variant would be necessary to adapt the results to the real context.

In addition, the shortage of FFRs and surgical masks during the COVID-19 emergency prompted the researcher to evaluate the filtration capacity of homemade reusable cloth masks. Previous results have shown that the filtration efficiency of these fabric masks can be achieved when several layers and specific combinations of different fabrics are used (Konda et al. 2020). For example, Konda et al. (2020) reported that the combination of fabrics (2–4 layers) including silk, muslin, flannel, cotton and various synthetic fabrics significantly improves filtration efficiency by 5 to 80% (for particle sizes  $< 300$  nm) and

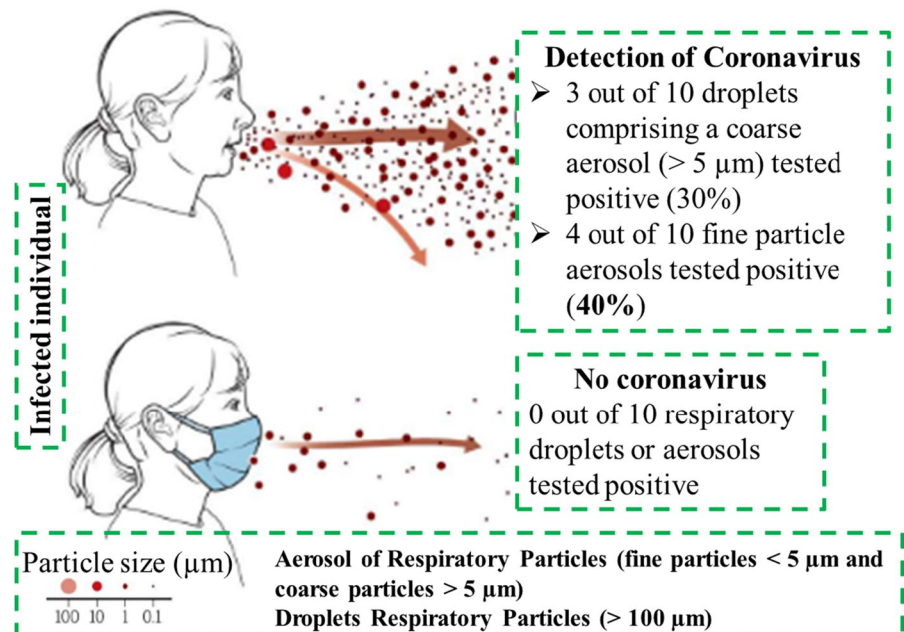
5% to 95% (for particle sizes  $> 300$  nm) compared to a single fabric layer used. Although multi-layer fabric masks are a promising way of capturing particles, special rules must be adopted in their production to ensure filtration efficiency and breathability. Therefore, for the general public, face masks and respirators are used to reduce COVID-19 contamination by acting as a barrier to airborne pollutants, including airborne pathogens.

### Performance and environmental impact of disposable masks and respirators

Materials and structure of disposable masks used against airborne transmission

Analysis of droplets emitted during normal human actions such as speech assessed by laser light scattering yields approximately 1000 droplets per second, and these particle emission rates can vary with the speed and intensity of the spoken sounds (Asadi et al. 2019). When wearing a surgical mask, laser light scattering reveals the absence of droplet emissions from the wearer (Bandiera et al. 2020). The mask therefore acts as a barrier to protect the wearer's mouth and nostrils from infected droplets.

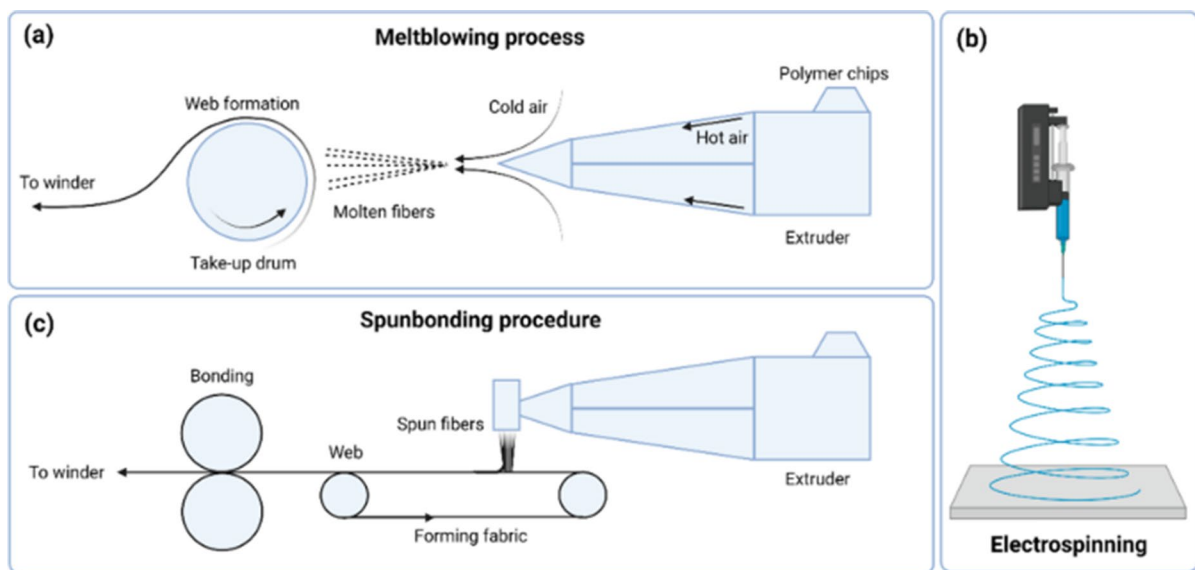
**Fig. 2** Face mask to reduce airborne transmission of respiratory viruses. Modified from Prather et al. (2020)



Originally, the use of the face mask was to prevent the nose and mouth of the wearer from being exposed to fluids or large airborne droplets, as well as to contain their respiratory secretions (Benson et al. 2021). The unprecedented rapid spread of COVID-19 in 2020 prompted the WHO to recommend the use of PPE, personal hygiene, social distancing and testing to reduce the spread of the virus (World Health Organization 2020a). In communities, wearing a mask is one of the most effective tools for limiting human-to-human contamination. Global demand for face masks due to the COVID-19 pandemic is estimated at 4.3 billion per day and disposable commercial face masks currently use melt-blown polypropylene (PP) non-woven fabric as active layer due to their non-absorbent properties and ability to wick away moisture (Benson et al. 2021; Zhang et al. 2021). To overcome the shortage of surgical masks and FFRs, reusable cloth masks designed by several tailors are commonly used, although there is no scientific evidence of their effectiveness.

Since the beginning of the twentieth century, non-woven fibrous membranes such as polypropylene, sandpaper and, wool felt have been the most explored materials in the manufacture of masks for PPE (Dowd et al. 2020). This is due to the ability to maintain their structural integrity when subjected to high temperatures during autoclaving. The preparation of filter

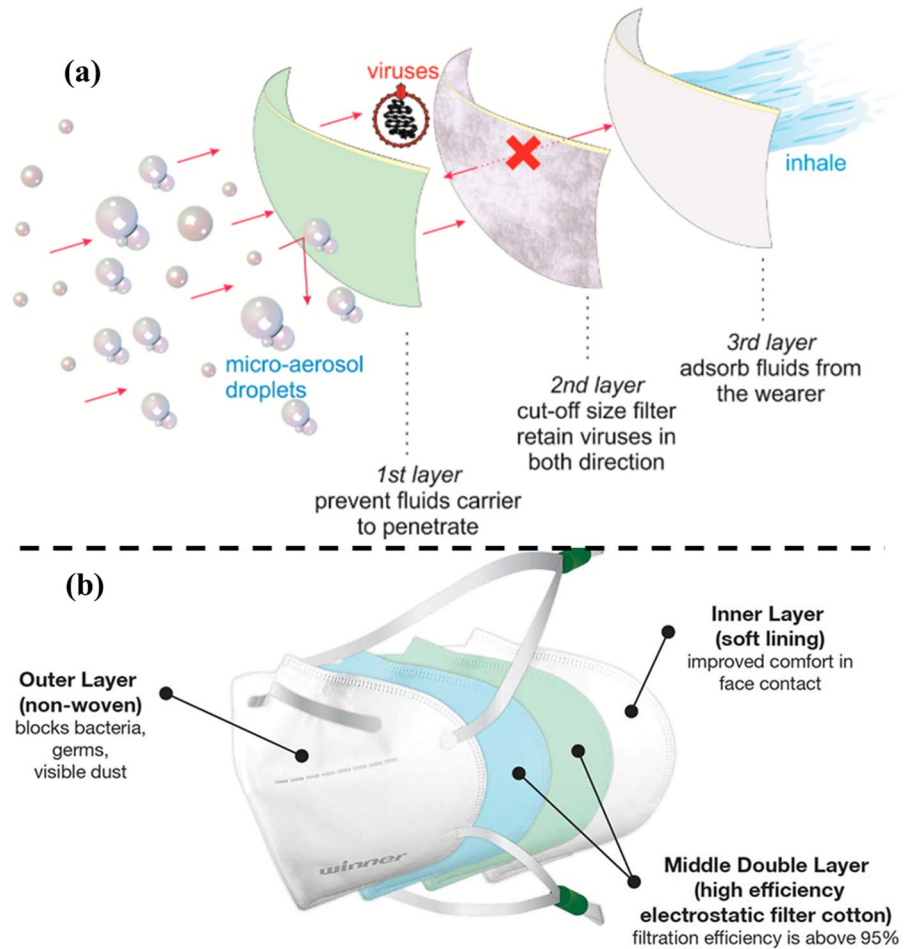
media for respirators and surgical masks is usually done with polypropylene (PP), but some other polymers such as polyethylene (PE), polyethylene terephthalate (PET), polyacrylonitrile (PAN), polylactic acid (PLA) and polyamide (PA) are also often used (Pullangott et al. 2021). Surgical mask manufacturing done with multi-layer non-woven filter media can be prepared via several technologies such as melt-blown (M), electrospinning (E), spunbond (S) and their combinations (Fig. 3). The filtration efficiency of a mask regularly depends on the structure and types of non-woven fabrics used in its manufacture and these can vary, depending on the application. For instance, surgical masks are designed to effectively filter particles, such as bacteria larger than 1 micron (Allison et al. 2020). Their structure is made by spunbond–meltblown–spunbond designed to achieve high bacterial filtration efficiency (about 98%), acceptable breathability (differential pressure  $< 40 \text{ Pa/cm}^2$ ) and hydrophobic surface (Tuñón-Molina et al. 2021; Wibisono et al. 2020). This filtration performance is the result of the combination of different functions of each of the three layers, as illustrated in Fig. 4a: the outer layer imposes hydrophobicity, while the middle and inner layers operate respectively as a filter membrane and an absorbent membrane to trap the virus and droplets emitted by the wearer (Wibisono et al. 2020). The main filter layer of the mask (the middle



**Fig. 3** Schematic view of the meltblowing **a**, electrospinning **b** and spunbonding **c** processes (Tuñón-Molina et al. 2021)



**Fig. 4** Illustration of structure of **a** surgical face mask (Wibisono et al. 2020) and **b** N95 respirator (Richardson, 2022) to prevent contagious virus contained in aerosol micro droplets



layer) is manufactured using meltblown technology, which involves the conventional manufacture of micro- or nanofibres from molten polymer extruded through tiny nozzles, blown at high speed (Fig. 4a).

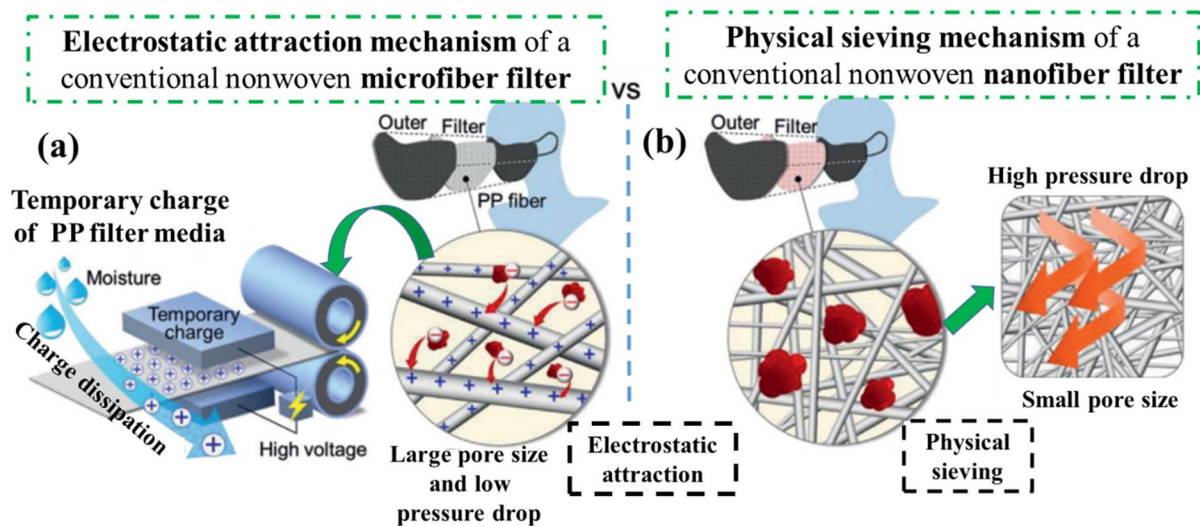
Compared with the structure of surgical masks, the N95 respirator is made of four layers of membranes, as shown in Fig. 4b, but is more complex regarding its structure than a surgical mask (Forouzandeh et al. 2021). The N95 respirator also has a hydrophobic polypropylene (PP) membrane on its outer layer, followed by positively charged cellulose and polyester layers which attract bacteria and viruses via electrostatic interactions (Babaahmadi et al. 2021). Then, the fourth layer (inner layer) is made by spunbond or melt-blown technology (Table 1). Compared to surgical masks, N95 respirators are usually dedicated to healthcare personnel to prevent pathogen infection due to their tight fit, high filtration efficiency,

and relatively high cost (Karmacharya et al. 2021). However, during respiration, humidity gradually reduces the effectiveness of the electrically charged filter media (Choi et al. 2021). Thus, according to the WHO, the surgical mask and N95 respirators should be worn for a maximum of 4 h and 8 h, respectively, to avoid self-contamination (World Health Organization 2020b).

The micro-scale of polypropylene fibre used to make respirator and surgical mask filters leads to inappropriate use as a physical screen against aerosolised infectious agents smaller than 300 nm (Choi et al. 2021; Davison 2012). Therefore, a melt-blown filter membrane is subjected to a high energy temporal electric field for electrostatic capacitance. In contrast to the physical sieving mechanism observed on the passive air filter membrane (Fig. 5b), the melt-blown microfibre membrane

**Table 1** Materials and type of commercial disposable masks and respirators

Masks type	Surgical			Respirator			
	type I	type II	type IIR	N95	KN95	FFP2	FFP3
Standards	EN14686			NIOSH 42CFR84	GB2626-2006	EN149:2001	EN149:2001
Materials/structure	PP non-woven and meltblown fabric			Meltblown fabric, hot air cotton and non-woven fabric		Non-woven meltblown and spunbond fabric; a layer of PP cotton is sometimes included	
Wearing duration	4 h			8 h			
References	Melayil and Mitra, (2021); Tcharkhtchi et al. (2021); Tuñón-Molina et al. (2021)			Forouzandeh et al. (2021); Kelly et al. (2021); Tcharkhtchi et al. (2021), Kelly et al. (2021); Tcharkhtchi et al. (2021)		(Liao et al. 2021; Pandit et al. 2021)	

**Fig. 5** Filtration mechanism of conventional nonwoven **a** microfiber and **b** nanofibre filter. Modified from Choi et al. (2021)

captures extremely small particles by the adsorption mechanism due to their electrostatic charge, as shown in Fig. 5a. In general, porous membranes are charged by turbocharging, corona charging and in-situ charging techniques to effectively trap particles (Tsai et al. 2002). Additionally, electrostatic air filters have the advantage of maintaining particle removal efficiency and low pressure drop under continuous air flow, when the membrane thickness changes (Chua et al. 2020). However, during human breathing, the moisture emitted reduces the electrostatic surface charge of the filter media, leading to a gradual loss of its adsorption capacity (Choi et al. 2021).

#### Standards and classification of disposable masks and respirators

Disposable face masks or (FFRs) are subject to various regulatory standards worldwide (Table 2) to control the quality of this kind of material available on the market and to ensure effective health protection for the public or staff. Therefore, in order to claim that your respirator or medical mask meets a certain standard, several physical properties and filtration performance are required (Table 2). According to the National Institute for Occupational Safety and Health (NIOSH) classification, there are three series of face masks, designated by the capital letter N, R

**Table 2** Comparison of the standards and classification of different international respirators and filter masks

Classification	Mask standards (country)	Aerosol filter efficiency	Inhalation resistance (Pa)	Exhalation resistance (Pa)	Flow rate (L/min)	Test agent
N95	NIOSH-42CFR84 (USA)	95%	$\leq 343$	$\leq 245$	85	NaCl
KN95	GB2626-2006 (China)	95%	$\leq 350$	$\leq 250$	85	NaCl
P2	AS/NZS1716:2012 (Australia and New Zealand)	94%	$\leq 70$	$\leq 120$	30	NaCl
FFP2	EN149-2001 (Europe)	94%	$\leq 240$		95	NaCl + Paraffin oil
			$\leq 70$		30	
			$\leq 240$		95	
				$\leq 300$	180	
Korea 1st Class	Korea KMOEL-2017-64 (Korea)	94%	$\leq 500$			NaCl + Paraffin oil
			$\leq 70$		30	
			$\leq 240$		95	
				$\leq 300$	180	
DS	Japan JMHLW-Notification 214, 2018 (Japan)	95%		$\leq 70$	40	NaCl
			$\leq 70$		85	

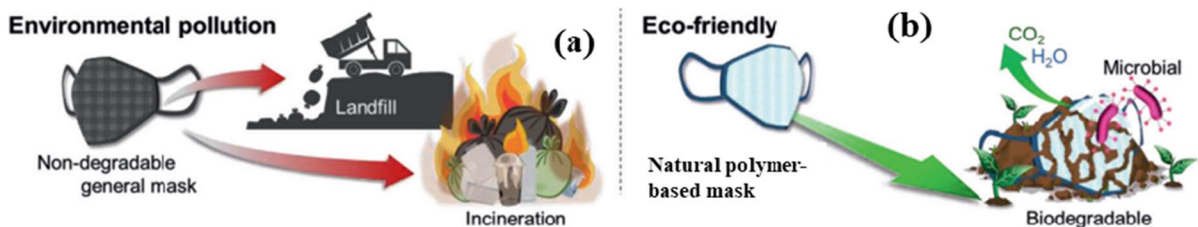
or P, according to their resistance to oil, followed by the value of the filtration efficiency in case of exposure to oil-based aerosols, such as glycerine and lubricants (Shanmugam et al. 2021). The letter "N" is for non-oil resistant, "R" for moderately oil resistant and "P" for highly oil resistant. For example, the N95 series refers to a non-oil resistant mask with a filtration efficiency of 95% of airborne particles larger than 300 nm (Forouzandeh et al. 2021). In Europe, masks are labelled FFP2 and FFP3 and can filter up to 94% and 99% of aerosol particles respectively. The equivalent of FFP2 respirators are N95 (USA), P2 (Australia/New Zealand), KN95 (China), DS (Japan) and Korea first Class (Korea) (Zhang et al. 2021). For the protection of hospital staff, the N95 respirator is generally used to achieve a very tight face fit and high

filtration efficiency of pathogenic aerosols emitted by infected patients (Tuñón-Molina et al. 2021).

#### Environmental impact of disposable facemasks

Although disposable masks are a viable solution to reduce the spread of SARS-CoV 2, the management of their wastes is a major environmental problem, as they are made from non-degradable polymeric materials. To date, due to difficulties in sorting and cleaning medical plastics such as surgical masks, their recyclability is limited and they are either subjected to inappropriate incineration or landfilled (Joseph et al. 2021) (Fig. 6a).

These single-use masks, discarded in the environment after use, are transported by rainwater to rivers

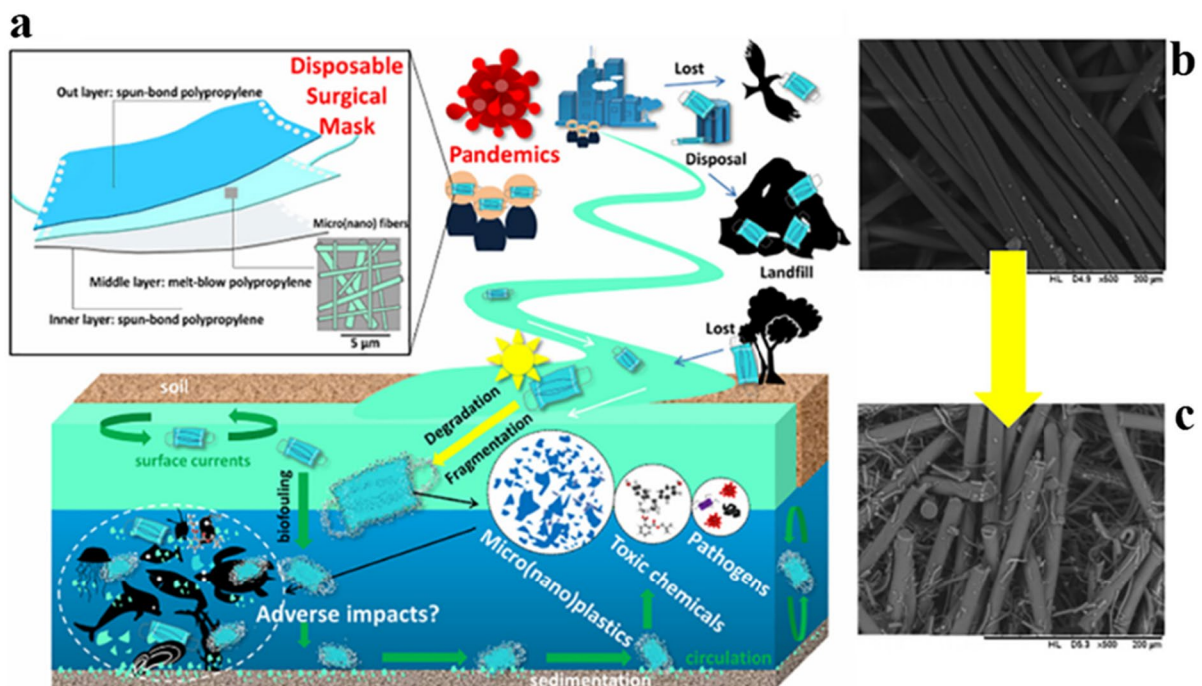


**Fig. 6** Environmental impact of masks from **a** non-biodegradable material sources and **b** biodegradable material sources. Modified from Choi et al. (2021)



where they enter the marine environment, adding to the presence of other plastics. Several authors have highlighted in recent years the environmental concern related to surgical masks, made of synthetic materials, as a potential source of microplastic pollution in the ecosystem (DYBAS, 2021; Fadare and Okoffo 2020; Mghili et al. 2022) as illustrated on Fig. 7. In 2020, the marine conservation organisation OceanAsia estimated that 1.56 billion pieces of plastic waste from discarded masks entered the marine environment (DYBAS, 2021). These large quantities of the new type of plastic waste from the mismanagement of discarded masks have a negative impact on marine wildlife and eventually enter human food chains, as they slowly turn into microplastics and can take up to 450 years to break down completely (Aragaw 2020; Fadare and Okoffo 2020). For example, Mghili et al. (2022) studied quantitatively and qualitatively the waste of respiratory masks on five Moroccan beaches during the period from February to June 2021. The results reported the presence of approximately 321 protective masks with a predominance of disposable masks (single-use masks) evaluated at 96.27%.

Furthermore, Allison et al. (2020) demonstrated that during the COVID-19 pandemic, if everyone wore a disposable face mask in the UK, contaminated plastic waste per year would increase by up to 66,000 tons. According to Babaahmadi et al. (2021), the global plastic waste resulting from the disposal of synthetic masks should be estimated at 4.1 million tons per year (estimating the weight of a mask at 3 g), of which nearly 80% is disposed of in the marine environment. Another major risk is that these microplastics can pass from the environment to living organisms, including mammals (Ragusa et al. 2021). As evidence, Ragusa et al. (2021) analysed five human placenta samples from consenting pregnant women by Raman Microspectroscopy. The results revealed the presence of 12 microplastic fragments between 5 and 10 microns in size, three of which were identified as PP. In addition, Aragaw, (2020), pointed out that the easy ingestion of masks by organisms such as fish in the aquatic environment can have a significant impact on the food chain and degrade human health. Further research is therefore urgently needed to provide environmentally friendly and biodegradable



**Fig. 7** Illustration of **a** the fate and potential environmental impacts of disposable surgical masks during COVID-19 (Babaahmadi et al. 2021; Xu and Ren 2021), **b**, **c** SEM micro-

graphs of the surgical mask taken before and after application of the experimental fragmentation and degradation treatment (Babaahmadi et al. 2021; Saliu et al. 2021)

alternative materials with high filtration performance, while leading to an effective waste management system that can provide a sustainable solution to plastic pollution (Fig. 6b).

Cellulose is the most promising material to partially or completely replace petroleum-based fibers for disposable membrane air filters, for several reasons, including its low cost, abundance, renewability, biodegradability, strong mechanical properties, low density, tunable aspect ratio, and ease of processing and functionalization (Ukkola et al. 2021). Therefore, the development of disposable masks from cellulose-based nanofibres with a filtration capacity comparable to that of N95 respirators and surgical masks may ease the burden of the medical mask shortage and promote cleaner production.

### Biodegradable air filter media for facemasks

Due to their multiple advantages, such as corrosion resistance, and adjustable chemical functionality, polymeric materials have been widely used throughout the world, resulting in the production of a large amount of plastic waste, causing serious environmental problems (Aragaw 2020; Hassan et al. 2022; Shanmugam et al. 2021). Environmental concerns generated by the extensive use of biostable (non-degradable) materials have led researchers to turn to biodegradable (hydrolytically and enzymatically degradable) materials such as biopolymers for various applications (Babaahmadi et al. 2021). The degradation process of biopolymers takes place in two steps: enzymatic or hydrolytic cleavage of the sensitive bonds, followed by the complete erosion of the polymer structure (Nair and Laurencin 2007). As a result, biodegradable materials decompose over time, through natural biological processes, into water, non-toxic gases and carbonaceous soil (Leja and Lewandowicz 2010). To date, biodegradable natural polymers have been widely recommended as alternative materials for making packaging films (Li et al. 2020), filtration membranes (Ahne et al. 2019; Liu et al. 2021a; Patil et al. 2021; Ukkola et al. 2021; Xiong et al. 2021), and, in the medical sector (Afshar et al. 2019; Doderio et al. 2020; Venkatesan et al. 2017), for tissue engineering, promoting sustainable solutions. For example, since 2020, with the urgency of the COVID-19 pandemic, several

sources of biopolymers, such as cellulose, alginate, poly(lactic acid) (PLA), gelatine, chitosan, chitin, poly(vinyl alcohol) (PVA), polyhydroxyalkanoates (PHA) and their mixtures are frequently used in the manufacture of filter membranes and face masks as viable and sustainable solutions (Essa et al. 2021; Li et al. 2018; Liu et al. 2021a, b; Xie et al. 2021), as shown in Table 3. The fibre diameter, porosity and filtration efficiency of the electrospun filter membrane are the result of the electrospinning (Santos et al. 2019). Liu et al. (Liu et al. 2021a, b) investigated the effect of Ag nanoparticle (AgNP) content and ultrasonication time of poly ( $\epsilon$ -caprolactone) (PCL)/zein/Ag nanoparticle (AgNP) mixture on the filtration capacity, biodegradability, mechanical and antimicrobial/antiviral performance of the air filter membrane prepared by ultrasonication followed by electrospinning. The results show that the filter membrane prepared with 1% AgNP and 30 min of ultrasound before the electrospinning process achieved a filtration efficiency of more than 97% for 0.3, 0.5 and 1.0 mm particles, as well as high antiviral and antibacterial efficiencies. In addition, according to Li et al. (2018), the nanoporous PLA/chitosan nanoparticles fibrous membrane prepared by one-step electrospinning with a chitosan:PLA mass ratio of 2.5: 8 achieves high filtration capacity compared to the N95 respirator (98.99% filtration efficiency and pressure drop (147.60 Pa)) and high antibacterial activity of 99.5% and 99.4% against *Staphylococcus aureus* and *Escherichia coli*, respectively. This filter membrane achieves 100% of removal efficiency when used in a confined space artificially polluted with cigarettes for 30 min, which may be related to the high specific surface area of the nanofibres and the small through-pore size of the nanofibre membranes. (Ahne et al. 2019) prepared cellulose acetate (CA) filter membranes via an electrospinning process with different CA concentrations (10–30%), deposition time (5–30 min), applied voltage (8–12 kV) and collector distance (10–15 cm) to evaluate the effect of parameters on fibre size. The results show that the filter media deposited for 30 min developed the highest filtration efficiency (about 99.8%), while the highest quality factor (QF) of  $0.05 \text{ Pa}^{-1}$  was obtained from the deposition time of 5 min, voltage of 8 kV, needle tip-collector distance of 12.5 cm and CA concentration of 20%.

**Table 3** Biodegradable filter media from biopolymer sources

Biodegradable media	Materials properties	Structure and materials	Membranes properties	Applications
Cellulose	Biodegradable, biocompatibility, lightweight, durability, and transparency	Cellulose acetate (CA) nanofiber (Ahne et al. 2019) 3-ply cotton-PLA-cotton layered (Patil et al. 2021)	Filtration efficiency of 99.8% and quality factor $0.05 \text{ Pa}^{-1}$ $\Delta p = 35.78 \text{ Pa/cm}^2$ and bacterial filtration efficiency of 97.9%	Air filtration Facemask
Poly (lactic acid) (PLA)	Biodegradable, biocompatible, non-toxic, linear aliphatic thermoplastic polyester, and soluble in organic solvents	Banana stem fibre (Sen et al. 2020) 3D printed and electrospun poly(lactic acid) (He et al. 2020) Electrospun PLA-chitosan core-shell nanofibers (Afshar et al. 2019)	Bioaerosol barrier properties Multi-layer filter as an alternative to KN95/N95 and FFP2 filters Broadly distributed, smooth, beadless fibres with a diameter of $(671 \pm 172) \text{ nm}$	Facemask Respirator filter Wound dressing, drug delivery and tissue engineering
Alginate	Biodegradable, biocompatibility, nontoxic nature and with gelling properties	Electrospun alginate membranes containing ZnO nanoparticles (Doderio et al. 2020) Chitosan-alginate-AgNPs membranes (Venkatesan et al. 2017)	Properties similar to human skin ( $E = 470 \text{ MPa}$ and water vapour permeability of $3.8 \times 10^{-12} \text{ g/m Pa s}$ ) Up to 1.5-fold increase in bacterial filtration efficiency by adding AgNPs	Surgical Patches and wound dressings
Chitosan	Biocompatible, biodegradable, binding energy, availability, with antibacterial properties and poor thermal and mechanical properties	Electrospun filter membranes from nanoporous PLA/(chitosan nanoparticles) (H. Li et al. 2018) Poly(butylene succinate) nanofibres/microfibres membrane coated with cationically charged chitosan nanowiskers (Choi et al. 2021)	Filtration efficiency (98.99%), pressure drop ( $147.60 \text{ Pa}$ ) at an air flow rate of $14 \text{ cm/s}$ and high antibacterial activity Permanent ionic charges and low pressure drop	Antimicrobial aerosol filtration membranes Air filtration media
Polyhydroxyalkanoates (PHAs)	Non-toxic, biodegradable and biocompatible	Nano fibrous structure (Al-Hazeem 2021)	High and regular fibre density	Air filtration media

\*  $\Delta p$ : Differential pressure, E: Elastic modulus

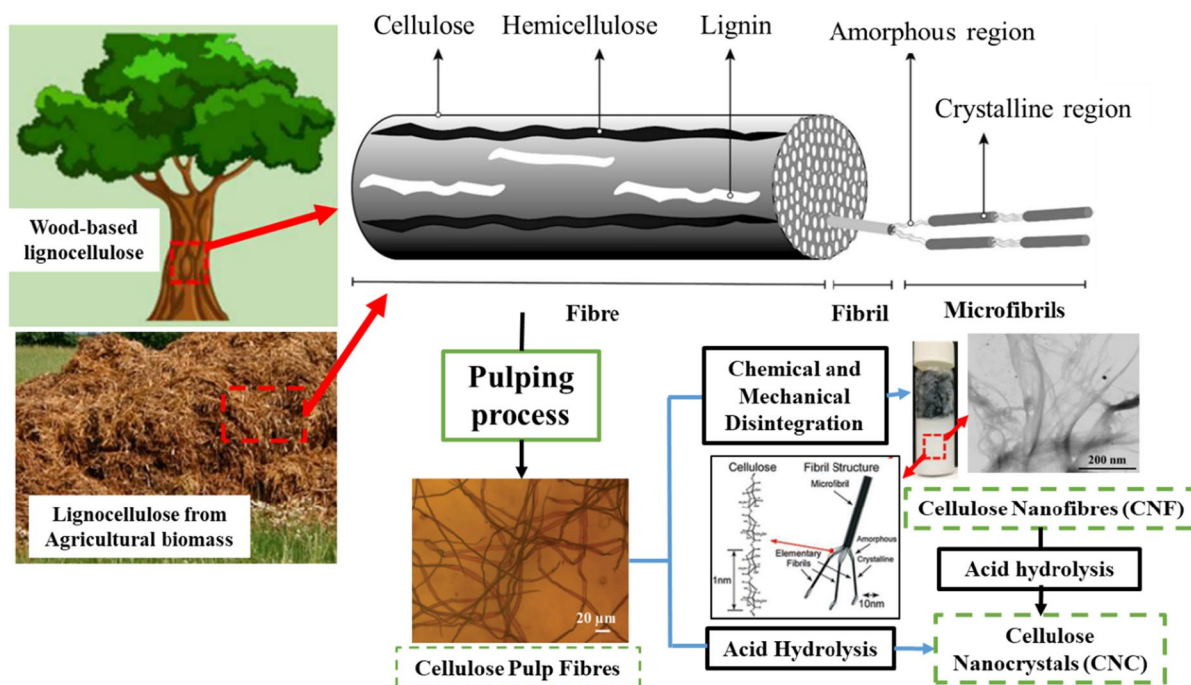
## Nanocellulose-based filter membrane

### Preparation and properties of nanocellulose

Due to its versatility, biodegradability and ability to substitute petroleum-based fibres for nanoporous membranes (Lu et al. 2018), cellulose is a potential material for disposable membrane air filters. Cellulose can be extracted from lignocellulosic biomass and accounts for more than 90% of plant material and 40–45% of wood (Correia et al. 2015; Halder and Purkait 2020; Garcia et al. 2021; Stanislas et al. 2020). It is embedded in the complex network of hemicellulose and lignin and its fibrous structure plays an essential role in the structural integrity of plant cell walls (Phuong et al. 2022), as shown in Fig. 8.

The macromolecular separation of lignocellulosic compounds is known as the pulping process including delignification which is the breaking of chemical bonds of photolignin (lignin "in situ") due to the solubilisation of the lignin fragments in an organic solvent in the case of the organosolv method or in an alkaline solvent in the case of the soda and kraft

methods (Correia et al. 2015). Nanocellulose is a one-dimensional cellulosic material in the nanometer range that is usually prepared from lignocellulosic fibres and can also be extracted from bacteria, algae and tunicates (Garcia et al. 2021). Depending on the expected properties and application, cellulose pulp fibres are subjected to mechanical disintegration to obtain cellulose nanofibres (CNF) or to treatment by acid hydrolysis to obtain cellulose nanocrystals (CNCs), as shown in Fig. 7 and Table 4. Nanocellulose technology gives the filter membrane a high mechanical filtration capacity and the possibility to make them smart materials by their functionalization (Alavi 2019). Unlike nanocellulose filter membranes, cellulose pulp filters form relatively large pores due to their micrometric width, which results in low filtration efficiency against airborne aerosols (Garcia et al. 2021). In addition, the size of the nanocellulose (nanoscale, Table 4) and its high specific surface area (up to 101.8 m<sup>2</sup>/g) (Jiang and Hsieh 2015) provide a thin filter media with a high porosity (Liu et al. 2021a) and better breathability, as well as an ability to capture and absorb small particles (Chua et al. 2020; Sim and Youn 2016).



**Fig. 8** Illustration of the steps for the preparation of cellulose nanofibres and cellulose nanocrystals from agricultural biomass and wood sources. Modified from (Amorim et al. 2020; Mohammed et al. 2018; Stanislas et al. 2020)



**Table 4** Comparison between cellulose nanofibres (CNF) and cellulose nanocrystals (CNCs) properties

	Cellulose nanofibre (CNF)	Cellulose nanocrystals (CNCs)
Extraction from pulp fibres	Mechanical disintegration of plant cellulose fibres in an aqueous medium, such as homogenization, extrusion, or grinding	Various mineral acids, such as sulfuric, hydrochloric, and phosphoric acids can be used for the hydrolysis of pulp fibres to produce CNCs
Diameter	5–100 nm	5–70 nm
Length	0.5–5 $\mu\text{m}$	0.1–0.4 $\mu\text{m}$
Crystallinity Index	60–80% (Mohammed et al. 2018)	80–91% (Kusmono et al. 2020)
Mechanical properties	Young's modulus of 100 GPa to 140 GPa and tensile strength of 7500 MPa (Tavakolian et al. 2020)	Transverse modulus of elasticity of 82.3 GPa and adhesion capacity of 11.73 nN (Correia et al. 2016)
Application	Filter membrane barrier for liquid (Sehaqui et al. 2016) and aerosol (Alexandrescu et al. 2016; Sim et al. 2015; Ukkola et al. 2021) barrier	Coating of the filter membrane (Bai et al. 2018, 2019) and electrospun membrane reinforcement (Santos et al. 2022) for aerosol filtration

### Preparation of nanocellulose-based filter membrane

Nanocellulose-based filter media, which could replace petroleum-based masks and respirators (FFP2 or FFP3 for European Standards and N95 or N99 for US standards) in the filtration of airborne viruses, have been intensively developed recently around the world as an environmentally friendly solution (Liu et al. 2021a, b; Ukkola et al. 2021; Wang et al. 2019b). The preparation of cellulose nanofibrils (CNF) from cellulosic materials has several advantages such as high specific surface area, easy functionalization and high mechanical strength (Correia et al. 2016; Stanislas et al. 2022, 2020; Xiong et al. 2021), which improves the capture efficiency of small particles due to the nanoscale of the pores (Ukkola et al. 2021). Recently, CNF have been used to prepare filter media by the freeze-drying method for face masks (Mao et al. 2008; Segetin et al. 2007; Sim and Youn 2016; Ukkola et al. 2021), water decontamination (Sehaqui et al. 2016; Wang et al. 2020), battery separator (Sim et al. 2015), coating layers (Bai et al. 2019), transparent devices (Wang et al. 2020) and vehicle exhaust treatment (Liu et al. 2021a, b), as shown in Table 5. In addition, the cellulose nanofibre filter can be made by mixing it with cellulose pulp (filter pulp/CNF) (Alexandrescu et al. 2016), pulp and PET (filter pulp/PET/CNF) (Sim and Youn 2016), corrugated paper (corrugated filter paper/CNF) (Xiong et al. 2021), and filter paper (FP/CNF filter) (Wang et al. 2019b) for air filtration applications. Despite the hydrophilic character of cellulose-based materials which must be taken into account, all these previous studies strongly

recommend their application in active layers of FFRs and masks, acting as a barrier against airborne aerosol contamination (Table 5). That hydrophilic character of nanocellulosic materials is a major problem in relation to their application in face masks, as on contact with moisture, the fibre absorbs water, which could alter the structure and performance of the filter due to the low water resistance and swelling of the fibre (Stanislas et al. 2021a, b; Stanislas et al. 2021a, b). The wet mask can promote the growth of bacteria and fungi, as well as an increase of the risk of virus penetration (Zhou et al. 2020). Therefore, modification of the properties of the cellulose-based filter membrane by hydrophobic and antibacterial treatment is necessary to prevent self-contamination of the face mask user and to maintain the filtration performance and structural integrity of cellulose-based masks.

### Functionalization of nanocellulose-based filter membrane

The use of non-woven material to reduce the rapid spread of SARS-CoV-2 through the filtration barrier is a promising solution in the community despite the inability of the mask to kill the viruses, which become an additional source of contamination after disposal (Zhou et al. 2020). However, the integration of the simultaneous properties of hydrophobicity, filtration capacity and antiviral/antibacterial in a mask, particularly in a nanocellulose-based mask, offers a guarantee of effectiveness, long-term use and easy post-treatment. The abundant presence of hydroxyl groups in the cellulose structure offers the possibility

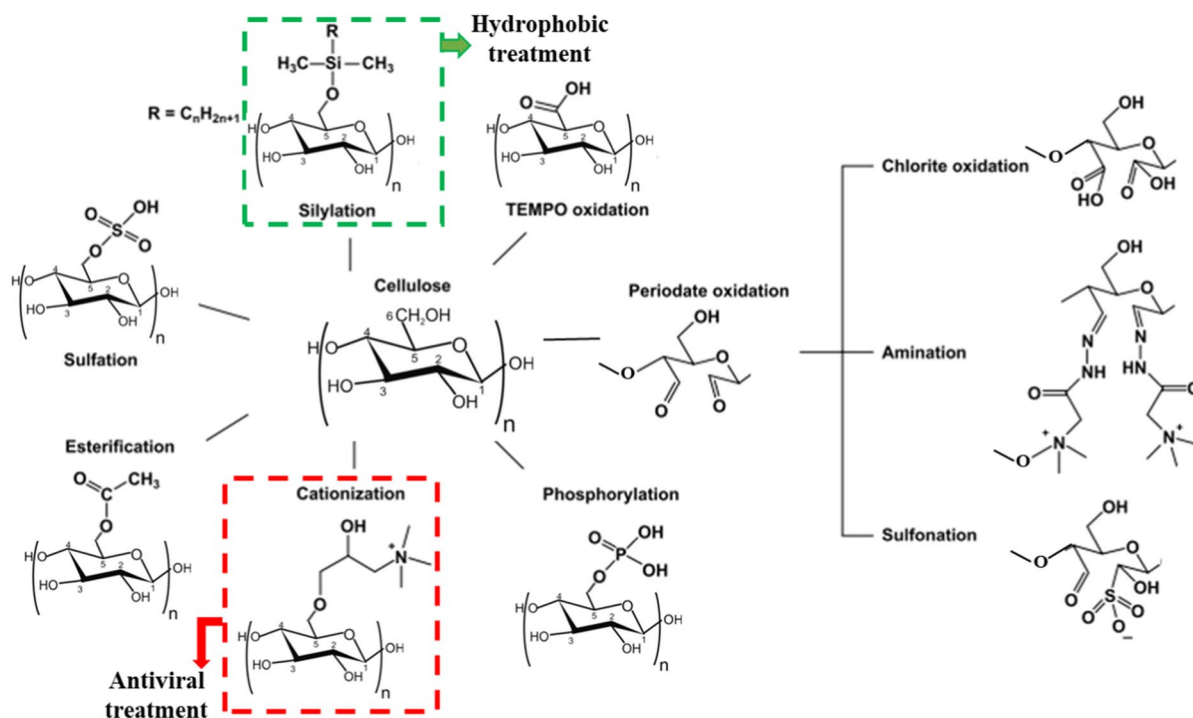


**Table 5** Preparation methods and properties of cellulose nanofibre filter membrane

Cellulose materials	Preparation methods	Properties and Applications
Fibrillated cellulose (bleached kraft pulps fibres)	Softwood and hardwood (Mao et al. 2008)	The filtration capacity of this filter is comparable to that of commercial N95 synthetic filters. Potential application for respiratory filters
	Softwood (Lu et al. 2018)	-TBA allow the separation of the microfibrils as well as the construction of a spider web structure
	softwood kraft pulp board (Ma et al. 2019)	-Capture efficiency of up to 99.07–99.78% for particles > 300 nm in diameter. Potential application for facemask
		The use of an organic solvent as a freezing medium significantly reduces the pore channel, leading to a capture efficiency of 99.66% and 99.70% for 0.3 µm and 0.5 µm particles, respectively, at a flow rate of 32 L·Min <sup>-1</sup> . Potential application for respirator to capture fine particles
Nanocellulose	CNF prepared from eucalyptus bleached kraft pulp (Sim et al. 2015)	The freeze-drying method resulted in a CNF filter media with high porosity (up to 95%) and low density compared to air drying methods. Potential application for filtration media, or battery separator
	Cellulose pulp+PET+CNF (Sim and Youn 2016)	-The inclusion of CNF improves the tensile strength and reduces the permeability of the membrane
	Cellulose NFC aerogel (Toivonen et al. 2015)	-A composite pulp/CNF membrane prepared by freeze drying achieves a particle capture efficiency of 99.944%. Potential application for air filter media
	CNF from eucalyptus pulp (Alexandrescu et al. 2016)	-Mesoporous (pore diameter 10–30 nm), -Highly transparent (transmittance > 90%) CNF aerogel membranes, -Tensile strength of 97 MPa, -Modulus of elasticity of 6 GPa Potential application for transparent and flexible devices, and gas filtration
Commercial CNFs (Liu et al. 2021a, b)		At the filtration face velocity of 5.3 cm.s <sup>-1</sup> , the filter membrane containing 0.1% CNF showed a higher quality factor. Potential application for filtration of airborne nanoparticles
		-Air filter water contact angle of 154.2°, -Porosity (up to 99.21%), -Specific surface area (26.54 m <sup>2</sup> /g), -Pressure drop = 42 Pa.

**Table 5** (continued)

Cellulose materials	Preparation methods	Properties and Applications
CNF prepared from softwood bleached pulp (Xiong et al. 2021)	<ul style="list-style-type: none"> <li>-Spray various suspensions of CNFs (varying concentrations, sizes and masses) onto the corrugated paper sheet</li> <li>-Monitor the formation of the self-assembly by a freeze-drying process</li> </ul>	<ul style="list-style-type: none"> <li>-Capture efficiency of 99.31% and 99.75% for PM1.0 and PM2.5 particles, respectively). Potential application for breathing masks, indoor air purification, and chimney exhaust</li> <li>The air filter prepared a rapid freezing rate (<math>-196^{\circ}\text{C}</math>) from lower concentrations and sizes (0.05 wt%) of CNF was able to self-assemble with well dispersed fibril networks</li> </ul>
CNC and CNF coating on filter paper (Wang et al. 2019)	<ul style="list-style-type: none"> <li>-Aqueous suspensions of CNF and CNC were prepared separately and filtered through filter paper (FP) as a substrate to produce a composite NC/FP membrane</li> <li>-Various drying conditions (solvent, pressure, temperature) were applied</li> </ul>	<ul style="list-style-type: none"> <li>-Improvement in PM0.3 capture efficiency from 6 to 95%, while maintaining a relatively low pressure drop (174.2 Pa). Potential application for facemask, industrial protection, and indoor air purification</li> <li>The membrane filter prepared from 0.1% CNF and dried under vacuum at <math>60^{\circ}\text{C}</math> showed satisfactory filtration performance (up to the level of an ultrafiltration membrane) with a capture efficiency of 97.14% and a flux of <math>46,279\text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}</math>. Potential application for advanced separation membranes for water purification</li> </ul>
CNC and CNF coated on polyethersulfone (PES) membrane (Bai et al. 2019)	<ul style="list-style-type: none"> <li>-Soaking the PES membrane in a solution of 75% ethanol and deionized water for 30 min and 24 h respectively</li> <li>-Ultrasonic dispersion of the CNF and CNC solution for 30 min before being loaded onto a PES membrane surface (2, 5 and <math>10\text{ g/m}^2</math>) at the pressure of 100 kPa</li> </ul>	<ul style="list-style-type: none"> <li>The results show that the CNF and CNC coating improves the anti-fouling properties of the PES membrane and with greater efficiency when using a CNC coating which reduces irreversible and reversible fouling. Potential application for membranes surface coating</li> </ul>
Cationic NFC from residual Pulp (Schaqui et al. 2016)	<ul style="list-style-type: none"> <li>Cationic CNF filter membrane prepared by:               <ul style="list-style-type: none"> <li>-papermaking,</li> <li>-solvent exchange,</li> <li>-supercritical drying,</li> <li>-lyophilization process</li> </ul> </li> <li>-Deep eutectic solvent pretreatment,</li> </ul>	<ul style="list-style-type: none"> <li>The CNF filter membrane obtained by the freeze-drying method has the highest porosity and robust mechanical stability compared to other drying methods. Potential application for decontamination of water</li> </ul>
Lignin-containing CNF prepared from recycled cardboard (Ukkola et al. 2021)	<ul style="list-style-type: none"> <li>-Mechanical grinding preparation of lignin-containing CNFs</li> <li>- Using two silane agents (MTMS and HDTMS) to prepare the porous membrane with CNF suspensions of 0.2–1.0% by weight,</li> <li>-lyophilization process</li> </ul>	<ul style="list-style-type: none"> <li>-For all nanoporous membranes, filtration efficiency was <math>&gt;96\%</math> for most particle sizes, with the highest value (99.5%) reported for particles <math>&lt;360\text{ nm}</math> on the membrane prepared with 0.7% of CNF</li> <li>-The nanoporous membrane composed of 0.3% by weight of CNF meets the requirements of the N95 respirator. Potential application for respirator mask</li> </ul>



**Fig. 9** Illustration of chemical modifications of cellulose fibre by various functional groups. Modified from French (2017) and Tavakolian et al. (2020)

of functionalization (Alavi 2019). Carboxyl, amino, sulphate, aldehyde, thiol and phosphate groups are the most commonly used functional groups for the functionalization of cellulose, as shown in Fig. 9. In the case of the nanocellulose-based mask, silylation and cationisation treatments are more appropriate to achieve both high hydrophobicity properties (contact angle with water reaching  $154.2^\circ$ ) (Liu et al. 2021a) and permanent ionic charges (Choi et al. 2021) for antiviral performance (Fig. 9).

During filtration, bioaerosols such as fungi, viruses and bacteria usually adhere to the surface of the filter and remain viable, posing a risk of secondary contamination as they can reproduce inside of the filter membrane (Chua et al. 2020). This accumulation of bioaerosols can lead to an increase in filter pressure drop due to clogged pore. Therefore, the development of an air filter with antimicrobial/antiviral properties for face masks is strongly recommended by authors (Choi et al. 2021; Li et al. 2018). Several antimicrobial agents (such as metal and metal oxide nanoparticles, natural products and organometallic structures) have been used by researchers to make respiratory

masks with antimicrobial activity, i.e., to eliminate viruses or bacteria or fungi in contact with the mask (Zhou et al. 2020), as reported in Table 6.

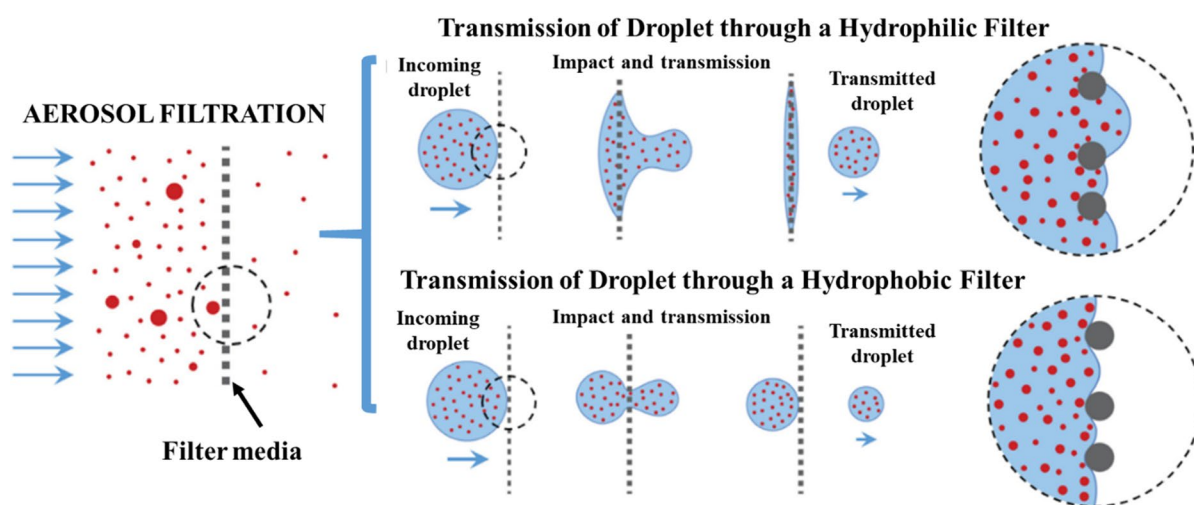
Furthermore, during the transmission of droplets across the filter membrane, hydrophobicity plays an important role in enhancing the interfacial energy barrier (Aydin et al. 2020), as shown in Fig. 10. When filters are impacted by high velocity droplets, some of them immediately crash through the pores, while another part is transmitted. In general, this process involves energy costs related to shear stresses and interfacial energies that can be influenced by droplet viscosity, filter type and filter porosity (Aydin et al. 2020).

Recently, hydrophobic modification of filter membranes has received considerable attention due to their moisture resistance properties, which can be summarised in two points: firstly, chemical resistance, as well as resistance to water absorption, can be achieved after hydrophobic treatment (Liu et al. 2021a, b) and secondly, hydrophobic treatment allows more water vapour channels to be created through pores, with low surface energy and more reactive binding sites (Zhai

**Table 6** Properties of some antimicrobial treatments for respirators

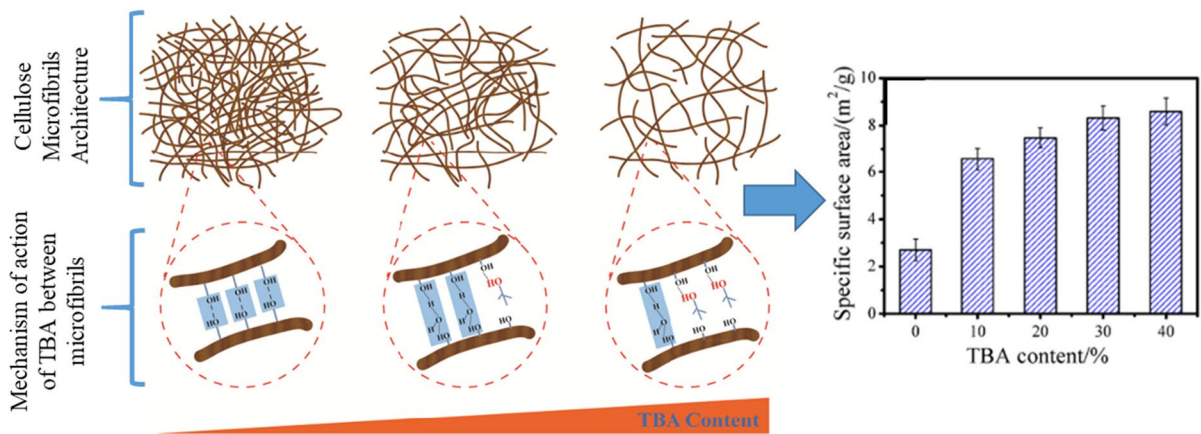
Antimicrobial agent	Microorganism removal	Preparation method	Reference
Ag NPs	Bacteria, fungi	Electrochemical	Huy et al. (2017)
CuO NPs	Virus	Surface modification	Borkow et al. (2010)
Cu <sub>2</sub> O NPs	Bacteria, virus	Chemical reduction	Hang et al. (2015)
Au NPs	Virus	Chemical reduction	Meléndez-Villanueva et al. (2019)
TiO <sub>2</sub>	Virus	Sonochemical	Akhtar et al. (2019)
Zn NPs	Virus	Surface modification	Limited (2019); Steward et al. (2018)
Citric acid	Virus	Surface modification	GlaxoSmithKline (2010); Limited (2019)
Chitosan Nanowhiskers	Bacteria, virus	Surface modification	Choi et al. (2021)

\*NPs: Nanoparticles

**Fig. 10** Illustration of the transmission interaction between large droplets carrying nanoparticles and hydrophilic and hydrophobic filter membranes. Modified from Aydin et al. (2020)

et al. 2020). Silane agents (Table 5), such as hexadecyltrimethoxysilane (HDTMS) and methyltrimethoxysilane (MTMS), are commonly used to prepare a CNF filter membrane, improving the hydrophobicity of the nanoporous membrane and promoting the cross-link of CNF (Liu et al. 2021a, b; Ukkola et al. 2021), thereby significantly improving the filtration capacity and mechanical performance of the material. Furthermore, in the preparation of cellulose-based microporous (Lu et al. 2018) and nanoporous (Liu et al. 2021a, b) filters, tert-butyl alcohol (TBA) has proven to be an effective chemical hydrophobic modification technique. The inclusion of TBA in the cellulose fibre suspension promotes the separation of the microfibrils, which results in the formation of a

regular spider web-like pore architecture during the freeze-drying process (Ma et al. 2019). This is attributed to the intermolecular bonding created between the TBA molecule and the surface of the microfibrils through hydrogen bonding interactions, which leads to hydrophobic surfaces of the microfibrils by introducing tert-butyl groups (Lu et al. 2018). Therefore, as illustrated in Fig. 11, the self-association behaviour of the microfibrils may be limited by the chemical steric obstruction effect of tert-butyl groups. Figure 11 shows that increasing the TBA content enhances the hindering effect of TBA on ice crystal growth, resulting in the structural transformation of the crystal from a thick to a thin needle-like shape.



**Fig. 11** Diagram illustrating the mechanism of action of TBA in preventing hydrogen bonding between microfibrils and the resulting increase in specific surface area. Modified from (Lu et al. 2018)

**Table 7** Comparative performances of cellulose-based air filter membrane

Reference	Production technology	Filtration capacity			Moisture resistance	Mechanical properties
		FE (%)	$\Delta P$ (Pa)	QF (Pa <sup>-1</sup> )		
Ukkola et al. (2021)	Freeze-drying	96.50	150.0	0.0020	WCA > 150 °C SC-Si = 4.8%	Dynamic compressive strength is 0.09–0.39 MPa
Liu et al. (2021a)	Freeze-drying	97.96	42.0	0.1220	WCA = 152.4 °C	
Xiong et al. (2021)	Spray coating and freeze-drying	94.6	174.2	0.0168		
Lu et al. (2018)	freeze-drying	99	< 450			
Alexandrescu et al. (2016)	freeze-drying	56	55	0.0149		Tensile strength = 10 MPa and E = 220 MPa
		46	25	0.0246		
Santos et al. (2022)	Electrospinning	95.59	9.60	0.0340		

where FE: Filtration efficiency,  $\Delta P$ : Pressure drop, QF: Quality factor, WCA: Water contact angle, SC-Si: Surface concentration of Silicon, E: Elastic modulus

### Performance of nanocellulose filter membrane

Masks and respirators are primarily used as a barrier for industrially generated particulate matter (PM) (diameter < 10  $\mu\text{m}$ ) and contaminated aerosols, such as the new SARS-CoV 2 virus (diameter between 80–150 nm), while maintaining acceptable breathability (pressure drop < 350 Pa for N95 respirator), mechanical properties and moisture resistance (Tuñón-Molina et al. 2021). Due to the shortage of commercial disposable masks and respirators

during the COVID-19 pandemic and their non-biodegradability, several researchers attempted to use nanotechnology (Table 5) to design an alternative nanoporous membrane from available biodegradable materials to meet the demand. The results show that cellulose-based materials (cellulose pulp, NFC and CNC) (Table 7) are a promising source of air filter membranes produced by electrospinning or freeze-drying, although the challenge remains to develop a uniform pore size, while maintaining a relatively low pressure drop and high moisture resistance. A



significant improvement in the mechanical properties of the polymer-based electrospun membrane by introducing CNCs has been reported in previous studies (El Miri et al. 2015; Santos et al. 2022; Peresin et al. 2010; Zhang et al. 2019). For instance, Santos et al. (2022) demonstrated that the inclusion of CNCs as a reinforcing agents in the production of electrospun PAN/CNCs aerosol filter membranes significantly improves mechanical strength (tensile strength and elastic modulus) and filtration performance, compared to pristine PAN membrane. By replacing the PAN polymer with 20 wt. % of CNCs, the filtration performance of the membrane has increased, showing potential of the material to be used as an active filter layer in the manufacture of FFRs. Table 7 shows the comparable performance of the air filter membrane made from cellulose-based materials.

## Conclusions and prospects

This study discusses potential methods for preparing a high-performance, moisture-resistant and highly breathable nanocellulose air filter membrane as an environmentally friendly solution. The worldwide availability, renewable nature, adjustable aspect ratio, ease of processing and functionalisation, strong mechanical properties, biodegradability of cellulose justify its growing interest in the production of disposable air filters to replace petroleum-based membranes. The high filtration performance (high filtration efficiency and low pressure drop) of the nanocellulose-based air filter justifies the growing interest of researchers in this material as an alternative solution to the shortage of medical masks for a cleaner solution. However, the challenge of manufacturing biodegradable masks from nanocellulose-based materials lies in the ability to design a filter membrane with a uniform pore size that is relatively smaller than the diameter of the coronavirus (50–200 nm), while retaining their breathability, mechanical properties and resistance to moisture, like commercial disposable masks. The hydrophilic nature of nanocelluloses is a major challenge for their application in air filtration. Therefore, the use of silane coupling agents or tert-butyl alcohol has proven to be effective in improving their moisture resistance. In addition, the antibacterial/viral treatment of the nanocellulose air filter is essential against

self-contamination of the mask user as well as clogging of the filter pores when the pathogen attaches to the filter surface. Although the above properties are necessary for the effectiveness of the aerosol protection capability of nanocellulose-based air filters, little research has simultaneously incorporated antibacterial and hydrophobic treatment, as well as evaluated the impact of the porous membrane production process on their mechanical properties.

Furthermore, the production of the filter membrane with a high porosity contributes to the reduction of the mechanical performance of the membrane. Therefore, the insertion of cellulose nanocrystals (CNCs) into the cellulose nanofibrils (CNF) filter membrane can help maintain the mechanical integrity of the membrane structure while achieving high porosity. In addition, the idea of incorporating sol–gel technology into the production of the cellulose nanofibre filter membrane to tailor the pore size (slightly smaller than the diameter of the viruses/bacteria) could be a viable physical screening solution for future studies.

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**Author contributions** I declare that all the authors had a significant participation in the development of this work. TTS: Conceptualization, investigation, writing- original draft; KB: Supervision, writing- review & editing, funding acquisition; RPdeOS: Visualization, writing- review & editing; CO-P: Supervision, writing- review & editing, funding acquisition; HSJ: Visualization, writing- review & editing, funding acquisition; M-AA: Conceptualization, supervision, writing- review & editing, funding acquisition.

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## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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