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Antibacterial/Antiviral Face Masks: Processing, Characteristics, Challenges, and Sustainability

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ABSTRACT

The face mask has become a part of our daily life after the emergence of SAR-CoV-2, commonly known as the novel coronavirus 2019 or, COVID-19 all over the world. On a day-to-day basis, previously the face mask has been used to filter airborne particles entering the body and affecting the respiratory system, especially by individuals in pollution-prone areas. But as the pathogens having severe acute respiratory disease-causing abilities emerge with the potential to create a pandemic, the necessity of virus/bacteria killing ability along with the filtration efficiency of the face mask has come into account. Existing ordinary face masks have filtration capacity only. Sometimes it cannot restrict particles and pathogens of nano or even micro-scale. Moreover, when it is disposed of after use, it can be a potential source of pathogen transmission. Therefore, the development of antiviral/antibacterial face masks is the need of the hour. This article focuses on the advancement of face mask processing methods, existing and promising antibacterial/antiviral agents, socio-economic sustainability, and challenges in achieving the goal of a green environment. Besides, various characteristics of the face mask like swelling and degradation properties, morphologies (SEM, FESEM), mechanical strength, antioxidant property, and antimicrobial activity are also revealed. Lastly, some future perspectives and directives are accordingly discussed with the hope that the grim of any future pandemic should not shroud us and make the world stalled again.

1. INTRODUCTION

Highly transmissible disease outbreaks have long been a cause of concern for people around the world. As the population grows and the number of people living in clusters increases, the possibility of accelerating the spreading potential of diseases. Many people die every year due to infectious diseases caused by pathogens such as bacteria, viruses, fungi, protozoa, etc. Most pandemics, such as the Russian flu of 1889 and the current COVID-19 outbreak are caused by influenza viruses and non-influenza viruses, such as Flaviviruses, Filoviridae, and Coronaviruses (COVID-19). The four contagious infections that sent shockwaves throughout the globe were influenza, Ebola, AIDS, and COVID-19 (Pullangott *et al.*, 2021).

The whole world has been experiencing the devastating effects of the pandemic COVID-19 from its first detection in 2019 to the current date. About 761 million confirmed cases and 6.9 million deaths have been recorded as of 04 April 2023 throughout the globe due to the disease (WHO Coronavirus (COVID-19) Dashboard, 2023). The World Health Organization (WHO) has advised a set of approaches, such as facial coverings, basic sanitation, and social distancing, as well as personal protective equipment or PPE for service holders and healthcare professionals ("Anti-Viral Coatings," 2020). Among the most effective ways to prevent the global spread of the Coronavirus and other highly transmissible respiratory diseases is to use face masks. The majority of surgical masks are made of polymer-based compounds, like polyester, polypropylene, and polystyrene, among others. These commercially available existing face masks have no significant bacteria or virus inactivation potential (Tuñón-Molina *et al.*, 2021). As a result, transmission of the diseases can occur by contact with the contaminated masks and these can also lead to hazardous biological wastage and serious threats to the environment. These impelled many researchers to develop face masks made of advanced materials with exclusive antibacterial/antiviral, reusable, and biodegradable properties to fulfill the goal of its sustainability.

An in-depth analysis of the face mask is provided in this paper, with a focus on antimicrobial face masks as a newly developed tool for preventing the transmission of infectious diseases. Some important categories of antimicrobial agents and the methods of incorporation are discussed thoroughly. Later on, their shapes along with other significant properties are evaluated. Waste management, environmental impacts, and sustainability of the face masks are depicted in this paper. A brief history of face masks is also presented to give a proper insight into their evolution to the readers. At last, some concluding remarks have been made as well as future directives to successfully encounter the current pandemic and also the impending ones.

2. ANTIMICROBIAL MATERIALS

A. Natural Extracts

Non-natural antimicrobial agents are effective, but they have various side effects. The creation of reactive oxygen species (ROS) is one of them. ROS are responsible for different types of cancer and the development of tumors (Cheung & Vousden, 2022). On the other hand, natural extracts have no harmful characteristics e.g. henna, cinnamon, mint, clove, portulaca, eucalyptus, garlic, eryngium, ginger, turmeric, fennel, tamarind, burdock, mallows, lemon balm, chamomile, etc.

Clove has antifungal effects against several bacteria, including *Listeria monocytogenes*, *Salmonella Typhimurium, Staphylococcus aureus, and Escherichia coli*, according to the studies (Heredia-Guerrero *et al.*, 2018; Radünz *et al.*, 2019). Clove oil's antibacterial activity begins with the clove molecule's ability to interact in the cytoplasmic membrane due to its high solubility. Then, as a result of its hydroxyl group, it causes disruption. It can then flow through the cell's hydrophilic section. After that, the hydroxyl group of clove oil can attach to the proteins in the bacterial membrane and penetrate the essential parts of the cell (Cui *et al.*, 2018). Cinnamon is effective against *Salmonella typhimurium*, *Staphylococcus aureus*, *Escherichia coli*, *Listeria monocytogenes*, *Bacillus*, *Enterococcus faecalis*, *Yersinia enterocolitica, and Pseudomonas aeruginosa* resulting from the existence of essential oil with potent antibacterial effect, cinnamaldehyde (Abbaszadegan *et al.*, 2016; Bouhdid *et al.*, 2010; Brnawi *et al.*, 2019; Reyes-Jurado *et al.*, 2020). Cinnamon essential oil inhibits Campylobacter jejuni better than other Gram-negative bacteria according to experimental findings (Friedman *et al.*, 2002). The antifungal activity of cinnamon essential oil against the cell walls of *L. monocytogenes, S. aureus, and E. coli* has been reported by other studies (Vasconcelos *et al.*, 2018). Turmeric (Curcumin) is one of the natural medicines historically utilized. It has both antibacterial and antifungal activity (Gitika *et al.*, 2019; Singh *et al.*, 2019). It also shows strong anti-cancer potential (Singh *et al.*, 2019). Some polyphenols can be found in ginger including phenolic acids, gingerols, paradols, and shogaols. Its biological characteristics, including its anti-oxidant, anti-diabetic, anti-microbial, renoprotective, anti-hypertensive, anti-ulcer, anti-inflammatory, cardiovascular, analgesic, and gastrointestinal effects, are due to these main ingredients (Daharia *et al.*, 2022; Idris *et al.*, 2019; Shalaby *et al.*, 2016; Takeuchi *et al.*, 2014). Garlic nanoparticles have also been shown to have antibacterial effects against a wide range of bacteria (Gram-positive and Gram-negative), such as *Streptococcus mutans, E. coli, P. gingivalis, and S. aureus* (Gabriel *et al.*, 2022). According to certain research, garlic has strong antibacterial and antioxidant properties due to a chemical interaction between allicin and the thiol groups of different enzymes (Huang *et al.*, 2022). Tables 1 and 2 demonstrate the antimicrobial and antiviral activities of some natural extracts based on various research results.

Table 1
Natural antibacterial agents and their effects (Parham *et al.*, 2020)

Natural Biomaterials	Minimum Inhibitory Concentration (MIC)	Antibacterial Activity Against Type of Bacteria
Cinnamon	~ 63 mg/mL	S. aureus
Clove	0.30 mg/mL	*S. Typhimurium*, *S. aureus*, *L. monocytogenes*, and *Escherichia coli*.
Turmeric	0.05 mg/mL	*B. coagulans*, *S. aureus*, and *B. subtilis*
Pennyroyal	400 mg/mL	*Klebsiella* and *S. aureus*
Tribulus	2.0 mg/mL	*E. faecali, S. aureus, P. aeruginosa*, and *Escherichia coli*
Eryngium	~ 13 mg/mL	*S. aureus*
Ginger	1 mg/mL	*S. aureus*
Thyme	~ 3 mg/mL	*Klebsiella pneumoniae*
Fennel	~ 0.13 mg/mL	*S. dysenteriae*
Chamomile	8 mg/mL	*Klebsiella pneumoniae*
Mint	64 µg/mL	*E. coli*
Mallows	0.45–0.75 mg/mL	*P. aeruginosa*, *S. aureus, and P. vulgaris*
Burdock	256 µg/mL	*S. aureus*
Eucalyptus	1000 µg/mL	*S. aureus, E. coli*
Primrose	0.07 mg/L	*Listeria monocytogenes*
Lemon balm	~ 0.30 mg/mL	*Listeria strain*
Garlic	~ 0.08 mg/mL	*E. coli*

Table 2
Natural antiviral agents and their properties (Parham *et al.*, 2020)

Natural Extracts	Antiviral Activity Against Type of Virus
Tribulus	Newcastle disease virus
Cinnamon	Types 1 and 2 of herpes simplex virus, influenza A virus
Clove	Herpes simplex and hepatitis C
Turmeric	Epstein–Barr virus
Portulaca	Influenza A viruses (H9N2)
Eryngium	HIV
Ginger	SARS-CoV-2
Garlic	Influenza B and herpes simplex
Thyme	Influenza virus
Pennyroyal	HSV-1
Fennel	Type 3 influenza and type 1 herpes simplex
Chamomile	Influenza A virus (H9N2)
Mint	SARS-CoV-2
Burdock	SARS-CoV-2
Eucalyptus	SARS-CoV-2
Mallows	Influenza virus
Primrose	Hepatitis C virus
Lemon balm	H9N2 virus, SARS-CoV-2

B. Metal and Metal Oxides

It has been observed that inorganic nanoparticles (INPs), such as metals (such as Ag, Cu, Fe, etc.) and metal oxides (ZnO, CaO, CuO, MgO, ferrites, and magnetite), have the ability to fight against strains of both Gram-positive and Gram-negative bacteria (Spirescu *et al.*, 2021).

Silver (Ag) nanoparticles inhibit a broad range of Gram-positive and Gram-negative bacteria, such as *S. typhi*, *Proteus vulgaris*, *Bacillus cereus*, *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Streptococcus agalactiae*, *M. luteus*, *Shigella sonnei*, *Aeromonas hydrophila*, *Salmonella typhi*, *Bacillus subtilis*, *Vibrio alginolyticus*, *Hafnia alvei*, *Vibrio cholerae*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Salmonella typhimurium*, *Salmonella enteritidis*, *Bacillus megaterium*, *Penicilliumitalicum*, *S. dysenteriae*, *Bacillus subtilis*, and *Listeria monocytogenes* (Anees Ahmad *et al.*, 2020; Chudasama *et al.*, 2010; Ghetas *et al.*, 2022; Hossain *et al.*, 2019; Loo *et al.*, 2018; Urnukhsaikhan *et al.*, 2021). This increased antimicrobial effects of silver at the nanoscale is caused by two factors: direct intracellular uptake of silver (Ag) nanoparticles (NPs), which results in the localized release of silver ions, and the surface-to-volume ratio to be high, which promotes the silver ion release and enables binding with bacterial cells (Li *et al.*, 2017). Different mechanisms of silver nanoparticles acting on bacterial cells are demonstrated in Figure 1.

In a previous study, partially oxidized copper nanoparticles (Cu/Cu_2O) with crystallite dimensions of 15 nm were compared to silver nanoparticles of equivalent size and fabrication technique for their antibacterial efficacy against *Staphylococcus aureus* and *Escherichia coli*. Against *S. aureus*, the antibacterial activity of Cu nanoparticles was equivalent to that of silver nanoparticles, while it was somewhat less effective against *E. coli* (Zia *et al.*, 2018). The Newcastle viral disease, Hepatitis C, and the herpes simplex virus have all been tested for the antiviral efficacy of CuO inorganic nanoparticles (Tortella *et al.*, 2022).

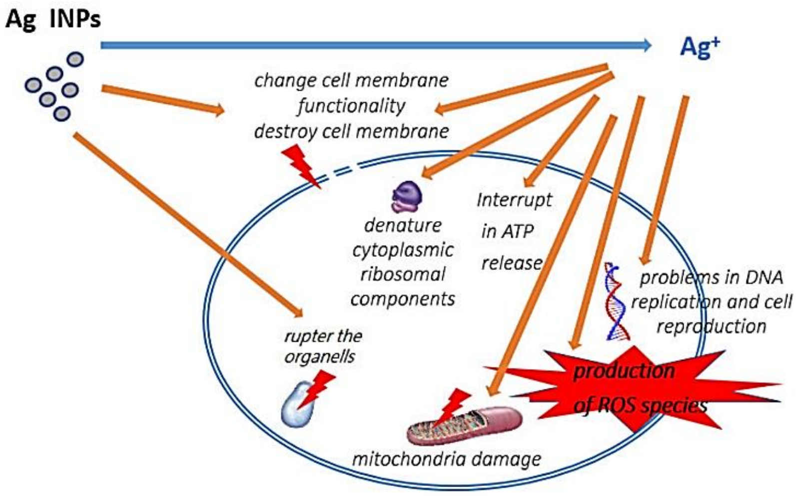

Figure 1: Antimicrobial mechanisms of silver nanoparticles (Shabatina *et al.*, 2022)

Gold (Au) nanoparticles have a broad range of action and aggressively inhibit bacterial growth. Bacterial strains which can be suppressed by Au nanoparticles include *Bacillus megaterium*, *E. coli*, *S. aureus*, *Bacillus subtilis*, *S. typhimurium*, *K. pneumoniae*, *B. subtilis*, *Mycobacterium tuberculosis*, *S. saprophyticus*, *L. monocytogenes*, *P. syringae*, *S. pyogenes*, *Mycobacterium smegmatis*, *E. cloacae*, and *P. aeruginosa* (Gu *et al.*, 2021; Kuo *et al.*, 2016; Singh *et al.*, 2020). Au nanoparticles' bacteria inhibitory effect improves as their particular surface area increases, as is common for inorganic nanoparticles. Their minimum inhibitory concentration (MIC) for *S. salivarius*, *S. sanguinis*, and *S. mutans dropped* as the particle size reduced from 90 to around 20 nm (Lavaee *et al.*, 2021). At lower concentrations, the antibacterial efficacy of shape-dependent Au inorganic nanoparticles (INP) against *Escherichia coli* and *Staphylococcus aureus* was assessed. There were three distinct forms of Au INPs used: nanocubes, nanospheres, and nanostars. The values of the bacterium strains' zones of inhibition (ZOI) reduced over time in the pattern zones of inhibition nanocubes> zones of inhibition nanospheres> zones of inhibition nanostars. The morphological inspection of the SEM images of *Escherichia coli* and *Staphylococcus aureus* (treated with Au nanostars, nanocubes, and nanospheres) revealed noticeable surface damage, disruptions, and death of cells. The formation of thicker aggregates by Au nanostars generated less surface damage. Au nanocubes displayed maximum surface damage and cell death. Gram-positive *S. aureus* cells were more resistant to cell damage than gram-negative *E. coli* cells (Hameed *et al.*, 2020). Additionally, gold nanoparticles show considerable antiviral activity against HIV, influenza A virus, measles virus, and herpes virus (Gurunathan *et al.*, 2020; Kim *et al.*, 2020; Meléndez-Villanueva *et al.*, 2019). The antiviral properties of nanomaterials are illustrated in Figure 2.

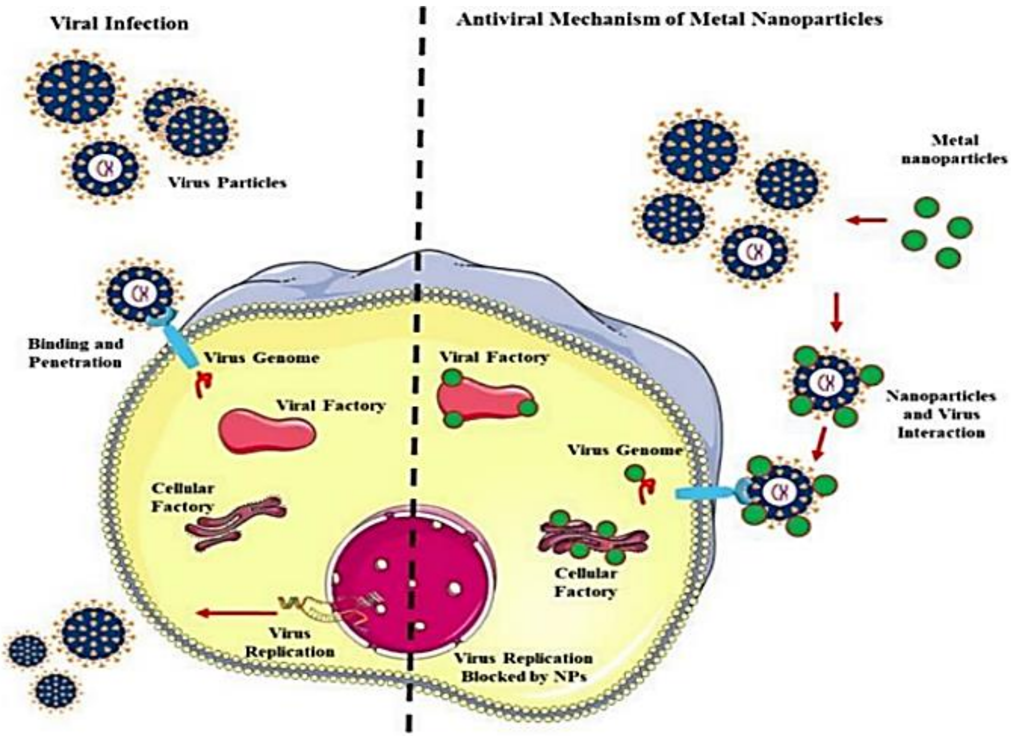

Figure 2: Schematic of the antiviral effect of nanoparticles (Gurunathan *et al.*, 2020)

Titanium oxide (TiO2) and Zinc oxide (ZnO) also inhibit a broad range of microbes. Through photocatalysis, the surface of TiO2 combines with water to produce hydroxyl radicals, which then go on to form superoxide radicals. Site-specific DNA damage is brought on by the synergistic action of the ROS on polyunsaturated phospholipids on the surface of bacteria (Huh & Kwon, 2011). When it comes to ZnO-NPs' antibacterial action, particle size and concentration are key factors. Smaller ZnO-NPs have a greater interfacial area, which increases their antibacterial activity by allowing them to readily pass through bacterial membranes (Heidary *et al.*, 2019).

C. Natural and Synthetic Polymers

Contrary to discrete molecular antibiotics, antimicrobial polymers have non-specific mechanisms for preventing pathogen growth, such as bacterial lysis, which disrupts the cell membrane as a result of different charges, whereas polymer antibiotics prevent bacterial gene transcription through receptor binding (Camacho-Cruz *et al.*, 2021). As a result, microorganisms are not developing resistance to antimicrobial polymers. Polymers are now employed to develop antimicrobial surface coatings because of their adaptable macromolecular chemistry, which helps to customize the physicochemical features of polymers (Jain *et al.*, 2014).

The cationic polymer is the most often used antibacterial agent because of the electropositively bound groups present in the polymer chain. As an antibacterial polymer, cationic polymers such as poly [2- (N, N-dimethylamino) ethyl methacrylate] (PDMAEMA), polydimethylsiloxanes

(PDMS), and poly(ethyleneimine) (PEI) are currently used. Because there is no chemical release, the biocidal activity of cationic polymer is influenced by contact (Erkoc & Ulucan-Karnak, 2021). A cationic polymer can also be derived from organic materials like chitosan, cellulose, dextran, etc. (Samal *et al.*, 2012). These natural cationic polymers, like synthetic polymers, are both biocidal and antibacterial. Fascinatingly, natural cationic polymers are biocompatible, biodegradable, and non-toxic. Additionally, by altering the reactive site, they may have their qualities increased (Farshbaf *et al.*, 2018).

Against Gram-positive and Gram-negative pathogens, amphiphilic polymers with more hydrophobic terminal groups showed substantial antibacterial activity. The antimicrobial activity of polymer (ester urethane) has also been altered by adding hydrophobic groups. Adding a hydrophobic group to an amphiphilic polymer, like poly (ester urethane), has also altered its antimicrobial activity (Peng *et al.*, 2019). Unfortunately, as the hydrophobic groups grew, so did the polymer's toxicity to mammalian cells, which is also in line with a discovery made in a research by Cuervo-Rodrguez *et al.* (Cuervo-Rodríguez *et al.*, 2020). Surfactant, one of the amphiphilic molecules, can be cationic, amphoteric, anionic, or non-ionic according to the polar head charge.

The antimicrobial activity of surfactants against many microorganism species has been demonstrated (Figure 3). In one instance, a cationic surfactant aggregate containing amide fragment was able to damage *Escherichia coli*'s ability to form a protective barrier while being just marginally hazardous to mammalian cells (Zhou *et al.*, 2016).

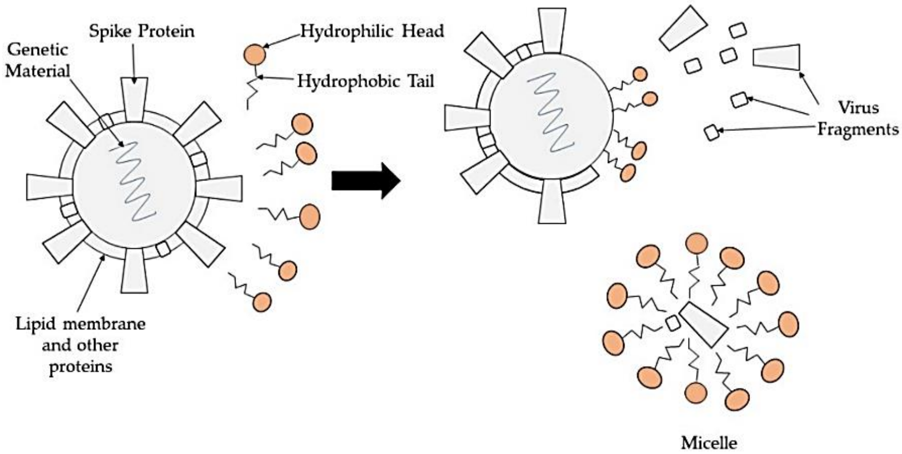

Figure 3: Surfactants' method of viral inactivation (Nasri *et al.*, 2021)

D. Other Agents

Surgical mask surfaces can become more hydrophilic when treated with saline (NaCl), which facilitates microbial adherence. The swine flu virus and other strains, such as different strains of HA hemagglutinin, were more resistant to infection in mice subjected to virus aerosol made from saline-treated filters in in-vivo trials (Quan *et al.*, 2017).

Graphene has been an extensively utilized nanomaterial for several purposes, including antibacterial uses, since its discovery in 2004. In 2010, the initial study on graphene's antibacterial properties was released. Statistically, 85 µg/mL of graphene oxide resulted in an approximate 98% decrease in the amount of *Escherichia coli* from a starting load of around 110 CFU/mL (Hu *et al.*, 2010). By bio-reduction, graphene and graphene oxide degrade the virus' lipid membranes and release its RNA (Song *et al.*, 2015). A fullerene is an allotrope of carbon that acts as an antioxidant and antiradical (Gacem *et al.*, 2020). Another investigation conducted in 2011 revealed that C70-fullerene derivatives have high solubility in water and antiviral action over the HIV and H1N1 viruses. C70-fullerene is a fullerene molecule made up of 70 carbon atoms (Kornev *et al.*, 2011). Another member of the family of carbon-based nanoparticles, carbon dots (CDs), often referred to as C-dots, have smaller dimensions up to 10 nm in diameter. Recently, human Huh-7 liver cells were used to demonstrate the antimicrobial property of 4-aminophenyl boronic acid-functionalized carbon dots against human coronavirus (HCoV) infections (Łoczechin *et al.*, 2019). Viruses such as JEV, DENV, and ZIKV were all successfully combatted using benzoxazine-monomer-derived CDs (S. Huang *et al.*, 2019). Another form of carbon-based filamentous nanomaterial known as functionalized multiwall carbon nanotubes (MWCNTs) has shown strong viral suppression against HIV. This study found that the influence of the nanoparticles' hydrophilicity and dispersibility was crucial in regulating the antiviral property of MWCNT-based nano-materials. Contrary to pristine multiwall carbon nanotubes, carboxylated MWCNT and drug-conjugated multiwall carbon nanotubes (MWCNT-C-CHI36) had a strong antiviral effect (Iannazzo *et al.*, 2015).

3. PROCESSING METHODS

A. Electrospinning Method

Electrospinning is a fiber production technology that uses an electric field to pull charged threads of polymer solutions with diameters of around a few hundred nanometers. Positive and negative charges are provided at the collector and nozzle, respectively, enabling the charged jet of polymer solution at the tip of the syringe (nozzle) and generating a Taylor cone. Through the nozzle, charged polymeric fluid is sprayed and dragged by electrostatic force (El-hadi & Al-Jabri, 2016; Keavey, 2004). Radial charge repulsion causes the flow of the jet to break into several fine filaments when it speeds up in the electrical field. This process is known as "splaying," and it produces polymer-based electrically charged nanofibers that are obtained at the collector (Chinnappan *et al.*, 2022). The fiber diameter ranges from around 100 nm to 500 nm. Both the morphological and mechanical properties of nanofibers are primarily influenced by both electrostatic forces and the viscosity of the polymer solution (Subbiah *et al.*, 2005). The physical shift that occurs during electrospinning is depicted in Figure 4. To study the relationship between fiber diameter and volume charge density, Stepanyan *et al.* developed a fluid jet model inside an electric field. The diameter of the end of the jet that the model predicts is the outcome of a balance between normal stresses imposed by both surface tension and the charge repulsion of the surface (Hoque *et al.*, 2018; Stepanyan *et al.*, 2014). Another research by Lou *et al.* utilized the electrospinning method to fabricate patterned nanofibrous membranes using polyacrylonitrile polymer. To make the patterned membrane, the bulge patterned mesh was employed as the collector. When compared to a nanofibrous filter, they found that even while the pressure drop decreased from around 152 to 25 mm H2O, the filtration efficiency only decreased from approximately 99.9% to 96.3% (Lou *et al.*, 2017).

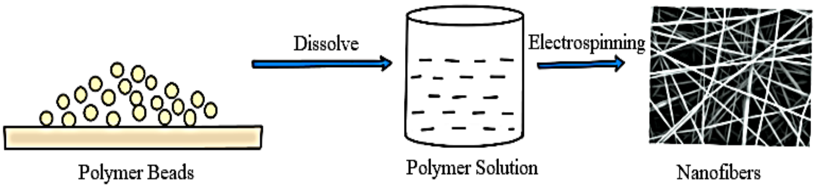

Figure 4: Physical transformation happening during the Electrospinning process

The production of patterned nanofibers is crucial for air filtration applications since it helps to minimize pressure drop and preserve filtering performance. The number of nanofibers depends on the specific polymer and the desired filtration quality. In general, between 0.5 and 5 g/m2 have been utilized, depending on the required level of filtration efficiency and the type of application (Leung & Sun, 2020). The results indicate that the electrospinning method may be viable for fabricating a nanofibrous matrix that can be employed in the fabrication of filters to handle dangerous extremely fine particles and microbes, even viruses (e.g., coronavirus). A study conducted by Lackowski *et al.*, suggests that these nonwoven mats have greater filtration effectiveness for submicron to nanoparticles, with a filtering efficiency of 99.9% for particles of size as minute as 0.3 microns (Lackowski *et al.*, 2011). This extremely high filtration efficiency is due to the creation of charged filters which is in turn attributed to the presence of electrostatic force. Electrospinning is suited for the majority of natural polymers such as chitosan, dextran, alginate, gelatin, silk fibroin, collagen, and polymers of synthetic nature such as polyamide, polyurethane, PET, PAN, and PVC. However, Polyvinylidene fluoride (PVDF) and Polyvinyl chloride (PVC) are two of the most prevalent polymeric compounds (Adanur & Jayswal, 2022; Esmaeili *et al.*, 2019).

However, nanofiber membranes are naturally highly porous; hence, their tensile strengths are poor. Typically, an efficient support fabric (e.g., polyethylene, polypropylene, or polyethylene terephthalate) is utilized, and electrospun fiber is collected on a support fabric stretched over an aluminum collector plate. On top of the nanofiber film, another polyester nonwoven is layered, and a heat-setting is performed to generate a firm mask (Naragund & Panda, 2022). Figure 5 depicts the steps involved in manufacturing the electrospun nanofiber for the face mask.

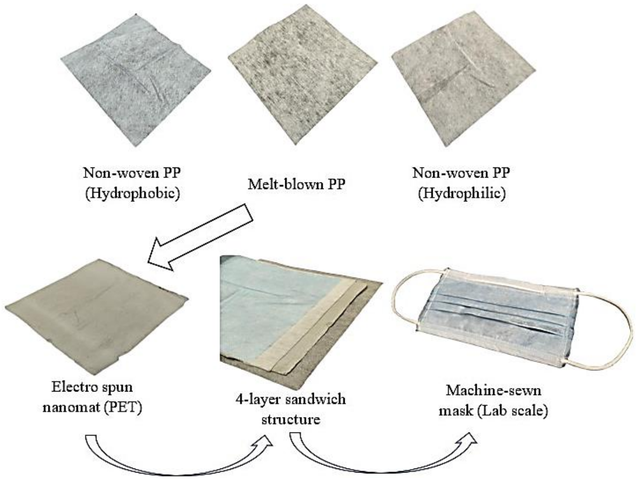

Figure 5: Step-by-step manufacturing process of a face mask (Lab scale) using electrospun nanofibrous membrane

B. Meltblown Method

While electrospinning is highly recognized for fabricating fibers with reduced diameters that can bolster particle filtration efficiency, it is important to underscore that this method is not the primary technology employed in commercial face mask production. In contrast, the pivot to melt blowing technique signifies a foundational aspect of contemporary mask manufacturing, owing to its extensive usage and high effectiveness. The majority of layers in commercial face masks are crafted using the melt-blown technique (Adanur & Jayswal, 2022), solidifying its pivotal role in creating effective filtration barriers.

Typically, the electrospinning method is used to fabricate fibers with small diameters, ranging from micron to nano scale, which can then be used to improve particle filtration efficiency. However, electrospinning provides a relatively low production rate, and thus the industrial upscaling for mask fabrication becomes costly (Uppal *et al.*, 2013). Thus, the inclusion of nanofibers into face mask filter media was therefore explored via a range of techniques such as combining nanofibers with relatively larger fibers. The melt-blown method is an example of such an alternative (Uppal *et al.*, 2013). An extruder die with several small nozzles, blows melted thermoplastic polymer onto a conveyor to produce a fine fiber that forms self-bonding networks (Figure 6). The fibers produced by this process have comparatively small diameters, ranging from 1 mm to 5 mm and, as a result, their pore size is significantly smaller; making the fiber exceptional in terms of filtration efficiency (Bresee & Ko, 2003; Soltani & Macosko, 2018). Consequently, this technology is primarily employed for the manufacturing of nonwoven fibers for a variety of filtering applications, including surgical face masks, respirators, liquid filters, etc. Additionally, by incorporating superabsorbent polymer (SAP) into melt-blown nonwoven fibers, it is feasible to enhance particle capture efficacy, sanitary comfort, and capacity of air moisture absorption (Brochocka, 2017). During the manufacturing of the fibers, factors such as airflow varieties, polymeric varieties, die-to-collector distance and angle, temperature and the rate at which the polymer is ejected have a role. Generally, polybutylene terephthalate, polyethylene terephthalate, and polypropylene are used to fabricate fibers by this method (Bhat, 2015).

In a new model, designed by Pu et al, an additional electrostatic field was introduced directly to the traditional melt-blown spinning head. This approach not only reduced mean pore size from 33.42 μm to 29.29 μm but also lowered the mean fiber diameter of polypropylene microfibers from 1.7 μm to 0.95 μm. As a direct consequence, the fiber size dispersion is narrower, resulting in improved filtration efficiency (Pu *et al.*, 2018).

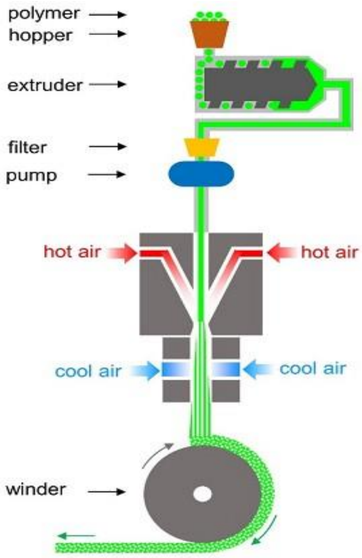

Figure 6: The representation of the manufacturing method of fiber by the melt-blown process [Reconstructed and adapted from (Pabjańczyk-Wlazło *et al.*, 2022)]

C. Spun Bonding Method

The spun bonding method is illustrated in Figure 7. The spun bonding method includes a polymer melt/solution feed, an extruder, a metering pump, a die assembly, filament spinning, web formation, bonding zone, and winding. The nonwoven fiber in the spun bond method is composed of a continuous bundle of filaments which is first spun, then the fibers are laid on a net to make a web form and lastly, fibers are embossed through heat bonding. The fabricated spun-bonded fabric has a high tear strength and a fiber diameter ranging between 1 and 50 μm with a random fibrous structure (Midha & Dakuri, 2017). Nonwoven fabrics become more porous when the fiber diameter is reduced, resulting in a more homogeneous distribution of fibers, which enhances particle capturing (Rahman *et al.*, 2022). Polypropylene, polyethylene, nylon-6, polyester, and polyamides, among others, are ideal polymers for the spin bonding method (Yan, 2016). Particularly, polypropylene is one of the most commonly used polymers in the fabrication of spun-bonded nonwoven fibers, as it is reasonably inexpensive and provides a higher yield than other polymers (Adanur & Jayswal, 2022; Arvidson *et al.*, 2010).

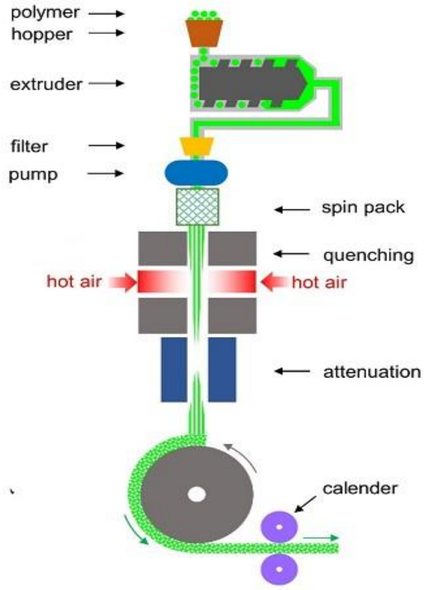

Figure 7: The illustration of the spun bonding process [Reconstructed and adapted from (Pabjańczyk-Wlazło *et al.*, 2022)]

D. Electret Technology

Even though electrospinning, melt-blown, and spun bonding methods are widely used for the processing of facial masks, these filtering technologies cannot provide appropriate protection over SARS-CoV-2 and viruses in general. Since they have a high filtration efficiency, cost-effectiveness, and minimal pressure drop, electret filters are commonly employed for particulate matter (PM) filtration and virus defense (Thakur *et al.*, 2013). Using a transmission electron microscope (TEM), the size of the SARS-CoV-2 was determined to be within 60 and 140 nm and is comparable to the common influenza virus (H1N1 and H3N2 strains) which has a mean diameter of 100nm. Assuming that the SARS-CoV-2 virus is negatively charged, applying electrostatic charges to the nanofibers is a helpful way to improve filter performance at the same time, ensuring a high level of breathability. The corona charging electret instrument consists of a high voltage power supply, a collector electrode, and a needle electrode.

The illustration of setup is illustrated in Figure 8 The parameters- charging distance, applied voltage, and charging time immensely influence the charging properties (Zhang *et al.*, 2020).

Leung has recently produced polyvinylidene fluoride-charged nanofiber membranes utilizing electret technology (Leung & Sun, 2020). The addition of positive charges to the PVDF fiber matrix can increase filtration efficacy by employing electrostatic attraction, without affecting the pressure drop, as the increase in fiber yield is a result of the positively charged fibers attracting negatively charged smaller-sized particles.

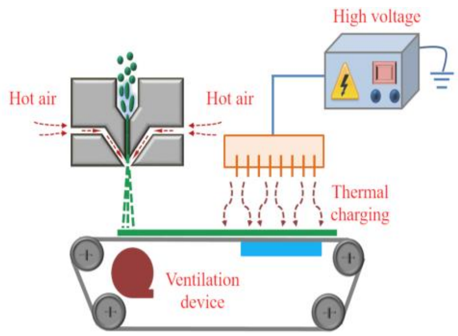

Figure 8: The set-up of the fabrication procedure by electret-melt-blown technology (Zhang *et al.*, 2020)

Table 3
Comparison of different mask manufacturing methods

Manufacturing Methods	Pros	Cons	Common Uses
Melt-blown	• Efficient filtration due to fine fibers • Suitable for fine particle capture • Well-established technology • Can incorporate additives for enhanced • Filtration properties	• May require additional treatments for enhanced functionality • Limited scalability for high-volume production • Energy-intensive process • High initial equipment costs • Limited materials versatility • Quality control challenges	• Outer and inner layers of medical and N95 masks • General-purpose face masks
Electrospinning	• Produces ultrafine fibers • High surface area-to-volume ratio • Customizable for different materials • Can create intricate structures	• Slow production rate • Complex equipment setup • Labor-intensive process • Limited scalability for mass production	• Specialized filtration layers in high-performance masks • Research and development of advanced filtration materials
Spun bonding	• Suitable for disposable applications • High production rate • Cost-effective • Durable and strong fibers • Versatile material compatibility	• Larger fiber diameters • Relatively lower filtration efficiency • Limited fine particle capture • Limited ability to create nanofibers	• Outer layers of surgical masks and non-medical disposable masks • Nonwoven fabrics for various applications
Electrtet technology	• Enhanced filtration efficiency • Captures particles through electrostatic attraction • Can be used in combination with other materials for improved performance	• Shorter effective lifespan • May degrade with time and use • Complex manufacturing process • Requires proper charging and maintenance	• Used in combination with other methods to enhance filtration efficiency • N95 and higher-grade respirators

4. ANTIMICROBIAL FACE MASK PROCESSING ADVANCES

The landscape of face mask manufacturing has undergone a remarkable evolution, particularly in the integration of antimicrobial properties, which has substantially enhanced their efficacy and protective capabilities. This section delves into pivotal research endeavors that have propelled the development of advanced antimicrobial face masks, focusing on the manufacturing techniques.

A study led by Kwon *et al.* (2021) conducted a research for creating antimicrobial and antiviral coatings. Conventional methods often face challenges related to uniformity and adhesion, which this research addressed by harnessing gallium liquid metal (LM) particles to facilitate the deposition of liquid metal copper alloy (LMCu) particles onto fabric surfaces. Beyond improvements in adhesion, this approach exhibited remarkable efficacy against a spectrum of pathogens, including bacteria, fungi, and viruses. The incorporation of gallium liquid metal acted as nucleation sites for the formation of LMCu particles, which showcased rapid and effective pathogen eradication within a mere 5 minutes of contact (Kwon *et al.*, 2021).

In another approach, Valdez-Salas *et al.* (2021) detailed a method to amplify the antimicrobial properties of surgical masks. By incorporating silver nanoparticles, researchers established an effective means of reducing microbial presence across a broad range of pathogens. Notably, the nano-formula demonstrated superior microbial reduction of 99.999% against a wide array of microorganisms. The technique effectively impregnated the masks with silver nanoparticles, contributing to prolonged antimicrobial efficacy and creating a protective shield against pathogens.

Presenting a sustainable and scalable method, Chen *et al.* (2023) conducted a study leveraging a water-mediated approach. The researchers harnessed copper iodide (CuI) nanoparticles, which were synthesized in situ on flexible cotton fabrics. This approach not only showcased potent antimicrobial efficacy but also minimized environmental impact by employing water as the processing solvent. The coated cotton fabric exhibited rapid pathogen inactivation within minutes, highlighting the technique's viability for large-scale adoption while underscoring its environmentally conscious nature.

Taking advantage of electrospinning technology, Salam *et al.* (2021) explored nanofiber-based hybrid nanocomposites. By ingeniously integrating Viroblock, polyacrylonitrile (PAN), and zinc oxide (ZnO), the researchers crafted nanofiber sheets exhibiting exceptional antibacterial and antiviral performance. The electrospinning process allowed precise distribution of functional components, enhancing their interaction with pathogens. This composite's unique structure and materials synergistically contributed to its efficacy against a broad spectrum of pathogens, positioning it as a viable and promising candidate for personal protective equipment.

Elevating the field even further, a study by Chen *et al.* (2022) introduced a technique for fabricating nanofibrous membranes tailored for medical masks. By incorporating plant extracts and nanoparticles, the study harnessed electrospinning to develop a material with enhanced antimicrobial and antiviral attributes. This technique facilitated even the distribution of functional components across the nanofibers, maximizing their effectiveness in pathogen inactivation.

Lastly, Zhao *et al.* (2023) presented an innovative approach to manufacturing biodegradable and self-disinfecting collagen fiber network masks. The method encompassed the modification of collagen fibers with tannic acid, which enabled in situ production of silver nanoparticles. This novel manufacturing process not only exhibited exceptional particulate and pathogen removal capabilities but also integrated wireless breath monitoring, thereby bridging health protection and real-time tracking seamlessly.

These studies collectively underscore the significant role of innovative manufacturing techniques in advancing antimicrobial face mask production. From novel deposition methods to sustainable fabrications and precision engineering, these approaches collectively contribute to the evolution of protective facewear, offering enhanced defense against emerging health challenges while embracing sustainability and practicality.

5. CHARACTERISTICS

A. *Morphology of Fibers and Breathability*

Fiber morphology, particularly fiber diameter directly correlates to the filtration efficacy of the facial mask. Among the respirable range of particle sizes which is below 100 µm, particles ranging from 5-10 µm can just reach the lungs, while particles less than 5 µm can accumulate deep within the pleura of the lungs (Pippin *et al.*, 1987).

In addition, in the case of microbes released into the atmosphere by an infected host, droplets of size between 5 µm and 12 µm are expelled after sneezing or coughing, and particulates of virus less than 5 µm in size are exhaled during speaking or even breathing. Especially in the case of SARS-CoV-2, the size ranges between 0.07 to 0.9 µm (Lin *et al.*, 2021). In contrast, the average size of *Mycobacterium tuberculosis* is approximately 5 µm, indicating that they are approximately 60 times larger than SARS-CoV-2 (Fennelly, 2020).

As previously discussed, fibers fabricated through electrospinning are the most desirable fibers with the least fiber diameter. In the study by Bai *et al.*, the size distribution of electrospun fibers is narrow, with an average size ranging from 616 nm to 890 nm for poly (methyl methacrylate) (PMMA) fibers (Bai *et al.*, 2016) as shown in Figure 9.

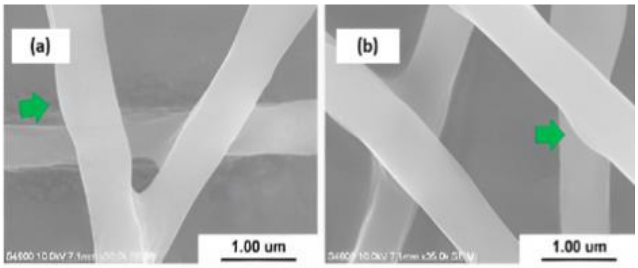

Figure 9: Comparison between the SEM images of electrospun nanofibers with (a)PMMA–DCDMH, (b)PMMA–DBDMH [Reprinted with permission from (Bai *et al.*, 2016), *Copyright 2016, American Chemical Society*]

The second most crucial performance for face masks is breathability. Not only must the polymeric filters operate as a barrier against viruses, bacteria, and dust particles, but they must also ensure convenient breathability. Standard testing methods for breathability include the quantification of the difference of pressure between known upstream air pressure and the downstream air pressure of the experimental mask following EN 14683:2019 (Jones & Rempel, 2021). Before testing, test samples must be conditioned at around 21 °C and approximately 85% relative humidity for a minimum of 4 hours. The flow rate (8 Lpm) is kept constant and is forcefully flown through the mask with a circular section of 25mm diameter (Tessarolo *et al.*, 2022). The pressure difference is calculated with the help of a pressure transducer which computes the differential pressure as the fraction of the pressure drop by the area of the surface (in cm2) of the material. The standard surface area of the material is taken as 5 cm2. The complete process should be conducted on at least 5 different regions of 5 different masks, and the conclusions must be based on those findings and computed as the average measurement value.

A decrease in breathing resistance suggests a higher level of user comfort (healthcare professionals, patients, and the general public). It indicates that the face mask allows for easy breathing.

B. Filtration Efficacy

The filtration process of filter fibers relies on interception, and physical filtration mechanisms including diffusion, gravitation, inertial impact, and electrostatic attraction. Evidently, in the particle filtering process when fiber pore size (from 100nm to 1 μm particle size) is smaller or equal to the particle size, interception occurs (Behera & Arora, 2009). There are a variety of parameters that can be used to demonstrate the filtration efficiency of filter material, depending on the particles being measured: viruses, bacteria, and particles. They can be categorized mainly by virus filtration efficiency, bacterial filtration efficiency, and particle filtration efficiency (Whyte *et al.*, 2022).

For PFE testing the test apparatus was designed following the NIOSH procedure for evaluating the filtration efficiency of respirators. This procedure involves pumping aerosolized NaCl particles through the sample material at 85 Lpm. Upstream and downstream of the respirator filter, particle concentration is measured with photometers, and the filtration efficiency is calculated as the percentage of particles blocked by the filter (Long *et al.*, 2020). On the other hand, the BFE test measures the performance of bacterial filtration of face masks as per the EN 14683:2019 protocol (Mezzer & N, 1973). An *S. aureus* aerosol chamber is used to get a similar bacterial growth. Testing the viral filtration efficiency (VFE) of the face masks determines whether the mask is capable of removing virions. Viruses are the smallest bioaerosol. Using a viral aerosol instead of a bacterial aerosol, the viral filtration efficiency test follows the same process as specified by EN 14683 for BFE. The filtration efficacy of certain nanofiber face masks commercially available is depicted in Table 4.

Table 4
Filtration efficiency of nanofiber masks currently available in the market

Name of the product	Country of origin	Particulate filtration efficiency (PFE) (%)	Bacterial filtration efficiency (BFE) (%)	Virus filtration efficiency (VFE) (%)	Material	URL
SonoFace	Israel	>98% (5 μm)		The number of viruses similar to SARS-CoV-2 has been reduced by 6 $\log_{10}$	Metal-oxide NP such as ZnO and CuO	*https://www.sonoviatech.com*
ViriFace	Israel	-		-	-	*https://www.virimask.com*
NASK nanofiber smart mask	China	>99%	~ 99.9% *Staphylococcus aureus*	~ 99%		*https://www.nask.hk/en*
Inofilter® fabric by Inovenso	Turkey/ USA	>99% of NaCl particles (0.26 μm)	> 99.8%	> 99% of bacteriophage (3 μm)	PVDF ~ 0.8 g/m^2	*https://www.inovenso.com/inovenso-inofilter-v*
Carbon RespiPro Half mask	Czech Republic	~ 98.4%, 0.26 μm NaCl particulate	-	-	PA-6, Activated Carbon fiber (45 g/m2)	*https://www.respilon.com/products/r-mask/home*
FNM RespiNano mask	Iran	>99%	-	-	-	*https://en.respinano.com*
Respilon 57 Antismog Scarf	Czech Republic	99% diesel smog	~ 99.9% *S. aureus*	~ 99.9%	PVDF (~ 10 μm thick)	*https://product.statnano.com/product/9921/respilon-r-shield*
Noveko™ RD2 respirator	Canada	-	99.8% *S. aureus, K. pneumonia*	99.7% H1N1, H5N1	-	*https://www.newswire.ca/news-releases/html*

C. Breathing Resistance

Even though a face mask must have a high particle filtering efficiency, it must also have a low breathing resistance for comfort. To minimize breathing resistance, the face mask must be air-permeable without compromising its effectiveness as a particle filter. Breathing resistance is measured by inhalation and exhalation following EN 149:2009, and it is a standard criterion for evaluating respirators such as FFR, FFP1-3, N95, and KN95 (Wang *et al.*, 2022). The assessment must begin with mask conditioning, specifically heating and cooling cycles at 70 °C that extend up to 24 h then -30 °C for another 24 h respectively, with at least 4 h of rest interval between the two phases. Using the combination of a Sheffield head and a digital lung with saturated air at a temperature of 37±1°C, 25 cycles per minute and a 20-minute wearing simulation must be done at least 10 times. Before experimenting, the detection device's airtightness and operational status must be double-checked and the system resistance of the detection device must be calibrated to 0. The inspiration and expiration tests must be performed using a simulated lung. Inhalation tests require two distinct airflows: 30 L/min as well as 95 L/min, whilst the expiration part takes into account 160 L/min only. The maximal respiratory resistance which is expressed in mbar/Pa is dependent on the mask varieties provided in Table 5.

Table 5
Maximum Inhalation and Exhalation Value of Breathing Resistance following the EN 149:2009 (expressed in mbar/Pa) (Otrisal *et al.*, 2021)

Type of mask	Inhalation		Exhalation
	30 L/min	95 L/min	160 L/min
FPP1	0.6/60	2.1/210	3.0/300
FPP2	0.7/70	2.4/240	3.0/300
FPP3	1.0/100	3.0/300	3.0/300

D. Antibacterial Activity

Bacteria have an average size of 1 µm to 5 µm, thus surgical masks with the least average pore diameter have the maximum bacterial filtration efficiency (BFE). The BFE of the face mask is computed by comparing the viable bacteria count at a certain period with the total viable bacteria count (Li *et al.*, 2006). The BFE values of various commercially available masks are shown in Table 4. However, the efficacy of bacterial filtration of a conventional disposable face mask with a 95% microbiological barrier decreased significantly after 4 hours of use, increasing the possibility of the spread of diseases (Barbosa & Graziano, 2006). Face masks treated with antibacterial substances could not only minimize the risk of disease transmission but also enhance the masks' durability. These antibacterial chemicals should block a broad spectrum of germs, be toxin-free to the user, prevent irritations, be hypoallergenic, and be effective with no detrimental impacts on the overall performance or look of these surgical masks. Both gram-positive and gram-negative bacteria such as *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas fluorescens*, *Streptococcus faecalis*, *Klebsiella pneumoniae*, and *Enterobacter aerogenes* among others, have been examined to determine the antibacterial activity of surgical face masks A recent investigation showcased the enhanced antibacterial efficacy achieved by introducing coffee grounds into polypropylene surgical face masks, particularly effective against gram-positive bacteria (Kalebek, 2022). The majority of closely related studies have been dedicated to exploring various antibacterial agents, including well-established choices like metal nanoparticles (Ansari *et al.*, 2020; Bolaina-Lorenzo *et al.*, 2022; Hiragond *et al.*, 2018; Li *et al.*, 2006), quaternary ammonium compounds (QAC) (Purwar *et al.*, 2016; Schrank *et al.*, 2020; Tseng *et al.*, 2016) and N-halamines (Demir *et al.*, 2015; Majchrzycka *et al.*, 2012; Ren *et al.*, 2018), all renowned for their proven antibacterial attributes. These studies collectively explore the integration of such compounds into face mask materials, with a primary focus on bolstering antibacterial activity while ensuring compatibility with mask biocompatibility and filtration efficiency requirements. Among metal composites incorporated in face masks for antibacterial effect, CuO and ZnO displayed quality performance against both gram-positive *Staphylococcus aureus* and gram-negative *Escherichia coli* without compromising the biocompatibility of the face masks. Additionally, antimicrobial electrospun air filtration membranes from polymer components (Y. ; Zhou *et al.*, 2022) such as Sericin/PVA/Clay (Purwar *et al.*, 2016) have demonstrated both high filtration efficiencies and good antimicrobial activity.

E. Antiviral Activity

Due to the steady increase in the number of SARS-CoV-2 cases, there is an urgent need for face masks that effectively prevent the spread of the virus. SARS-CoV-2 vesicles have a 3D circular shape with diameters less than 100 nm (Lin *et al.*, 2021). Due to their large pore size, the vast majority of prevalent face masks are incapable of protecting against such airborne viruses. Therefore, the addition of an antiviral component to masks, in addition to their filtering-out properties, would be extremely beneficial. Various antiviral agents can achieve antiviral potency through both direct and indirect sterilization and receptor inhibition. Natural viral inhibitors (Lin *et al.*, 2021; Yu *et al.*, 2012), conjugated polymers (Monge *et al.*, 2020), metal and metal oxide nanoparticles (Jung *et al.*, 2021), NaCl (Schorderet Weber *et al.*, 2022), graphene oxide, graphite oxide (Liu *et al.*, 2011), polyethyleneimine (Umar *et al.*, 2021), polyphenolic compounds (Tavassoli-Kafrani *et al.*, 2017) and silica composite (Balagna *et al.*,

2020) are some of the described agents. A preferred surgical face mask material would simultaneously filter and inactivate the viruses. The VFE of the commercially available masks are presented earlier in Table 4.

6. SUSTAINABILITY

Multiple approaches have been used to make face masks multifunctional, such as increasing filtration ability and inclusion of additional functions and properties into it. Various materials have been coated/incorporated with the face mask to make it resistant to different potential microbes. It has been suggested that face masks' antibacterial properties can be enhanced by combining metallic NPs and colloids with other nanomaterials, for example, carbon nanotubes (CNTs) and graphene (Pei *et al.*, 2013; Zhao *et al.*, 2017). It is anticipated that licorice nanofibers can be put together to provide more defense against COVID-19 and other related viruses (Chowdhury *et al.*, 2021). A triboelectric nanogenerator (TENG)-formed layer-by-layer filter has been proposed as a novel strategy for multifunctionality in face mask development, in which the outside layer serves as an electrocution layer and the inner three layers operate as triboelectric (TE) filters. Viral particles would be shocked by the electric field generated by contact electrification at the electrocution layer. To determine the effectiveness of the mask design, triboelectric materials such as latex rubber-PU, polyvinyl chloride (PVC)-nylon, polyimide (PI)-nylon, and polypropylene (PP)-polyurethane (PU) have been investigated. The triboelectric filter materials may experience enough stress to provide enough electric power to turn on the electrocution layer. The suggested mask may be self-generating, getting its energy from the user's breathing, talking, or other pertinent facial expressions. By electrocuting the charged virus particles, the accumulated charge can generate a strong enough electric field to turn their outside proteins inactive (Ghatak *et al.*, 2021).

Globally, businesses are vying to develop new antimicrobial face masks that they claim to be safer, more efficient, and environmentally friendlier than those currently on the market. The face mask market is influenced by several variables, including consumer demand, the number of face mask manufacturing facilities, the prevalence of lung diseases and awareness of consumer health, investments in the health sector, novel product introductions, and the availability of face masks. Based on usage (reusable, disposable), end-use (public, healthcare workers), and geography (Europe, North America, Latin America, Asia Pacific, Africa and the Middle East), the market has been categorized. Zion, a business consulting firm, has examined the international PPE market environment, with a focus on the face mask industry. According to the analysis, the N95 face mask had a market value of roughly 822.6 million USD in 2019 and is expected to bring in over 1890 million USD by the beginning of 2027, which would indicate an exceptional compound annual growth rate (CAGR) or compound yearly growth rate (CYGR) of over 12.8% throughout the projected timeline. Frontline workers, as well as the general population, are increasingly in need of face masks and respirators because of the COVID-19 and 2009 H1N1 epidemics. The largest proportion of the disposable market belongs to the Asia-Pacific region. Demands for surgical masks and respirators have surged among first responders and the general population as a result of the COVID-19 and 2009 H1N1 epidemics. With a market share of 33.9% in 2019 for disposable products, the Asia-Pacific region is leading the way due to an uptick in the market for N95 face masks in densely populated nations like India and China (Pullangott *et al.*, 2021).

Even before COVID-19, half of the face masks in the world were produced in China. To obtain nonwoven PP textiles, other nations are heavily dependent on them (Bradsher & Alderman, 2020). PP is in high demand because of the absence of latex, PVC, and di (2-ethyhexyl) phthalate in nonwoven PP face masks. Due to their broad availability, including on e-commerce sites like Amazon.com, AliExpress, and eBay, Inc., the demand for disposable surgical masks is increasing, and this trend is anticipated to last for some time. In addition, retail establishments such as supermarkets, hypermarkets, medicine shops, and grocery stores also add to the market shares for face masks globally.

7. ENVIRONMENTAL IMPACTS AND WASTE MANAGEMENT

The majority of commercial surgical face masks are disposable and comprise synthetic components. These masks are discarded in landfills, and some are strewn in the streets, resulting in huge amounts of polymeric waste in the shoreline, aquatic, and agricultural environments. According to reports, this leads to the daily production of approximately four million tons of plastic pollution, raising severe concerns about their efficacious and safe disposal (Haque *et al.*, 2021). It is important to note that improper handling and the dumping of surgical masks can cause a variety of ecological problems.

Even though there are severe rules and dumping processes for worn PPEs in healthcare situations, the vast majority of nations around the world are not ready to deal with the unprecedented number of such wastes generated in a short period. Land and marine environments are both threatened by the littering of face masks (Reid *et al.*, 2019). In the COVID-19 circumstance, there were also worrisome reports of surgical masks washing up on the shores, resulting in seafaring littering that diminishes the recreational and scenic aspects of shorelines and has a negative effect on the tourism business. Furthermore, the spread of face masks in the water system is a potential threat as it contributes to riverine contamination with microplastics (Rist *et al.*, 2018; Shen *et al.*, 2020). Nonylphenol, triclosan, organotin, and polybrominated biphenyl ether, used in face masks are extremely toxic and can cause serious harm when released during the disintegration of microplastics (Aragaw, 2020). Moreover, a study by Saliu *et al.* found loosely connected nano to micro-scale plastics on the surface of surgical mask debris after experimental fragmentation and degradation treatment (Saliu *et al.*, 2021). These microplastics leached from face masks are then consumed by aquatic species such as sharks and whales. Microplastics enter the food chain via sea life and cause health hazards to terrestrial living beings (Rist *et al.*, 2018).

During the COVID-19 breakout, the infected waste generated by the surgical face mask constituted a huge environmental and health hazard in several nations. Presently, billions of infected face masks, gloves, and materials needed to diagnose, detect, and treat the Coronavirus are classified as infectious waste (Mol & Caldas, 2020). Consequently, incinerators are not maintained and landfills are overburdened, making them unsuitable for handling face masks with their hazardous toxin leakage (Saliu *et al.*, 2021). The carbon emissions of polymer resin synthesis, conversion, and disposal are enormous. According to reports, the polymer resin production step alone might release 2.7 tons of greenhouse gas into the atmosphere per ton of face masks (Zheng & Suh, 2019).

It is thus important to investigate new methods for reducing and controlling waste through proper waste management. To address this issue, biodegradable polymers are an excellent raw material for surgical masks (Babaahmadi *et al.*, 2021; Nair & Laurencin, 2007). Furthermore, to address the issue of waste management and overuse of face masks, novel methods of repurposing discarded facial masks (Idrees *et al.*, 2022; Saberian *et al.*, 2021), reusing face masks (Duncan *et al.*, 2021; Lee *et al.*, 2020), and finding sustainable solutions (Capezza *et al.*, 2020) are being investigated.

8. CONCLUSIONS AND FUTURE DIRECTIONS

Infectious disease outbreaks on a massive scale and the resulting public health crises are not novel occurrences in human history. Pandemics, from COVID-19 through the Russian flu of 1889, are mostly caused by influenza viruses, non-flu viruses, and human coronaviruses. These major pandemics of the past and present have had a substantial detrimental influence on society, the economy, international security, and the environment. They have also posed serious public health concerns. Global economies have significantly suffered since the COVID-19 epidemic started because of the lengthy lockdown. Numerous thousands of individuals have died both directly and indirectly as a result of the outbreak globally. Moreover, the pandemic has destroyed opportunities and livelihoods, led to poverty and starvation, and irreparably damaged society.

To stop the COVID-19 virus from spreading and safeguard the lives of their populations, several preventative measures have been implemented by nations worldwide. The most successful and practical short-term countermeasures implemented to stop the spread of the disease, nevertheless, appear to be the recommendations made to wear face masks in public. The use of face masks prevents the transmission of harmful germs by airborne, droplet, and aerosol particles. Its effectiveness in halting the transmission of contagious diseases is well-known and proven over time. The continuing COVID-19 outbreak also demonstrates this. Face masks play a crucial part in pandemic prevention, and they have undergone material and design changes to suit evolving safety and comfort standards. These changes range from cotton coverings to more modern, sophisticated face masks. However, the majority of face masks on the commercial market were manufactured with only one application in mind. Due to the large-scale accumulation of hazardous waste, the widespread usage of disposable face masks might pose a serious environmental concern. Using reusable face masks with built-in antimicrobial characteristics has become increasingly important because of secondary transmission risks, cross-contamination, and the difficult handling of biohazardous waste. Reusable antimicrobial face masks can help ease the pressure on the supply chain and the spike in demand. It is known that antimicrobial face masks operate better than traditional face masks by offering instant antimicrobial protection.

Antibacterial/antiviral face masks appear preferable to regular face masks in several ways, but more research is needed to fully understand the advantages and disadvantages of their use and disposal from both a short- and long-term perspective. Researchers used a variety of tests and experimental procedures for antimicrobial testing which is not in a standardized form yet. As a result, all the studies cannot be compared with each other on a universal scale. In this context, further studies need to be done. No matter how reusable face masks are, they have to be thrown away at some point. So, picking up appropriate and non-toxic material should be ensured to preserve our ecosystem. The materials should also be suitable for human skin. Moreover, a mask should have both antiviral and antibacterial properties simultaneously to make it multi-dimensional. However, the inclusion of some antimicrobial materials will make the mask expensive. This will eventually deprive the people of low and middle-income countries of sustainable protection against potential diseases. The worldwide spread of the infection cannot be halted as a result. Proper authority should ensure the safe use, disposal, and maintenance of essential protocols regarding face masks. In conclusion, an affordable and sustainable antibacterial/antiviral face mask can be our emerging hero to effectively overcome the current and forthcoming pandemics.

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