DEVELOPMENT OF COMFORTABLE, REUSABLE AND ADVANCEMENT IN MASK

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ABSTRACT

The outbreak of the COVID-19 pandemic, in 2020, has accelerated the need for personal protective equipment (PPE) masks as one of the methods to reduce and/or eliminate transmission of the coronavirus across communities. Despite the availability of different coronavirus vaccines, it is still recommended by the Center of Disease Control and Prevention (CDC), World Health Organization (WHO), and local authorities to apply public safety measures including maintaining social distancing and wearing face masks. This includes individuals who have been fully vaccinated. Remarkable increase in scientific studies, along with manufacturing-related research and development investigations, have been performed in an attempt to provide better PPE solutions during the pandemic. Recent literature has estimated the filtration efficiency (FE) of face masks and respirators shedding the light on specific targeted parameters that investigators can measure, detect, evaluate, and provide reliable data with consistent results. The aim of this article was to develop a three-layer mask, which was made of a polypropylene filter containing mangosteen extract by spray-coating technique in order to enhance antibacterial and antituberculosis activities. The bacterial filtration efficiency was performed by spraying the biological aerosol through the filters. Breathability of face masks was also measured as a pressure drop parameters. The physical properties of filters were evaluated in terms of surface morphology and water contact angle. The coated filters were then challenged with multidrug-resistant tuberculosis, Staphylococcus aureus and Escherichia coli as the representative bacteria. The results showed that the increase in the mangosteen extract concentration for coating caused fiber diameter, hydrophilicity, % BFE (> 95%) and pressure drop of filters to be also increased. Investigation into release characteristic of mangosteen extract-coated polypropylene filters exhibited initial burst release after 60 min of immersion in a phosphate buffer solution. The coated filter exhibited good antibacterial performances against three types of pathogens. An in vitro cytotoxic test showed that 2% and 5% w/v mangosteen extract-coated polypropylene filters were not toxic by an indirect cytotoxicity test using L929 mouse fibroblast cells. This study demonstrated that the filters coated with mangosteen extract significantly play an important role in achieving antibacterial face mask.

KEYWORDS: *COVID;CORONA VIRUS;FILTRATION ;FINISHES; COMFORTABLE; AEROSOLS ;AIRBORNE COLLOIDS;VIRAL PARTICLES;FIBERS ;FABRIC*

1.INTRODUCTION

The unprecedented outbreak of the coronavirus disease 2019 (COVID-19) has caused the spread of Severe Acute Respiratory Syndrome Coronavirus (*SARS-CoV-2*) that is currently a global concern. *SARS-CoV-2* has a mortality rate of 3 to 5% and can cause severe pneumonia, acute myocardial injuries, and chronic damage to the cardiovascular system . The lack of knowledge and incomplete understanding of COVID-19 limits current advancements in research, product development, and manufacturing of respirators and face masks. Prior research into fabric masks dates back in history to the 1918–1920 *H1N1 Influenza A virus* pandemic, known as the Spanish Flu. However, since the COVID-19 outbreak, there has been a surge in conducting applied research and development to improve face masks and respirators, facilitate standard testing approvals, accept new standard and nonstandard practices, and accelerate the certification process for newly developed products. For instance, the use of expired respirators and the application of various decontamination processes have been accepted for use since March 2020, in order to prolong the use of respirators and face masks . Face mask is a term to express a wide range of face protective equipment that can reduce the transmission of infectious droplets. Surgical masks are intent to protect patients with open wounds against possible surrounding infectious agents during surgical procedures. Currently, due to the demand on face masks, surgical masks have been examined for their applicability in preventing the transmission of the human coronavirus and the *influenza* virus from symptomatic individuals. This review aims to address the mentioned environmental toll by discussing materials options for more eco-friendly face masks, and analyzing additional functionalities, such as antibacterial, antiviral, and self-disinfection characteristics. Using biodegradable precursors along with such multifunctional properties may be a new approach for controlling the pandemic while caring for our planet and people. The present review focuses on the general filtration mechanisms, manufacturing technologies used to make face mask media, characterization of different surgical face mask structures, biodegradable materials that have been used, desired added functionalities, and the future demands for such effective biodegradable multifunctional face masks.

To accomplish the above, our approach was to briefly review the available surgical face masks, their environmental impacts during the COVID-19 pandemic, the materials and processes available to make such structures, and the innovations thereof. In addition, the same was done to understand the scope of available functions in current face masks, and the emerging materials and technologies that have been explored. The intent is not to provide a given solution, but rather provide insight, connect the research community in this field, and spark new ideas to solve these issues together.

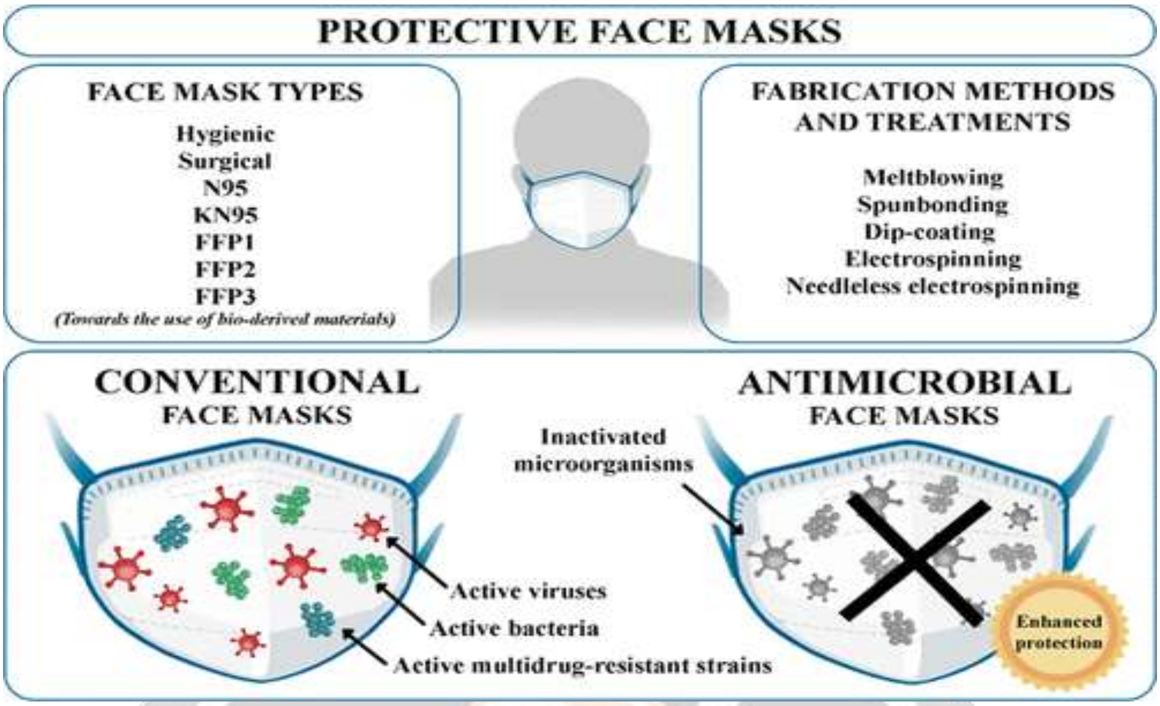
2.TYPES OF MASKS

There are four levels of ASTM certification that surgical masks are classified in, depending on the level of protection they provide to the person wearing them:

- **Minimum protection** face masks are meant for short procedures or exams that won't involve fluid, spray, or aerosol.
- **Level 1** face masks often feature ear loops and are the general standard for both surgical and procedural applications, with a fluid resistance of 80 mmHg. They're meant for low-risk situations where there will be no fluid, spray, or aerosol.
- **Level 2** masks, with 120 mmHg fluid resistance, provide a barrier against light or moderate aerosol, fluid, and spray.
- **Level 3** face masks are for heavy possible exposure to aerosol, fluid and spray, with 160 mmHG fluid resistance.

It should be noted that surgical masks are not the same as surgical respirators. Masks are made to act as barriers to splashes or aerosols (such as the moisture from a sneeze), and they fit loosely to the face. Respirators are made to filter out airborne particles such as viruses and bacteria, and create a seal around the mouth and nose. Respirators should be used in cases when patients have viral infections or particles, vapor, or gas are present.

Surgical masks are also not the same as procedural masks. Procedural masks are used in clean environments in hospitals including intensive care and maternity units, but they are not approved for sterile environments such as the operating room.



3.FILTRATION MECHANISM

The FE of face masks and respirators is the ratio of particles concentration upstream and downstream of the mask. Respiratory droplets are produced by various means such as breathing, talking, coughing, sneezing, and singing. Face mask filtration mechanisms by respiratory droplets and bioaerosols are governed by two major mechanisms: physical mechanisms and electrostatic and thermal rebound mechanisms. Physical filtration mechanisms can be defined as diffusion, interception, impaction, and gravity sedimentation. The filtration mechanism is a function of the particle and fiber size (Reynolds numbers), fiber-based Péclet number (for diffusion), particle-to-fiber size ratio (for interception), and Stoke's number (for impaction) . Moreover, these mechanisms affect the FE and are a strong function of the particle size and filtration velocity, which yields to the least efficient particle size under a specific range of filtration velocity, namely most-penetrating particle size (MPPS) . In literature, liquid aerosol particles sizes range from 10 nm to 10 µm and are treated as dry solid aerosol particles. This is a reasonable assumption as the particle surface tension is dominant at small scale, and liquid particles behave as solids . Therefore, parameters that affect the FE create nonlinear variation to filtration mechanisms depending on their contribution to the filtration process. On the other hand, electrostatic interaction forces are considered as an essential filtration mechanism especially for enhancing the FE of nano-sized bioaerosols. In addition, nucleocapsid protein crowned *SARS-CoV-2* possesses surface electrostatic potential characteristics that reinforce the importance of the electrostatic interaction role in filtration. In this section, recent research efforts that address the effect of different filtration mechanisms on the FE of face masks and respirators are reviewed.

4.COMMON FILTER (NONWOVEN) MATERIALS

4.1Polyolefins

4.1.1Polypropylene (PP)

Polypropylene is the most common polymer used for producing meltblown and spunbond fibers for making face masks. PP has a relatively low cost and can filter dry particulates. Amongst all synthetic fabrics, PP has the lightest weight due to its low density and specific gravity . PP has a high chemical (acid and alkali) resistance and can withstand elevated temperatures up to 150 °C . This material can be reused post decontamination due to its sustained structural integrity. In addition, its smooth surface, ease of processing, recyclability, and micropore distribution uniformity allow PP to be an attractive option for mask production. PP has a modifiable inherent hydrophobicity, good mechanical strength, and abrasion resistance .

4.1.2Polyethylene (PE)

This is another common polymer used in meltblown nonwovens. PE is synthesized by polymerizing ethylene monomer. The densities of PE can vary depending on the amount of monomer/comonomer used during the polymerization process leading to the different types of polyethylene; high density (HDPE), low density (LDPE), and linear low-density polyethylene (LLDPE). Like PP, PE has good chemical resistance, light in weight, and is hydrophobic . PE is easier to extrude than PP due to the high shear sensitivity and higher melting point of PP resins, resulting in a lower PP yield after extrusion . However, PP is preferred to PE because PP has more mechanical strength and is relatively inexpensive than PE .

4.2. Polyesters

Polyesters have some advantages over PP such as higher tensile strength, modulus, and heat stability but are not as cost-effective as PP. Another advantage of polyesters is that they can easily be dyed and printed with simple non-aqueous processes. However, it is challenging to recycle polyesters during spunbond manufacturing. Polyethylene Terephthalate (PET) is the most common polyester used in producing nonwoven fibers via spun bonding process .

4.3. Polyamide

Polyamides, such as nylon 6 and nylon 6-6, have been used for manufacturing of spunbond fabrics. Although nylon has some advantages such as fiber lightness, it also has a high melting point (>260 °C), making it more energy-intensive than polyolefins and polyesters. Nylon fabric readily absorbs water molecules making it unattractive for face mask production even though it can be modified to improve its hydrophobicity .

4.4. Cellulose Acetate (CA)

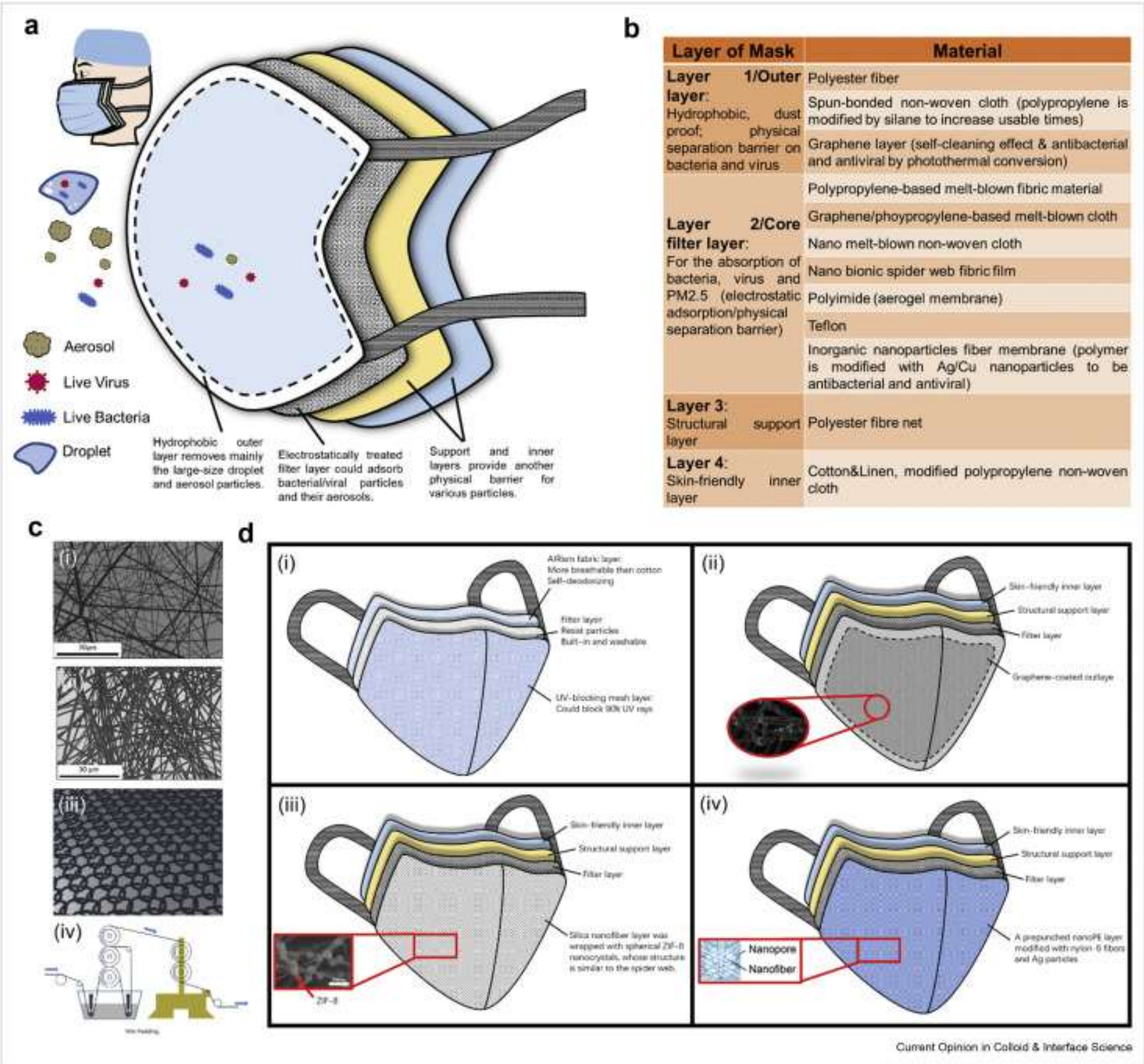
CA is an alternative to synthetic polymers since it is derived from biosources, has high FE and hydrophobicity, and is biodegradable. CA selectively filters low level organic compounds, has high water stability, and is soluble in organic solvents . Chattopadhyay et al. investigated the FE of filters made with electrospun CA fibers using aerosolized NaCl particles. It was observed that electrospun CA fibers filters, with much lower thickness, showed a higher FE compared to commercial glass fiber filter .

4.5. Polylactic Acid (PLA)

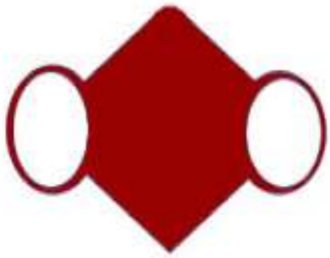
PLA is another alternative for synthetic polymers since it is biodegradable and cost-effective. It also has favorable mechanical properties and a smooth appearance. PLA is produced by a polycondensation reaction of lactic acid catalyzed by acid. L-Lactic acid is the common monomer used for this reaction and can be easily produced by lactic fermentation of biowaste by bacteria . Wang et al.fabricated a porous bead on string PLA nanofibrous membrane via electrospinning. It was observed that the morphology of these fibers could largely affect the FE and pressure drop across the membrane. The fiber morphology is affected by the polymer solution viscosity, which is a function of concentration and solvent vapor pressure . A 99.997% FE and a pressure drop of 165.3 Pa were observed in the nanofibrous membrane.

4.6. Polytetrafluoroethylene (PTFE) Membranes

These are chemically inert membranes that are effective in gas-solid separations. PTFE is widely used as an air filter membrane. It has high filtration performance due to its uniform pore structure with node-connected nanofibrils and low fraction factor. PTFE forms a lightweight and hydrophobic organic membrane with small footprints . These membranes show great chemical stability, high heat resistance, and high surface fracture toughness due to its strong C-C and C-F bonds . Biaxial stretching and electrospinning are used to manufacture PTFE nanofibers to achieve a high surface area required to increase contact between particles and fibers while maintaining good particle retention and gas permeability . During the manufacturing process, pore formers such as $ZnAc_2$, NaCl, and $BaCl_2$ are incorporated to improve air flow . PTFE membranes can be modified for a specific purpose by a wet chemical method, plasma treatment, and irradiation. PTFE membrane surface can be chemically modified without affecting the bulk property using plasma modification. This ranks the technique as one of the most promising surface modification methods . Irradiation using gamma, UV, ion, and electron sources has been shown to change surface property, substrate chemical composition, structure, and morphology of PTFE membranes . Modified PTFE have been shown to have fine particle rejection rate of greater than 99.99% with a pressure drop lower than that of unmodified PTFE membrane .



5.DIFFERENT TYPES OF FACE MASKS AND COMMON MATERIALS USED.

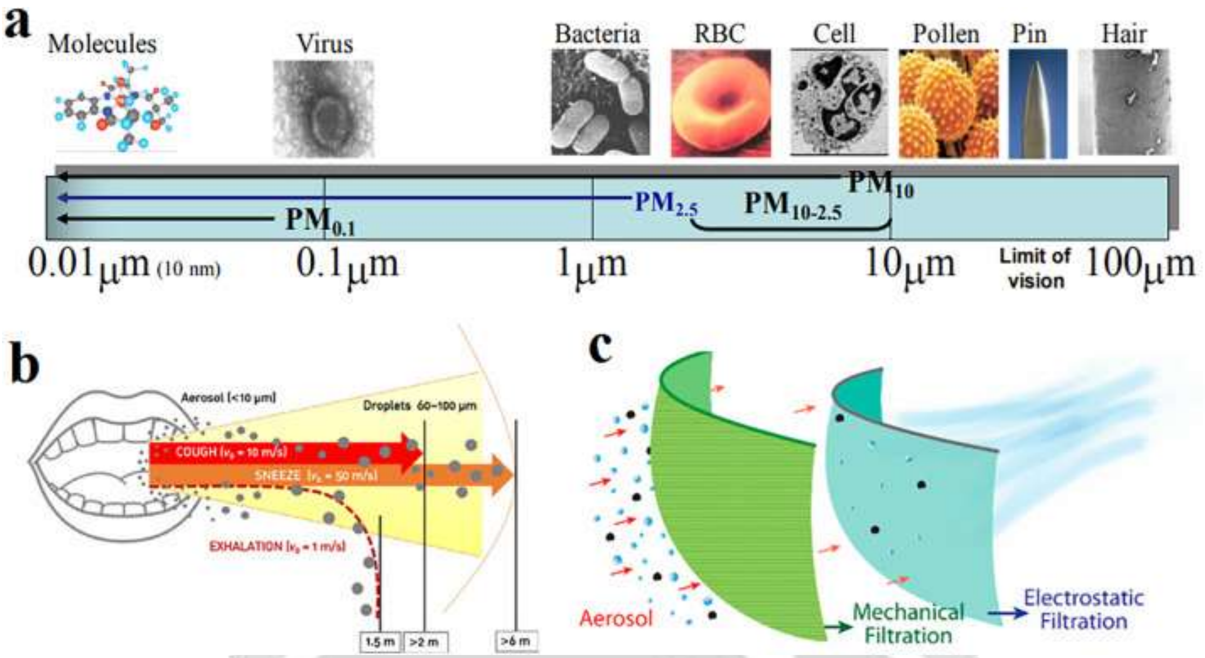
	Surgical	N95	Others
Mask Type			 
Common Materials	• Polypropylene • Polystyrene • Polycarbonate • Polyethylene • Polyester	• Polypropylene • Cellulose • PVDF • PTFE	• Cotton • Chitosan • Polyurethane • Natural fiber

6.MATERIALS

No.	Bio-based media	Structure and materials	Application	Ref.
		Electrospun Sericin nanofibrous mats	Air filtration mask	(Purwar et al., 2016)
1	Protein	Keratin/polyamide 6 nanofiber	Water and air filtration	(Aluigi et al., 2009)

No.	Bio-based media	Structure and materials	Application	Ref.
		Silk nanofibers	Air filtration mask	(C. Wang et al., 2016)
		Gluten nanofiber	Face mask	(Das et al., 2020)
		Soy protein isolate/polyvinyl alcohol hybrid nanofiber	Air filtration mask	(Fang et al., 2016)
		Nanomembrane lyocell fibrous	Surgical face mask	(Pragadheeswari et al., 2014)
		Cellulose non-woven layers	Surgical face mask	(Tiliket et al., 2011)
		Cellulose acetate (CA) nanofibers	Air filtration	(De Almeida et al., 2020)
2	Cellulose	3-ply cotton-PLA-cotton layered	Face mask	(Patil et al., 2021)
		Fungal hyphae and cellulose fibers (Wood and Hemp)	Alternative to synthetic melt and spun-blown materials for PPE	(Filipova et al., 2021)
		Banana stem fiber	Face mask	(Sen et al., 2021)
		Non-woven cellulosic fiber	Face mask	(Catel-Ferreira et al., 2015)

No.	Bio-based media	Structure and materials	Application	Ref.
		Nanofibrous chitosan non-woven	Water and air filtration	(Desai et al., 2009)
3	Chitosan			
		Chitosan nanowhiskers and poly(butylene succinate)-based microfiber and nanofiber	Face mask filter	(Choi et al., 2021)
		Poly(lactic acid) fibrous membranes	Air filtration	(Z. Wang et al., 2016)
4	Poly lactic acid (PLA)			
		3D printed and electrospun polylactic acid	Face mask filter	(He et al., 2020)
5	Gelatin	Gelatin/β–cyclodextrin composite nanofiber	Respiratory filter	(Kadam et al., 2021)
6	Polyhydroxyalkanoates (PHAs)	Nano fibroustructure	Face mask	(Al-Hazeem, 2021)

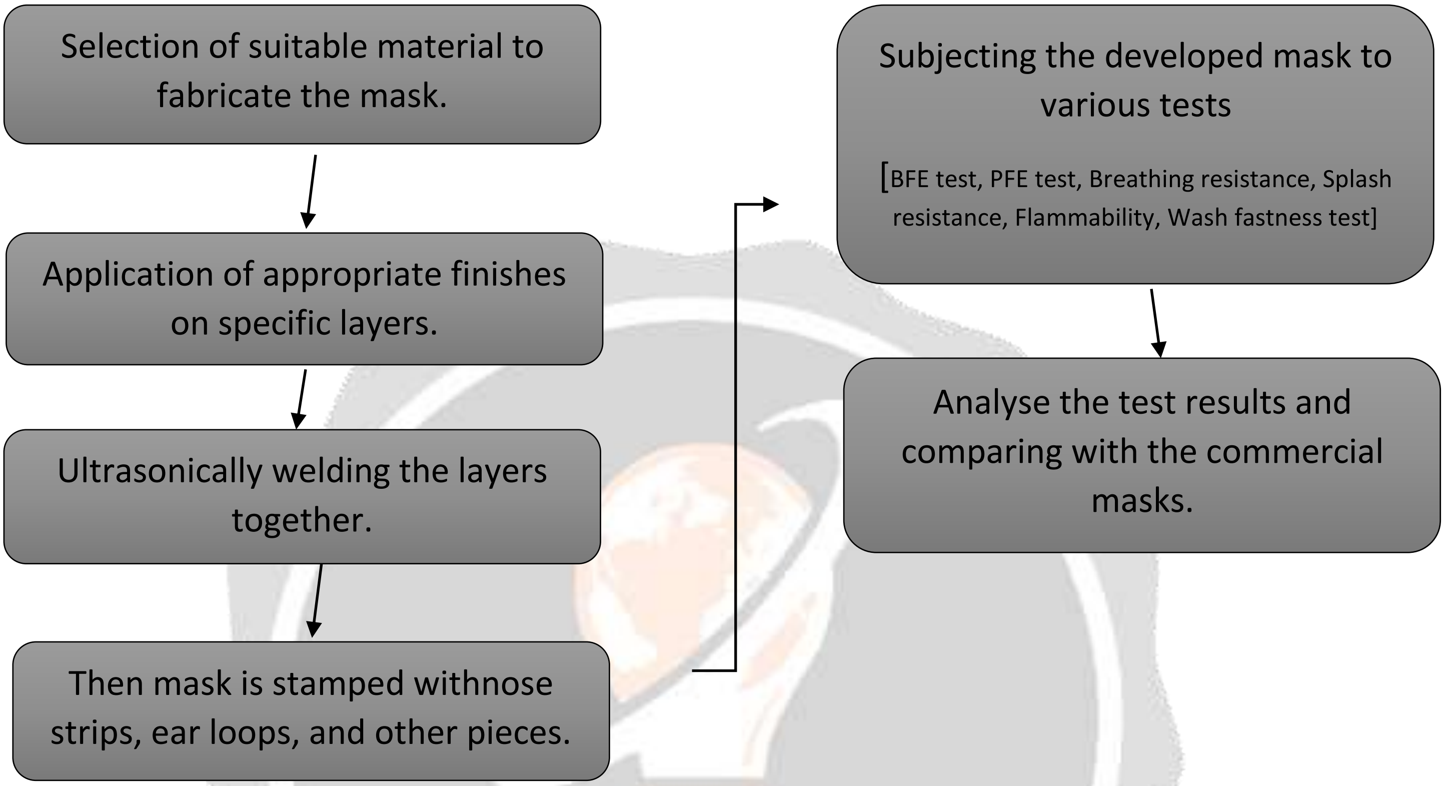


7.Mask Tests

Once surgical masks are made, they must be tested to ensure their safety in various situations. There are five tests they must be put through:

1. **Bacteria filtration efficiency in vitro (BFE).** This test works by shooting an aerosol with staphylococcus aureus bacteria at the mask at 28.3 liters per minute. This ensures the mask can catch the percentage of bacteria it's supposed to.
2. **Particle Filtration Efficiency.** Also known as the latex particle challenge, this test involves spraying an aerosol of polystyrene microspheres to ensure the mask can filter the size of the particle it's supposed to.
3. **Breathing resistance**. To ensure the mask will hold its shape and have proper ventilation while the wearer breathes, breathing resistance is tested by shooting a flow of air at it, then measuring the difference in air pressure on both sides of the mask.
4. **Splash resistance**. In splash resistance tests, surgical masks are splashed with simulated blood using forces similar to human blood pressure to ensure the liquid cannot penetrate and contaminate the wearer.
5. **Flammability**. Since several elements of an operating room can easily cause fire, surgical masks are tested for flammability by being set on fire to measure how slowly it catches and how long the material takes to burn. ASTM levels 1, 2, and 3 are all required to be Class 1 flame resistant.

8.METHODOLOGY:



9.1Antibacterial

The antibacterial activity of surgical face masks has been investigated based on various ranges of pathogens 5
e.g., *Escherichia coli*, *Pseudomonas aeruginosa*, *Candida albicans*, *Enterococcus faecalis*, and *Staphylococcus aureus* etc. Majority of these studies have utilized quaternary ammonium , metals nanoparticles , and N-halamines ; which are all well-known antibacterial agents that have been used for infection control before. Desirable characteristics of such antibacterial agents include effective inhibition against a broad spectrum of bacteria, non-toxic to the consumer, compatibility with resident skin microbiota, avert from irritations and allergies, and applicable with no adverse effects on the quality or appearance of the surgical face masks.

The reduction percent in bacterial count or BFE is calculated through the ratio of the viable count at a specific period . It is found that the bioburden of surgical face masks increased with wearing duration, making them a potential infection source due to bacterial shedding . Surgical face masks with the lowest mean pore size have shown the highest BFE against the bacteria . Also, antimicrobial electrospun air filtration membranes from PLA and other components such as Sericin/PVA/Clay have shown high filtration efficiencies along with the good antimicrobial activity. The BFE of a typical disposable surgical face mask with 95% microbial barrier has shown efficacy reduction just after 4 h of wearing .

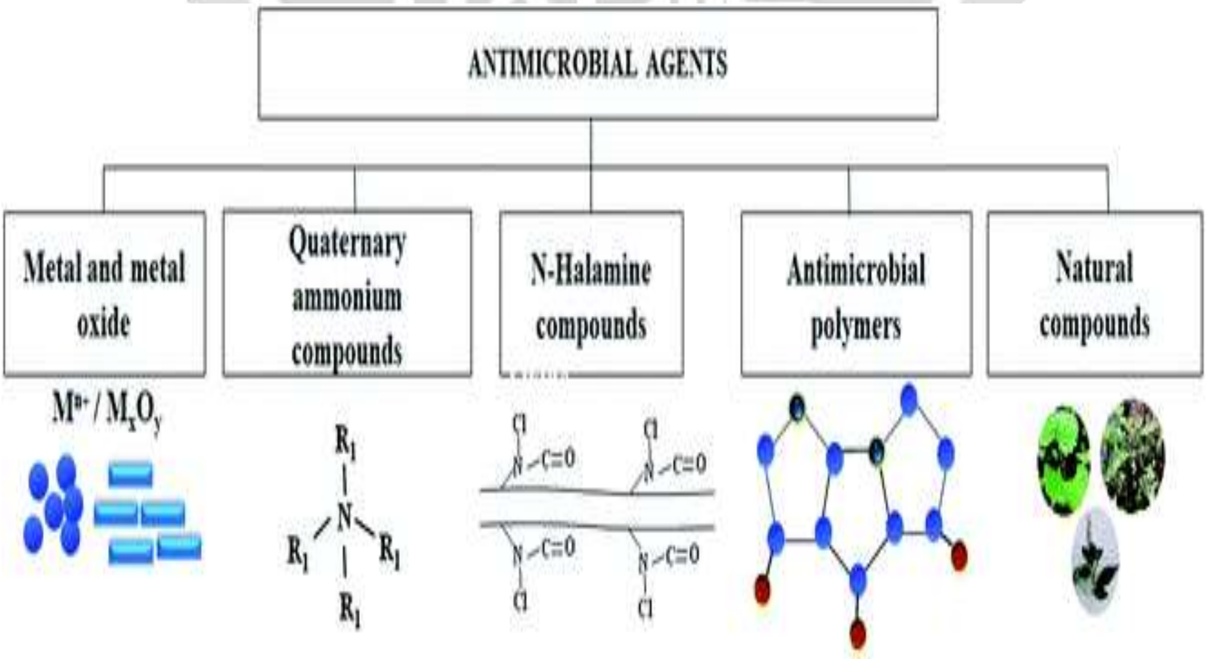
9.2 Antiviral

Viruses are responsible for respiratory diseases which can easily escape through filtration systems and cause severe infections . SARS-CoV-2 viral particles are categorized as small bioaerosols with an elliptical or spherical shape and sizes lower than 150 nm . Most of the conventional surgical face masks do not provide the best protection due to their large pore sizes and poor fit characteristics; meanwhile, respirators (e.g., FFP2 or FFP3 and N95) provide efficient protection against airborne viruses . In addition to capturing the droplets and large aerosols by filter media, it is also beneficial to deactivate viruses with antiviral or sanitizing molecules, when they pass through a face mask . Applying different antiviral agents can provide antiviral performance

through direct disinfection, receptor inactivation, and indirect disinfection mechanisms. Some of the reported agents include natural viral inhibitors , metal and metal oxide nanoparticles , sodium chloride , poly(ethylenimine) (PEI) , and polyphenol .
The ratio of live viruses sampled outside and inside the face masks determines the surgical face masks virus filtration efficiency (VFE) . Although surgical face masks have been demonstrated to block the spread of viruses, COVID-19 may survive over a day on the surface of the mask . Ideally, the surgical face mask materials should capture and, simultaneously, inactivate those viruses.

9.3.Antimicrobial

The use of a face mask as an RPD is instrumental in preventing airborne, droplet, and aerosol transmission, where the primary control mechanism lies in reducing exposure. However, there are serious concerns about the usage of conventional disposable face masks. When infected individual coughs or sneezes, the pathogen laden droplets can splash out and adheres to the immediate contact surfaces, and remain viable for several days. Many studies have proven the presence of SARS-CoV-2 on various material surfaces, including inner and outer layers of face masks for a period of 4 and 7 days, respectively. These contaminated face mask surfaces, in turn, becomes a source of fomite transmission. Besides, the warm and humid conditions inside the face mask due to breathing and saliva creates a favourable environment for the intercepted microorganisms to grow and flourish. The moist conditions will induce a capillary action due to which the intercepted microorganisms transfer further into the inner layers *via* suction, thus endangering the health of the wearer. Eventually, these microorganisms will aggregate as an extracellular polymeric matrix containing polysaccharides, proteins, and deoxyribonucleic acid (DNA) resulting in the formation of biofilms. In these situations, an unexpected danger arises due to the re-aerosolisation of the settled particles during intense sneezing or coughing by the wearer. Microbial survival and re-growth on conventional face masks after usage and improper storage can also lead to secondary infections in humans. So, face masks are typically discarded after a single-use to avoid the inoculation and spread of highly infectious pathogens. This type of single-use and discard culture can lead to its massive shortage and the generation of a large quantum of hazardous waste, especially during pandemic times. The gap in supply and demand coupled with unaffordability, disposal challenges, and possible adverse impact on the environment calls for reusable face masks.Antimicrobial face masks look attractive over conventional face mask and can address some of the concerns associated with single-use face masks by providing *in situ* real-time antimicrobial protection. Several AMA are developed over the years and are available in different forms, including films, coatings, beads, and NPs. The surfaces coated AMA are reported to be effective in deactivating/killing microorganisms and preventing the formation of biofilms. The active moieties which impart the biocidal qualities include metal and metal oxides, quaternary ammonium or phosphonium groups, antimicrobial polymers, N-halamine compounds, antimicrobial peptides, and natural compounds.



10.CONCLUSION

In the recent century, presence of bacteria and viruses in respiratory aerosols has played an important role in diseases transmission, especially with the COVID-19 global pandemic. Face masks (surgical face masks and respirators) have been used globally to protect both healthcare providers and patients in the recent pandemic. This has resulted in more than four million tons of plastic waste on a daily basis. Using biodegradable polymers in surgical face mask production can significantly help protect both the people and our environment at the same time. This paper has reviewed the viable biodegradable materials options, along with their respective processing requirements and their final performance. In addition, it is discussed that high-efficiency face masks can be further functionalized to incorporate other values and benefits beyond biodegradability, including temperature/health monitoring, antibacterial, antiviral, self-sanitizing properties, and fit and comfort. Each of these functionalities has been reviewed and potential materials, technologies, and protocols available to the industry and public have been proposed. While this review provides a broad perspective on the current status of multifunctional and biodegradable nonwoven face masks, it also sheds light on some of the current challenges and the future opportunities.

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