

Review Article

A Review of the Fabrication Methods, Testing, and Performance of Face Masks

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Improvement in the performance and compatibility of face masks has remained the focus of researchers in recent years, especially after the emergence of the COVID pandemic. Although a lot of progress in the design, tolerability, and comfort of the mask has been reported, there are certain limitations, requiring further improvement. The present review aims to highlight the filtration efficacy, comfort, and associated characteristic of various types of face masks and respirators as a function of their design and structure. In addition, the air pollutants, their adverse effects on health, certified respirators, and face masks are also discussed. The present review also provides an insight into different types of commercially available face masks in terms of their materials, filtration efficiency, and limitations. The role of emerging trends (such as nanotechnology and high-performance polymers) in the improvement and development of face masks and respirators is also discussed.

1. Introduction

Face masks comprise variously recognized but alike items, such as dental, isolation, laser, procedure, and surgical masks. These are commonly deliberated to inhibit exposure caused by splashes, large droplets, or fluid sprays moving towards the mouth and nose. Surgical masks perform an important special function for patient safety by preventing healthcare or non-healthcare workers from infecting a sight throughout a procedure [1]. Face masks, more importantly, do not have a proper mechanism for the protection of a wearer from the particles. Aerosolized materials can easily be inhaled from the mask layer and around the face mask because the seal is not present.

Except for face masks, respirators are also designed for the wearer's protection from a specific level of pollutants in the air. The National Institute for Occupational Safety and Health (NIOSH), in the United States, certifies the respirators based on their filtration capability test against the most penetrating size particles [2]. N95 respirators have a filtration efficiency of about 95% of such particles, whereas N100 and N99 respirators have 99.97% and 99% filtration efficacy of contaminants, respectively.

While performing their duties, the workers can face exposure to pathogens from contaminated environments or infected people [3–5]. Exposure to infectious disease can be significantly different such as disease, circulation, its method of biological transmission, and the mechanism of pathogenesis. Breathing in bioaerosols comprises active particles of different sizes present in the air. Bioaerosols are the results of the speaking, breathing, sneezing, and coughing of a person. The healthcare and non-healthcare workers perform intrusive respiratory like spraying chemicals or water on infected surfaces [6, 7]. Ear, throat, and nose surgeons, anesthetists, ophthalmologists, and dentists operate the patient in a position where social distancing is largely impossible, so face mask has huge importance in their profession. Despite the various administrative and engineered controls, people are not fully safe from these infectious diseases, so personal protective equipment (PPE) is needed to prevent these diseases.

With the emergence and rapid spread of the new viral outbreak (SARS-CoV-2 (COVID-19)), the usage of masks and PPE has been increased rapidly [8]. This pandemic has become a global challenge not only to developing countries, but also to other developed countries having strong healthcare systems. Infection control is key to reducing the COVID-19 infection, and this can be achieved through case identification, social distancing, hand washing, and PPEs are important to avoid community spread [9]. The frontline workers and health professionals need protective gear to fight this pandemic effectively. A vaccine for infection, protective equipment such as masks, respirators, hand hygiene, and social distancing are the most powerful tools for breaking the transmission chain of SARS-CoV-2 disease.

Now the question arises as to who should wear a mask and who should wear which type of mask in SARS-CoV-2. The recommendation of face masks is an ongoing debate. A mask is a PPE that is normally worn on the face, typically for protection, disguise, performance, or entertainment. Masks have been used since antiquity for both ceremonial and practical purposes, as well as in the performing arts and for entertainment. The World Health Organization has instructed that face masks must be used by frontline workers and other persons who show active symptoms such as coughing, sneezing, flue, shortage in breathing, or illness. But unfortunately, the unnecessary buying of masks by the public has led to a shortage of masks for the actual frontline fighters [10]. The shortage of these protective gears (masks) has caused serious problems. Major reasons for shortage were the difference between production and supply, centralized production, transportation difficulties, complications in buying, extravagant prices, and unequal distribution [11].

The healthcare workers and frontline heroes are most vulnerable to the deadly coronavirus or SARS-CoV-2; hence, they require PPE [12]. This disease is highly diffusible and increases the biological hazard to healthcare workers. The virus spreads from one person to another through close contact and droplets originating from the infected person [13]. The public health emergency of international concern authorities gives direction and recommendations to healthcare workers as well as to the public depending upon the characteristics and transmission of disease. A clear instruction on the usage of protective gear and masks for healthcare personnel and the public is regulated by these authorities.

An increase in the demand and excessive public usage of masks caused a serious deficiency of supply for frontline healthcare workers. The general public got better awareness that wearing any mask is better than without a mask, which led to increased demand for masks of all types [14]. Though a cloth mask cannot stop the SARS-CoV-2, it can break the transmission from one wearer to another by blocking large droplets produced by coughing. Moreover, a cloth mask will encourage most mindful behaviors such as touching a mouth, face, and eyes with a hand. The filtering efficiency of various masks also plays a vital role [15]. Depending upon

the filtering efficacy, these masks should be suggested for healthcare workers, active patients, and the public [16]. Although a lot of progress in the design, tolerability, and comfort of the mask has been reported, there are certain limitations requiring further improvement. The present review aims to highlight the filtration efficacy, comfort, and associated characteristic of various types of face masks and respirators. In addition, the air pollutants, adverse effects on health, and certified respirators and face masks are also discussed. The present review provides an insight into different types of commercially available face masks in terms of their materials, filtration efficiency, and limitations.

2. Protection Offered by Face Masks

A face mask is one of the efficient measures to reduce the transmission of viral infection [17, 18]. The mask should be tightly sealed to curb the deadly virus. A small amount of aerosol is released during coughing or sneezing [19]. Most of these particles convert into aerosolized tiny fragments which are 3- to 5-fold small. These dehydrated aerosols can stay in the air for a long time. Hence, a mask is needed to stop these aerosols from entering the human body during respiration. When aerosol hits the weave of varn instead of the hole, then these aerosol particles will be captured and unable to leak out into the air. Respirators are devices that are used to filter inhaled air [20]. Therefore, it should be a tight fit and not allow the particulate to enter the human body through the respiratory tract. These respirators only allow the air to pass through and stop all particulates from entering the body. Different mechanisms (filters) are applied to capture these particles of all sizes. Larger particles are directly captured by the fibers and smaller ones are blasted by the air molecules, which causes them to deviate from the mainstream and hit the fiber. These particles will stick to the fiber and this way mask filter will capture the particles smaller than the hole or pore size. Face masks can provide inward (protection from an infected person or other people) as well as outward protection (protection from other infected people) as shown in Figure 1. Wearing the face mask can remind them not to touch their face and nose [21].

2.1. Who Should Wear a Mask? The World Health Organization advised that people who have symptoms of sneezing and coughing must wear a face mask. The Center for Disease Control and Prevention (CDC) suggested fabric cloth masks for the public when it is hard to keep physical distancing measures. The public can wear cloth masks in hospitals, workplaces, grocery stores, and pharmacies. They also recommend that people aged 60 or more wear a medical mask when physical distancing is not possible.

2.1.1. Choosing a Face Mask. Different levels of protection can be obtained using different types of face masks depending on the mask type and how they are used. Several things that must be considered for choosing the face masks are:

(i) Layers of the mask and filtration efficiency of the face mask;



Protection of people caring for COVID-19 patients

FIGURE 1: Protection offered by face masks to healthcare and non-healthcare workers [21].

- (ii) Risk of illness from COVID-19;
- (iii) Fitness of mask on the face;
- (iv) Comfort to the face.

Fabric face masks can be used by unaffected people in the areas where the physical distancing is not possible. Multilayer fabric masks can protect unaffected persons up to a specific level. But when you need a good level of protection then fabric facemask cannot help you. A surgical face mask is the PPE that loosely fits the mouth and nose. These surgical masks can shield against sneeze droplets, sprays, splashes, and large coughs but these masks cannot be used to protect from smaller droplets. These masks provide more protection than fabric facemasks. Surgical masks are feasible to be used for a longer time. Depending on the environmental factors (temperature and humidity) it can work efficiently for 3–8 hours. It must be disposed of properly after a single time of use.

Respirators including N95, N99, and P100 have tangled fibers to protect from pathogens in the air and these fit close to the face. Only healthcare workers and affected people should use these respirators as these provide a higher level of protection. N95 respirators have good breathability as compared to N99 and P100 so 95 can be used for a longer time than other respirators.

3. Filtration Mechanism

The mechanical filtration mechanism mostly originates from the divergence of particles from streamlines across the fibers. Therefore, accurate estimation to capture the particles needs airflow knowledge that determines the nature of flow whether it is streamlined or turbulent [25-27]. Primarily, when the particles that follow the air stream deviate from the direction of the rapidly deforming streamlines, inertial impaction occurs. This mechanism depends on the particles' inertia and is the leading filtration method for large particles [22]. Interception occurs when the particles carried by streamlines are not well separated from the fiber's surface. Particles having greater radii than the distance between the streamlines and surface of fibers were caught by the fiber. This interception mechanism is dependent upon the particle's size and fiber, especially on fiber diameter and the ratio of the particles. Diffusion is caused by Brownian motion providing adequate kinetic energy to the particles to escape streamline and pose an impact on the surface of the fiber. This mechanism promoted filtration efficiency by capturing tiny particles [22]. Electrostatic filtration depends on the

electrostatic forces between the filter media and the particles. Two types of electrostatic forces are used to capture the particles: dielectrophoretic, and coulomb forces [23]. Coulomb force attracts the particles towards fibers if both have unipolar or bipolar charges. Dielectrophoretic forces dominate to attract the particles towards fibers when either fiber or particle is in a neutral state. These forces do not affect the streamlines; therefore, these forces can enhance filtration efficiency without affecting the air permeability [24, 25]. Mechanical filtration mechanisms can provide dimensionless numbers obtained from structural parameters [26]. Therefore, optimization and controlling these structural characteristics present a path to designing high-performance air filters.

3.1. Structure-Based Approaches. The primary design factor in air filters is the fiber diameter because it influences the structure of the filter. Nanofibers having diameters in the submicrometer size can increase filtration efficacy by penetrating particle size and slip effects [27-29]. There are other parameters related to the structure such as composition, morphology, and layer configuration that must be optimized using advanced techniques. Greater surface area promoted the capturing of the particles by Brownian diffusion, which can be achieved using fibers having a smaller diameter [29]. So, the first structural-based approach is to improve the surface morphology of the fiber to improve the filtration performance. Reported studies claimed that rough fibers can increase the filtration efficiency of air filters by allowing additional streamlines around the fibers [30, 31] and increasing the frictional forces between the fibers and particles.

Filters made of nanofibers have small pore size, narrowed air channels, and high packing density that causes significant pressure drop [27]. On the other hand, micro-sized fiber filters have loosely bound structures and large openings, making them inefficient to filter small size particles. Therefore, the second technique is to develop hybrid structures that contain diverse dimensions, i.e., microfibers and nanofibers, for the improvement of filtration efficiency as well as air permeability. There are many structures that have been developed such as multimodal dimensions [32-34], multimodal diameters [35-37], nanonet/scaffold dual networks [38-41] and so on. The filtration efficacy of air filters increases by increasing the thickness and weight of the filters due to the large surface area and prolonging the retention time of the particles. Therefore, this issue is resolved by the third technique in which multiple layers of filter are stacked into a single filter unit, providing required pore size and packing density.

3.2. Interaction-Based Approaches. Classical methods based on mechanical filtration can improve filtration efficiency up to a limited extent. Therefore, using electrostatic forces in air filters provides an outstanding strategy to increase the filtration efficiency with lower pressure drop. Coulomb force and electrostatic image force are induced in the air filters when particles and fibers have net charges [40]. These forces can be operated by two methods: (1) creating a strong electric field by an external energy source and (2) embedding an electric material with high potential.

Electrically activated materials called electrets produce electric fields themselves. So, air filters can be designed by embedding electric charges into the substrate or aligning dipoles within the dielectric material. Electric materials can be prepared by many techniques such as corona charging, induction charging, and triboelectric charging [42]. The electrostatic interaction between the filtering media and particles can be increased by many methods such as electric materials and the fabrication process, but the long-term and stable durability of these materials is critical [43]. Therefore, continuous energy is given to air filters by the energy sources to provide the charges and resolve the issue of durability of electrostatic effects. So electrostatic precipitators and triboelectric nanogenerators are used in this technique to improve the durability and long-term filtration efficacy of filters [44].

4. Types of Face Masks

The most efficient way to reduce the transmission of a viral infection, especially, SARS-CoV-2, is to use PPE such as gloves, gowns, face shields, and face masks. Various types of masks with different application areas have been discussed here. Some major face mask types are medical masks, cloth masks, and surgical masks. It is very important to make clear which mask should be used by which person and also it needs to be clear whether wearing a mask is essential for all public or only affected persons and whether health professionals should wear a mask [45]. The filtration deficiency of each mask should also be known.

4.1. Single-Layer Face Mask. Globally, all governments and the World Health Organization have provided guidelines on wearing single-layer cloth masks to cover the nose and mouth made of fabric. This type of mask is preferred in food processing units by workers. This type of mask is only for once used and never washable or reusable and does not protect against the viruses, bacteria, and microbes. Original masks have appeared in public, developed from some common fabrics such as cotton, silk, chiffon, and other synthetics as well as their combinations. The single-layered fabric has an efficiency of 5-80% with a particle size of >300 nm. The filtering efficiency can be improved by increasing the layers and using multiple fabrics as well as combinations. It has been reported that cotton is the most widely used fabric for mask and higher count cotton offer better filtering efficiency. A comparative analysis of cotton-based masks and surgical masks showed that the penetration efficiency in cotton was 97%, while that in the surgical mask was 45% [46].

4.2. Multilayer Face Masks

4.2.1. Surgical Mask. A surgical mask is permitted by FDA, which protects from large droplets, splashes, or hazardous fluids. It is a loose-fitting and fluid-resistant respirator. It is preferred for healthcare persons and infected patients [47]. MacIntyre et al. explored that the use of a surgical mask was better than wearing no mask at all in preventing the



FIGURE 2: Schematic diagram for functions of different layers of 3-ply surgical face mask.

influenza virus. A significant difference was found between these two kinds of masks in terms of risk reductions. The risk reduction of either mask mainly depends upon the fit of the mask to the face of the patient. The surgical mask is also called a medical mask or a procedural mask. First, it was used in the 1890s by doctors, assistants, and surgeons in operation theaters. It was only used to protect from the blood and blood splashes of patients, and it does not protect them from infection. Moreover, the patients were protected from the droplets of coughing and sneezing of doctors during operation time [48, 49].

Polypropylene is mainly used to produce typical surgical face masks. The non-woven sheet having 20 GSM of polypropylene fibers is produced by the spinning bond technology, and 25 GSM non-woven sheets are developed by the melt-blown technology. Surgical face masks come in various sizes, such as 14.5×9.5 cm for children, 17.5×9.5 cm for adults, and 12×7 cm for infants. They are normally available in yellow, green, blue, pink, and white [50]. Besides polypropylene, other fibers that are used in face masks include polycarbonate, polyester, polystyrene, and polyethylene. Filtration efficiency does not only depend on fiber selection but also depend on the manufacturing method and web structure [51].

A surgical mask contains three layers or three plies that are joined together by various methods. The outer layer, inner layer, and the innermost layer are shown in Figure 2. Each layer has a different composition and functionality. The innermost layer of the face mask captivates moisture from the user's breath, the middle layer filters the air, and the outer layer is hydrophobic that does not allow water and moisture passage. The outermost layer is hydrophobic, but some water droplets and moisture containing hazardous viruses can stay on it [52]. The outer layer and the innermost layer of the 3-ply face mask are comprised of spun bond, non-woven materials, whereas the middle layer is made up of melt-blown, non-woven materials as shown in Figure 2. The structure of the face mask contains 1–5 GSM of meltblown microfibers, which have a microporous structure and good breathability. Surgical masks are obtained by joining the very fine middle layer, having fine glass fibers or synthetic microfibers, in between the two layers made up of acrylic bonded materials. The weight of the middle layer ranges from 10 to 100 GSM. The filtering efficiency of the surgical mask is up to 98%. This mask can filter particles, and bacteria of >0.1 μ m in size as shown in Figure 2. This is the reason surgical mask gives little protection against infections. Depending on the environmental factors (temperature and humidity) it can work efficiently for 3–8 hours. It must be disposed of properly after a single time of use [53].

4.2.2. Fabric Mask. A fabric mask, a face covering made of well-secured cloth (bandana, shirt, or scarf) that covers the mouth and nose, is suggested for uninfected ones. Textile masks offer outstanding benefits depending upon the kind of fabric used, construction of fabric structure, type of infection encountered, and the number of layers. Fabric-based masks are largely used in Asian countries in resource-depleting settings. The prototype and advantages of cloth masks have been published previously [54].

Ramasamy et al. presented that cotton-based, polyesterbased, and cotton-polyester-blended fabric masks were used for filtering aerosol unit (100–300 nm) size. Moreover, they were not able to categorically give superiority to any fabric. The efficiency of filtering cloth masks can be enhanced by a tight seal to the face. In a SARS-CoV-2 outbreak, the Chinese State Council (CSC) suggested that masks are not important for the unaffected, but they report that nonmedical masks and cloth masks may be used. The CDC further urges that cloth masks may be the necessary last option only when there is a shortage of surgical and medical masks.

Various textile products such as woven and non-woven healthcare, hygiene, lab coats, and PPEs are used for



FIGURE 3: Composition and function of different layers in masks [55].

protection against viruses. Different textile products are being used based on the type of infection, type of exposure, extent of infectious disease, and end users of the product or time encountered during the performance of tasks. Non-woven materials encounter problems such as water repellency and oil repellency, but they are more versatile, easy to use, disposable, and cost-effective. Non-woven disposable masks and filtering face pieces and gown shortage lead to the use of textile base protective gears such as fabric masks, and fabric medical gowns. These fabrics can be used for respiratory protection. Before using these fabric-based filters their filtration and performance testing is very necessary. These fabrics are used for nano-sized particles such as virus filtration. Various types of masks such as surgical face masks, fabric masks, or any other dust masks should meet the standard requirements of ASTM F2100 level 2 or level 3 to be used for protection purposes. Moreover, these masks should follow the NIOSH certification criteria. N95 masks are designed for one-time use and are disposable. During an outbreak like corona, SARS, or influenza, this may not be possible due to its limited supply chain. The CDC provides guidelines and procedures for the extended use of N95 respirators. Respirator protection has been improved according to the NIOSH P100 filtering face mask respirator. It offers 99.7% against particle size of 0.3 microns and provides a better face fit than the N95 respirator.

4.2.3. Dust Mask. Another important type of mask is a dust mask. It protects against nontoxic dust in the construction

industry and house cleaning. This mask is developed from a paper pad. Moreover, this type of mask does not provide any protection against microbes. The composition, construction, and function of each layer for different types of masks are given in Figure 3.

5. Respirators

Except for facemasks, respirators are also designed to keep safe wearers from the level of contaminants in the air. NIOSH in the USA assessed the filtering efficiency of respirators for certification purposes. NIOSH approved the N, R, and P series of air-purifying respirators at 95, 99, and 99.97% filtration efficiency under 42 CFR Part 84 [56].

5.1. N95 Respirator. For personal safety from viruses, aerosol, and droplets, N95 masks or respirators are recommended. N95 mask is tightly sealed, which is approved by NIOSH. This respirator helps to reduce the wearer's exposure to large droplets as well as aerosols. Moreover, it can screen droplets up to 95% of particles [57].

The N95 mask consists of 3 types of fiber layers made of polypropylene as shown in Figure 4: the inner layer (7–8 layers), the filter layer (1 layer), and the outer layer (2 layers). The inner and outer layers are fabricated using the spun bond technology, while the filter layer is made using the melt-blown technology as shown in Figure 4. The thickness of the inner, filter, and outer layers is 0.08–1.2 cm, 0.01–0.15 cm, and 0.03–0.04 cm, respectively [58].



FIGURE 4: Multilayer N95 face mask.

The layer of the filter is made of microfibers of polypropylene, and these layers are combined to develop the filter of a respirator. These layers are combined by electrostatic charging, and this charge enables a filter for the microbes. Earlier, respirator masks were developed from fiberglass, which was used to prevent fine coal dust inhalation. One major drawback of the fiberglass respirator was that the user feels difficulty in breathing. In 1972, 3M developed the first N95 respirator. To make this respirator, air blasting was used to melt the polymer. Thin polymer layers were then combined by using an electrostatic charge. The filter stops the passage of small particles, but air can easily pass through it. Hence, this enables the user to breathe easily. In 1990, doctors used this respirator while treating HIV patients to protect them from drug resistance. Furthermore, it was also used in 2003, during the SAR outbreak [59].

There are three types of N95 face masks such as N-type, P-type, and R-type. Based on the ability to filter oil-based particles or not, N95 masks are classified as 'N', R, or P. N means not resistant to oil, so these respirator masks are used to filter particles that do not possess oil. On the other hand, R-type and P-type masks show resistance towards oil, hence will be used for filtering particles containing oil as well. The N-type respirator is classified further into three groups, N95, N99, and N100. This classification is based on filtering efficacy. The first two can filter particle size >0.3 μ m and filtering efficiency is 95% for N95 masks and 99% for N99. The particles >0.3 μ m can penetrate the lungs, hence this cutoff is preferred. The size of coronavirus or SARS-CoV-2 ranges from 0.06–0.14 μ m in thickness. Hence, the N95 mask efficiently filters or separates the coronavirus and other viruses of the same size and ensured that the mask is properly sealed and tight fit to face the person. Moreover, a fit test is important to ensure the functionality of masks. The N95 mask comes with or without a valve. N95 respirators having valves are not recommended for the coronavirus patient, because the virus can easily pass through the valve and affect other people around. Furthermore, they come with different certification standards for each kind of mask/respirator across the world: USA [NIOSH 42CFR Part 84], Europe [149:2001], and China [GB2626]. The European Union had categorized masks into the FFP1 category, FFPE category, and FFP3 category, where "F" stands for filtering, F for face, and P for the piece (FFP). N95 is roughly equal to FFP2, and N99 is almost equivalent to FFP3 masks. FFP1, FFP2, and FFP3 are also known as P1, P2, and P3, respectively.

5.2. N99, P100 Respirator. These are industrial masks with ultra-high filtration efficiency. The usage of these masks is limited in healthcare settings because of their very low breathability. The prolonged wearing of this type of mask can cause respiratory distress. N95 mask provides very good aerosol protection and viral droplet protection along with good breathability like a surgical mask. Therefore, the N95 mask is more suitable for prolonged wearing as well as in most health-related settings [55, 60].

6. Modern Techniques to Develop Efficient Face Masks

Nanotechnology is gaining interest in various applications due to its fascinating properties. Nanofiber web for filtration application is part of the growth of nanotechnology. Nanofibers-based filter media permitted ultra level of filtration in numerous applications. Today, many people have been involved in the market of air filters and looking for nanofibrous filters having improved filtration efficiency and holding capacity. There are several applications of nanofiber-based filter, which is commercially available and still under development [61].

6.1. Electrospun Nanofibers. The efficiency of the filter media is improved using the nanofibers and their webs in filter media [62]. The schematic diagram for the development of nanofibers using the electrospinning technique with their important parameters is given in Figure 5. The separation and filtration of sub-micron-sized particles are the foremost concern of today's nanotechnology. Engineered nanoparticles are produced for different applications because of their



FIGURE 5: Schematic of a conventional electrospinning setup, as well as environment, solution, and electrospinning [69].

good physical and chemical characteristics. The production of engineered nanomaterials has increased due to the increased growth of nanotechnology in the industrial workplace. Several properties of nanofibrous media such as small pore size, low weight, and high permeability make them suitable for various filtration applications specifically smaller particles [63]. In addition, nanofibrous membranes present fascinating properties such as high specific surface area (1– 100 m²/g), good pore interconnectivity, and the capability to incorporate functionality and active chemistry on the nanoscale [61].

Nanofibers are produced using the novel technique named electrospinning because it gives the precise composition of nanofibers, geometric features, low expense, and quick procedure. In electrospinning, high voltage is given to the polymer solution or melt to eradicate the surface tension of the liquid and created the nanofibers with a diameter ranging from 40 nm to 2000 nm [64]. Some parameters like voltage, syringe tip, the distance between the collector and syringe, and solution concentration are carefully controlled to get the desired nanofibers. Filter media based on nanofibers are an important part to improve the filtration performance [65–68].

Filter media made up of electrospun nanofiber web have a high surface-to-volume ratio, controllable connectivity, low-pressure drop, and better interconnectivity, which makes them suitable for filtration. Nanofibers cannot be used individually as filter media because of their poor mechanical properties; rather, they should be coated with non-woven fabric. Non-woven fabrics made up of nylon, glass, polyester, and cellulose, are commonly used as supporting materials (substrates) to nanofibers as shown in Figure 6. The supporting material should be strong enough to bear the toughness and fabrication of the filter during its usage [70].

Commercialized filters already have many applications as well as in progress. The use of nanofibers in respirators and face masks are better than the commercialized available filters. Polypropylene fibers having smaller diameters with a 500 nm to 1000 nm range are used in active filters for the manufacturing of commercial respirators and filters; static electricity is used for the filtration in these filters. Fibers per unit area will be increased and pore size will be decreased by decreasing the fiber diameter. The electrostatic charge on the melt-blown increases the filter quality by enhancing the fabric's absorption capability. Long-term use or exposure in the water of these filters can lose their static electricity and hence reduce the filtration efficiency. But nanofibers do not depend on static electricity for contamination filtration; rather, they use small pore size and sufficient pore distribution for aerosol filtration, which contains viruses and harmful dust [71].

Many researchers have worked on the development of nanofiber-based facemasks or respirators [73, 74]. Loesecke et al. [35] produced a nanofiber-coated cellulose web for a face mask and found that it could catch particles up to 0.1 microns and improved the efficiency of the filters with an insignificant effect on air permeability. Munzarova [75] used the electrospinning technique to develop nanofiber-based fabric and laminate it onto the face mask. The author found that the prepared face mask can protect the wearer from dust particles, microorganisms, and allergens. Skaria and Smaldone [76] developed the prototype of filter media based on nanofibers for face masks and compared it with an N95 respirator. The results showed that the airflow resistance has been significantly reduced by improving the filtration efficiency like the N95 respirator.

Li and Gong [77] developed nanofiber-based mask filters by coating the non-woven web with polysulfone electrospun nanofibrous web. They prepared webs of different thicknesses and compared them with non-woven disposable masks, N95, and R95 respirators. They found that the prepared nanofibrous non-woven face mask can filter out particles of size 2.5 microns or less with good breathability. Akduman and Akçakoca Kumbasar [78] developed a nanofiber web of cellulose acetate and polyvinylidene fluoride (a)



Gluten Electrospun Mat Gluten

(c)

FIGURE 6: Face mask with electrospun fibrous sheet [72].

for filtration in face masks or respirators and compared it with an N95 respirator. The researcher investigated the impact of factors such as thickness, the diameter of the fibers, and pore size on filtration efficiency. The diameter of the polyvinylidene fluoride nanofiber (236 nm) was less than cellulose acetate nanofibers (319 nm) so cellulose acetate shows better efficiency [79]. Nanofiber-based composite masks have also been developed using the solution blow spinning method [80, 81]. [82] used cellulose diacetate, polyacrylonitrile, and polyvinylidene fluoride to prepare a nanofiber web using the solution blow spinning method for the filter mask. They found that polyacrylonitrile shows the best filtration efficiency with good air permeability than other nanofibers. Shin et al. [83] presented an adaptive breathing protection based on a dynamic air filter obsessed by machine learning algorithms. A stretchy membrane of elastomer fiber was used in dynamic air filters for the adjustment of filtration

properties via microporous rescaling pneumatically, facilitating the seamless and constructive transition of filtration properties. The fabricated respirator proved real-time adapting exercises and continuously optimized protection under various circumstances.

6.2. Nanomaterials Coated Face Masks. Carbon nanotubes, titanium dioxide, and silver can easily be used as additives to prepare the coated electrospun nanofibers. Titanium dioxide has incredible shielding properties and catalysis of UV rays, which can be imparted to materials by coating its nanoparticles [84, 85]. Ruan et al. [86] developed polyacrylonitrile-co-polyacrylate and titanium dioxide electrospun membrane. The SEM images of the electrospun membrane containing titanium dioxide particles are given in Figure 7. They determined the aerosol inspection, air permeability, and micron size particle trapping. They found



FIGURE 7: TiO₂-based nanofibers membrane for face masks [86].

that the prepared membrane can remove micron size particles effectively with good air permeability. Some studies show that the use of carbon nanofiber and activated carbon composite is appropriate for the cartridge of the respirator because of its light weight and absorption ability [87]. Jahangiri et al. [88] developed respiratory mask cartridges using granules of activated carbon and carbon nanofibers to absorb and eliminate VOCs from the air.

Jung et al. [89] designed a filter using graphene oxide (2-D material) for the removal of $PM_{2.5}$. They assembled nanoplates of graphene oxide onto a porous structure using ionmediated assembly method and then reduced the graphene oxide by thermal reduction. The resulting reduced graphene oxide assembly possesses a large porous structure capable of airflow with little drop in pressure. The developed filter is efficient due to its high surface area and little pressure drop. De Maio et al. [90] used graphene oxide for coating polyurethane and cotton fabrics to make them antiviral textiles as shown in Figure 8. They found that virus filtration via graphene or graphene oxide functionalized cotton and polyurethane wholly eradicated SARS-CoV-2. The functionalized fabrics also showed antibacterial properties but did not affect eukaryotic cells.

Han et al. [91] developed self-sterilized and transparent air filters using copper nanowires. These filters successfully seized particulate matter by electrostatic and mechanical filtration mechanisms. The temperature of the filter can be controlled up to 100 °C with good thermal stability. The fabricated filters effectively inhibited the E. coli growth because of the copper effect. This filter showed stable filtration efficiency with high reusability and antibacterial property after 5 repetitions. Jeong et al. [92] fabricated a $PM_{2.5}$ filter made up of a percolation network of silver nanowire through all solution processes. A nylon mesh was used to reinforce the percolation network of the silver nanowire. The pore size of the used nylon mesh was 53 μ m with good air permeability and reinforced to stabilize the silver nanowire structure. This PM_{2.5} filter can be used as a highly effective, energy efficient, active, and reusable filter.

6.3. Face Masks Containing Antimicrobial Agents. Filters can also make antimicrobial by incorporating antimicrobial agents, such as silver in the filters [93]. Microorganisms are killed during filtration and get in contact with silver nanoparticles like polyacrylonitrile nanofibers containing silver nanoparticles [94, 95]. Yang et al. [66] developed a face mask using nylon 6 and nonporous polyethylene to capture the sub-micron size particles and obtained 99.6% filtration efficiency with low-pressure drop. They further coated silver particles on fiber web and found that the filter efficiency was reduced up to 87%.

6.4. Super-Absorbent Polymers-Based Face Masks. Nanofibers synthesized from super-absorbent polymers have been developed for the protection against viruses and bacteria. Some studies have been conducted to develop electrospun super-absorbent nanofibers to improve the absorption capability for various applications such as microbe biofilters, disposable face masks, and hygiene products [96, 97]. Sivri [98] synthesized polyvinyl alcohol electrospun nanofibers to impart liquid absorption and virus obstacle function to face masks. The researcher successfully coated the polyvinyl alcohol web onto the face masks as investigated by SEM and FTIR spectroscopy. The use of a nanofibrous web increases the hydrophilicity of the composite mask but decreases the air permeability.

The above discussion exhibits those membranes and nanofiber-based webs that are suitable to be used in filter



FIGURE 8: Schematic diagram to trap SARS-CoV-2 using graphene oxide and functionalized fabrics for inhibition of viral and bacterial infection [90].

media because of their extraordinary properties such as hydrophilicity, high porosity, and improved catalytic performance by the addition of catalytic material. The functioned nanofibers containing catalysts can also decompose other biological and chemical warfare agents. The layers of different nanofibers can be used together with a substrate to develop the protective garment [99].

7. Filtering Efficiency of Masks

Fit- and seal-tested respirators are well-thought-out as the gold standard for PPE to protect from droplet-transmitted infections [100, 101]. The filtering efficiency of such masks varies from manufacturer to manufacturer and depends on the particle size which will be filtered. In the current COVID-19 or SARS-CoV-2 context, the diameter of the virus is almost 125 nm as determined by cryo-electron tomography and cry-electron microscopy. According to Qian et al., the N95 respirator showed 99.5% efficacy for particle size of 750 nm. As the size of particles decreased to 100–300 nm size, the filtering efficiency of the N95 respirator decreased to 95%. These masks are only sold when the minimum filtering efficiency is up to 95% as per the standard set by NIOSH. Moreover, N99 and N100 respirators showed filtration efficiency of 99% and 99.7%, respectively, for the

particle size of 100–-300 nm. There is no specific standard requirement for the surgical mask to be sold. Based on producers and the NIOSH filtration standards, the filtering efficiency of surgical masks ranges from <10% to \leq 90%. Good fit and tight seals are also important parameters linked to risk reductions. The performance and efficiency level of different masks are given in Table 1.

8. Recommended Face Masks for Health Professionals

Wearing any type of mask is far better than no mask, regarding protection from infections and other harmful particles. The usage of masks varies from context to context and person to the person dealing with working or dealing with patients. When the public goes out, they should wear even cloth masks and N95 masks are not recommended for the public. A surgical mask is suggested for medical staff who are dealing with non-COVID-19 patients. These respirators are recommended for a healthcare person who deals with risk patients in hospitals. The N95 mask helps healthcare professionals while dealing with high-risk patients [102]. According to the Cochrane review, putting on the N95 mask plays a key role to reduce the spread of respiratory viruses.

Performance of various masks					
Type of mask	Bacterial filtration efficiency (filter particle 3 microns e.g., pollens and droplets)	Particulate filtration efficiency (filter particle 0.1 microns e.g., viral particles)	Fluid resistance	Breathability	FDA cleared for maintaining the sterile surgical field
Surgical n	nask (ASTM)				
Level 1	≥95%	≥95%	Poor	Cood	Yes
Level 2	≥98%	≥98%	Fair	Good	
Level 3	≥98%	≥98%	Good		
N95 mask					
Surgical	≥99%	≥99%	Good	Fair	Yes
Industrial	Not tested	≥99%	Not tested		No
Carbon ch	narcoal mask (nuisance odor relief)				
	Offer limited protection	Offer limited protection	Not tested	Good	No
Comfort mask (for warmth and comfort)					
	Offer limited protection	Offer limited protection	Not tested	Good	No

TABLE 1: Performance efficiencies of various masks [74].

The use of face masks has become very critical in the current SARS-CoV-2 outbreak [103].

A lot of progress and changes have been made in the design of masks. This has remained one of the primary tools to reduce the risk of disease spread like current coronavirus transmission. Besides the limited supply of masks, numerous other problems also exist to design the mask. The N95 mask provides excellent protection against hazardous particles and protects workers, but there is the problem of intrinsic tolerability with it. In this mask, the metal strip compresses the bony nose and sensory nerves present on the scalp which lead to a headache when a person uses it for an above four-hour period.

The discomfort confines users' compliance while frequent readjustments by the worker threaten his safety. Healthcare workers deserve comfortable respirators. Moreover, apart from face masks other PPE for healthcare professionals and the public regarding SARS-CoV-2, are listed below in Table 2.

9. ASTM Standards for Testing Mask and Respirators

Surgical masks are primarily controlled by the "Food and Drug Administration" and must satisfy the standards set by ASTM. Surgical masks have three levels (level 1, level 2, and level 3) and the functionality and performance of surgical masks have been shown in Table 3. The N95 respirator masks are developed for the protection and safety of industrial workers to lessen particulates and other harmful particles inhaled by the user. The regulating body of the N95 respirator is the NIOSH. NIOSH regulates in the direction of "NIOSH 42 CFR Part 84" by a mark" NIOSH" Written on the exterior of the mask [105]. A new standard test method ASTM F3502-21 was created by modifying the NIOSH test method (42 CFR Part84, subpart K). There are

some different steps in ASTM F3502-21 as compared to NIOSH. This method tests 10 unused samples and 10 additional samples after maximum laundering cycles for reuseable masks. In this method, the face velocity is kept narrow, i.e., 10 ± 0.5 cms⁻¹ but the flow rate should be a maximum of 85 VLPM. Two target filtration efficiencies of \geq 20% (Level 1) or \geq 50% (Level 2) are specified, with corresponding flow resistances of \leq 147 Pa and \leq 49 Pa. This mask filters particles of 0.3-micron size, up to 95%. Moreover, N represents that it can only filter non-oily particles. They are tested in strict protocols to pretend the "worst case" state. Noncharged sodium chloride particles of 0.3 mm were nominated, which represent the most penetrating particle size, and most particles bypass through different techniques to attract them. Experimental results are also being presented on the efficacy of the N95 mask which confirmed its filtration efficiency >99% for uncharged particles having a size of 1 mm [106]. The total filtration proficiency of N95 respirators is greater than surgical masks of all ASTM levels [60]. The advantages and disadvantages of using facemasks are given in Table 4.

10. Recycling and Reusability of Masks

During the pandemic, if the full-time reopening of the businesses is maintained then for each month a country's population needed nearly 1 billion face masks. If a mask weighs 3 grams then one billion masks will produce 3000 tons of waste every month [112]. A study was reported by Izzaty et al. [113] on the effect of different face mask adoption on the environment. They found that if a disposable mask is used during the day, it will have a substantial effect on the environment and if a washable facemask is used then it will have less impact on the environment as compared to the disposable mask, but washable masks have the disadvantage of water scarcity. It is clear from this report that the

Area	Specific staff	Actions	DDF required		
Inca	opeenie stan	Actions	11 E required		
SARS-CoV-2 patient ward	Frontline staff (doctors)	Offering direct treatment	Must wear safety kits, put on a surgical mask, and wear gloves and gowns. Moreover goggles/face shield also required		
		Aerosol-generating procedures done on coronavirus patients	While working with aerosol procedure, put on an FFP2 mask, wear gloves, a hydrophobic gown with tight sleeves, and face shield are necessary tools.		
	Cleaners	Entering the ward of SARS- CoV-2 patients	Similarly, an FFP2 mask and gloves on hand, a tightly sealed gown, and shoes as well as goggles for eye protection are necessary.		
Ambulance or shift vehicle SARS-CoV-2 patient	Healthcare staff	Transporting suspected SARS- CoV-2 patients	The FFP2 mask standard mask, double nonsterile gloves, water resistance, and hydrophobic gowns and face shield are important.		
Outpatient facilities	Frontline worker (doctor)	Patient with respiratory symptoms	Must wear the surgical mask, put on gloves and a tight seal gown and use goggles for eye safety.		
	Cleaners	After and between meetings of patients with respiratory symptoms	For face protection FFP2 mask and gloves on hand, a tight sealed gown and shoes as well as goggles for eye protection, are necessary.		
Waiting room area	Patient		Patients with respiratory symptoms must wear a medical mask. Isolate and keep a distance of 1 m.		
Laboratory premises Laboratory staff		Working with respiratory samples	The FFP2 mask standard mask, double nonsterile gloves, water resistance and hydrophobic gowns, and a face shield are important.		

TABLE 2: Proposed type of PPEs in the context of SARS-CoV-2 infection [104].

TABLE 3: Various protection levels of surgical masks according to ASTM.

Levels	Function	ASTM standard/performanc		
	FR	80 mmHg		
Level 1	BFE	95%		
	PFE	>95%		
	Breathability	<4		
	FR	120 mmHg		
	BFE	98%		
Loval 2	PFE	>98%		
Level 2	Breathability	<5%		
	FR	160 mmHg		
	BFE	98%		
T	PFE	>98%		
Level 3	Breathability	<5		

ASTM, American Society for Testing and Materials; BFE, bacterial filtration efficiency; FR, fluid resistance; and PFE, particle filtration efficiency.

impact of the disposable mask is the biggest challenge of this solution [113].

It can be deduced from this discussion that the impact of disposable face masks on the environment should be limited, or they must be recycled. Before the pandemic, the situation was different because face masks were only employed in the confined area or the medical environment on a small scale [114]. Usually, these face masks are incinerated or landfilled after their use but a different solution should be proposed [115, 116]. As the first option, domestic materials such as cleaning cloth and air filter fabric were suggested as alternative materials [117, 118]. The disposable face masks can be reused directly by sterilization and make them disinfectant [119–121], but this solution is not recommended by the scientific-technical committees due to possible other infections and decrease in filtering effectiveness of the face masks after sterilization.

The ultraviolet (UV) irradiation method is one of the physical approaches to disinfect medical equipment. The disinfection of N95 respirators with ultraviolet light has been investigated and found that the impact of contamination on filtration performance of the mask is less than 5%. The recommended energy to disinfect the contamination is 3 J/cm² [122]. The second method of decontamination of face masks is heating the masks using autoclaves, rice cookers, or microwaves [123]. Lin et al. investigated the dry heating and steaming of an N95 mask in an autoclave for 15 min at 121 °C which killed almost 100% of *Bacillus subtilis spores* [124].

There are some chemical methods to decontaminate the face masks after use. Hydrogen peroxide vapors are used to sterilize the face masks because they get decomposed and do not leave harmful residuals. This method does not have any blind spots and sanitizes the whole area homogeneously. Kumar et al. treated the N95 respirator using 35% hydrogen peroxide vapor for 1 hour and found that all viable SARS-CoV-2 were removed [125]. Lin et al. used 100% isopropanol, 70% ethanol, and 0.5% bleach to disinfect the face masks [126]. Shaffer et al. decontaminate N95 and P100 respirators using 1 g/L soap solution for 2 and 20 minutes. They found that particle penetration increased in both respirators due to loss of fiber charge [127].

TABLE 4:	Advantages	and	disadvantages	of	face	masks.

Advantages	Disadvantages
Wearing masks could reduce the spread of virus droplets and the risk of transferring SARS-CoV-2 in areas where distance is not feasible like transportation and public areas.	If the mask is not fit properly on the wearer's face, then a higher amount of air will pass via the edges of the mask causing leakage flow. This problem is normally faced in N95 respirators due to a lack of fitting other than the average faces such as children. Those masks that do not fit properly on the wearer's face cannot provide adequate protection to the user.
When an infected person talks, sneeze, or coughs, the primary way produced coronavirus spreads from person to person. Facemasks block these droplets and act as barriers to keep contamination from escaping from an infected individual and landing on another.	Breathing resistance can be caused using respirators which could result in a lack of oxygen or long-term accumulation of CO_2 gas. Nanofiber or microfiber face masks and multilayer masks made up of clothes have high filtering efficiency, but they lead to a reduction of oxygen saturation or can cause mild hypoxia.
Cloth face masks provide some protection to the wearer, but when everyone covers the nose and mouth then protective perks are obvious. The more the people cover their faces by wearing the mask, the fewer will be chances to transfer the virus circulating in the community. This reduces the risk of infection.	Kellogg and MacMillan [107] observed that American users misused the mask by only covering their mouths but not their noses during the Spanish contagious disease (H1N1). Many of them frequently remove their masks or only wear them in public places.
Preventive measures like physical distancing, wearing facemasks, and handwashing are important to fight against coronavirus in the absence of effective drug therapies and vaccine. These strategies are low-cost and easy to implement.	Asthma patients have an impaired ability to breathe due to respiratory diseases. So, respirators and facemasks with high resistance can be problems for these types of people. The use of face masks for the children might be difficult because of the difficulty in teaching the children not to touch their faces [108].
Economic boon can also be achieved using face masks because it prevents the spread of the coronavirus and hence substitutes for the lockdown. Otherwise, it causes a reduction in GDP growth.	The main problem with cloth masks is the failure of filtering the diseases after using them for 30 to 90 minutes [109]. Rengasamy et al. [110] concluded in their study that cloth masks can filter 10–60% NaCl aerosols. In another study, MacIntyre et al. [111] reported the difference between cloth masks and surgical masks in their capability for healthcare workers' protection against contagious diseases. They found that transmission chances of the diseases are more in cloth masks than the medical masks.

The other proposed method is to recycle the materials from which the face masks are made. Facemasks disposal caused agglomeration of masks in public places and pose a great impact on the environment [128]. So, this agglomeration is like other plastics that are dumped and pose serious concerns related to the environment. These materials could be indirectly or directly incorporated by the wildlife which causes gastrointestinal or respiratory problems or can be died by starvation. The study reported by Fadare et al. [129] in which face masks are proved to be the potential source of microplastics. So, plastic residues produced by the facemask must be treated in the COVID-19 pandemic to eliminate the new way of contamination the environment [130]. Various approaches to recycling the surgical mask are proposed by Battegazzore et al. [112]. They also studied the ear loops that are made up of elastomers and fabrics.

Another way to avoid the contamination of face masks to the environment is to use biodegradable materials to produce face masks. A biodegradable antiviral facemask was developed using nanofibers that can be reused and washed various times and today it is commercialized. A French company also commercialized a fully biodegradable facemask made up of hemp fiber [131]. The use of green and biodegradable precursors for the development of fibrous products is the best solution to eliminate the impact of face masks on the environment in this COVID-19 pandemic situation [132–134].

11. Conclusion and Future Perspective

The face mask has emerged as a strong agent to fight various diseases and protect from particulates, dust, and other harmful pathogens. Globally, there is clear evidence that the transmission probability is very high when the SARS-CoV-2 patient without masks encounters healthy individuals. In this article, we reviewed the recently published literature on types of masks, their development techniques, the protection they offer, and recent trends in the development of face masks and respirators. Surgical face masks and various types of respirators have already been used by patients and healthcare workers in the recent pandemic. Multilayer face masks or respirators such as N 95 provide protection up to 95% and N 99 provides protection up to 99%, but both can cause suffocation if used for a long time. So, these face masks and respirators are better for the healthcare workers that will use these masks during duty. Furthermore, membrane-based technology made face masks advance by increasing the filtration efficiency for the separation of viruses and aerosol droplets. Various techniques (nanofiber web, hydrophobicity, super-absorbent polymers, nanoparticle embedment, and surface charge) have been discussed to increase the filtration efficacy and protection from viruses and bacteria. But all these advanced face masks are better for the use of healthcare workers who need ultra-protection from viruses and aerosol droplets. Surgical face masks are better than

respirators for the public and patients as they must wear them for a long time. But it has the disadvantage that its protection decreases with time, so it can be used only for one day and cannot be reused. But these masks produce plastic waste of more than four million tons on a daily basis. Using biodegradable polymers in surgical face masks can help to protect both the people and the environment simultaneously.

The use of surgical face masks is high, which requires special bio-based structures. The encapsulated system can be integrated into the layer of filter to provide disinfection and drug delivery in the case of COVID-19. These special smart face masks can help the infected wearers in treatment as they breathe. A huge amount of biological waste from surgical face masks is produced that may cause impact the environment. So, a biodegradable and self-sanitizing mask is the need of the future. Since nanomaterials coatings are used to impart biodegradability in surgical face masks. Reusable, biodegradable, and antivirus masks have gotten attention as a sustainable solution to overcome the current shortage. Filtering and blocking of inhaled aerosols, there should be chemical deactivation of droplets with sanitizing, antiviral, and antibacterial molecules as they move through the fibrous layers. The challenges in introducing biodegradable multifunctional surgical face masks are limited resources in the supply of bio-based surgical face masks for huge consumption and affordable price of the face masks. These issues should be addressed to fabricate high-performance and nontoxic multifunctional biodegradable surgical face masks.

Data Availability

The data will be made available as per requirement.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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