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## The face behind the Covid-19 mask – A comprehensive review

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### ABSTRACT

The threat of epidemic outbreaks like SARS-CoV-2 is growing owing to the exponential growth of the global population and the continual increase in human mobility. Personal protection against viral infections was enforced using ambient air filters, face masks, and other respiratory protective equipment. Available facemasks feature considerable variation in efficacy, materials usage and characteristic properties. Despite their widespread use and importance, face masks pose major potential threats due to the uncontrolled manufacture and disposal techniques. Improper solid waste management enables viral propagation and increases the volume of associated biomedical waste at an alarming rate. Polymers used in single-use face masks include a spectrum of chemical constituents: plasticisers and flame retardants leading to health-related issues over time. Despite ample research in this field, the efficacy of personal protective equipment and its impact post-disposal is yet to be explored satisfactorily. The following review assimilates information on the different forms of personal protective equipment currently in use. Proper waste management techniques pertaining to such special wastes have also been discussed. The study features a holistic overview of innovations made in face masks and their corresponding impact on human health and environment. Strategies with SDG3 and SDG12, outlining safe and proper disposal of solid waste, have also been discussed. Furthermore, employing the CFD paradigm, a 3D model of a face mask was created based on fluid flow during breathing techniques. Lastly, the review concludes with possible future advancements and promising research avenues in personal protective equipment.

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## 1. Introduction

The rise of epidemic outbreaks is increasing with a rapid rise of global population and the continual increase in human mobility (Mei et al., 2015). One of the most significant pathways of spreading respiratory infectious diseases is by airborne transmission (Liu et al., 2021). These airborne microorganisms may be propagated by fine mist, dust, aerosols, or liquids, that are subsequently transported over a large region by air currents and inhaled by susceptible hosts (MacIntyre et al., 2017). Each year, about 24.1 million instances of whooping cough are recorded globally, resulting in 0.16 million fatalities; seasonal influenza, on the other hand, kills another 0.5 million. Wuhan, China, the epicentre of the Severe Acute Respiratory Syndrome Coronavirus type 2 (SARS-CoV-2), reported its first case on December 31, 2019. While India, the second most populous country, was decimated by SARS-CoV-2 with its first case being reported on January 27, 2020, signalling a highly concerning situation with over 200 million individuals being affected and over 4 million fatalities confirmed globally (Gangwar and Ray, 2021).

Apart from COVID-19, India has the largest burden of airborne illnesses such as multidrug-resistant Tuberculosis (TB), accounting for nearly a quarter of all TB cases worldwide. Despite public health measures, 127 subjects were reported to be TB positive out of 644 tests post-outbreak of SARS-CoV-2 (Srivastava and Jaggi, 2022). Controlling such airborne diseases

may be accomplished in several ways. For example, active devices like air cleaners and equipment for the protection of the human respiratory system, provide personal protection and help in avoiding exposure to these infected individuals (Abboah-Offei et al., 2021). In response to the COVID-19, irrespective of boundaries, governments worldwide have made face coverings mandatory thereby increasing the usage of face masks (Amendola et al., 2020). In a similar event in 1918, Japan witnessed a high surge in demand for face masks due to the sudden outbreak of influenza. Since then, masks have become extremely popular in Japan as a simple means of preventing infection (Short et al., 2018).

Disposable face masks can also help reduce contact with aerial pollutants and different types of airborne pathogens such as environmental contaminants and allergens. Several Asian countries, including Indonesia, China, India, Nepal, South Korea, and Bangladesh, have significant levels of particulate matter and pollution, necessitating the use of face masks for personal protection (Anwar et al., 2021). Specifically, they were used in Indonesia during and after volcanic eruptions to avoid the inhalation of volcanic ash, which was a severe cause of concern for the affected populace (Horwell et al., 2019). It was claimed that people who used face masks had fewer adverse effects from inhaling polluted air, since they may filter out up to 95% of harmful particulate matter. In general, the effectiveness of any face mask may be evaluated, depending on its design and the materials used in its manufacturing (Cherrie et al., 2018). Whereas in China the need for face masks surged significantly during the current COVID-19 outbreak, demand for N95 and cloth masks has boosted polypropylene (major raw material used in fabrication) manufacturing by 126%, while cloth mask production has risen by 227% (Yang et al., 2021). WHO anticipated a global monthly requirement of around 90 million protective masks and filters for frontline health workers in 2020, and gradually the production of personal protective equipment increased by 40% to meet the rising demand (World Health Organisation, 2020). While in India, the production capacity of three-ply face masks expanded from roughly 2 million to more than 20 million units each day.

Face mask as a prophylactic step was reported to be successful in restricting the spread of the novel coronavirus – however, improper disposal and prolonged usage pose a considerable environmental threat and health risks. Inadequate management of face masks and other PPE is now being researched for its environmental impact. Face masks that have already been inappropriately disposed off, have also become a source of microplastics and nano-plastics (Shen et al., 2021). Over the last two years, researchers have started to focus on masks as a probable source of microplastics in the sea, and to examine their toxicological effects on soil (Kwak and An, 2021; Selvaranjan et al., 2021). Their presence in masks pollutes the environment, and is also hazardous to users who may inhale these components (Ma et al., 2021). Recently, the researchers investigated the hazards to humans and marine habitats by measuring the abundance of these components in masks (Fabra et al., 2021; Prata et al., 2021).

In the year 2021, face masks alone could cause 0.15 to 0.39 million tonnes of plastic trash to end up in the oceans due to improper waste management, as reported by Dharmaraj et al. (2021). As a result, proper disposal is essential to mitigate the adverse impact of masks on human wellbeing and the ecosystem. Asim et al. (2021), proposed multiple approaches for effective disposal, enhanced management and sustained reuse of discarded face masks including pyrolysis, incineration, valorisation, etc. While, many developing countries are still practising open-air burning to manage these wastes, on the other end of the spectrum, advanced economies recycle the discarded face masks into pavement bases, building materials, fillers, porous sound absorbers, etc. (Saberian et al., 2021; Maderuelo-Sanz et al., 2021).

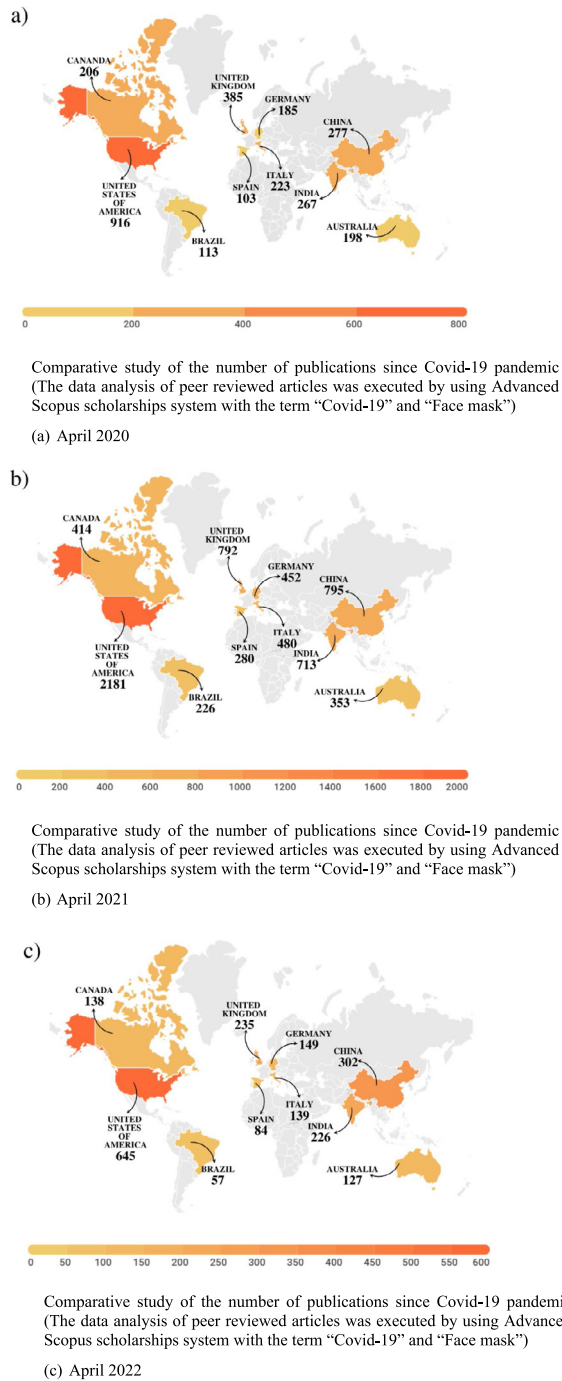
MacIntyre and Chughtai (2020), in their work pointed out that only a few studies have been performed to assess the potential risk to consumers posed by the various materials contained in face masks and on their prolonged usage (MacIntyre and Chughtai, 2020). Among them, the impact of CO<sub>2</sub> retention due to rebreathing was analysed in healthcare professionals using face masks Özdemiş et al. (2020) and Fernández-Arribas et al. (2021), reported that extended exposure to phthalates and organophosphate esters might be toxic.

The current review examines the various form of masks and filters in use and assesses their relevance to a broad section of the population. Additionally, the health and environmental consequences of the components used in face masks are assessed to ensure their safety. This review also discusses appropriate disposal, effective management and sustainable recycling solutions of discarded face masks to reduce the associated health and environmental issues. Finally, based on the fluid flow during breathing practices, a 3D model of face mask has been developed using the CFD concept. Overall, 5 scenarios were replicated and analysed: (a) coughing indoors in the absence of a facemask, (b) coughing indoors in the presence of a clinically approved facemask. Simulations were performed in stagnant air (emulating indoor conditions) and in a minor draft with a linear flow of velocity 4.5 m s<sup>-1</sup> (emulating outdoor conditions) on a computational grid with over 650 × 106 nodes.

### 1.1. State of the art literature review

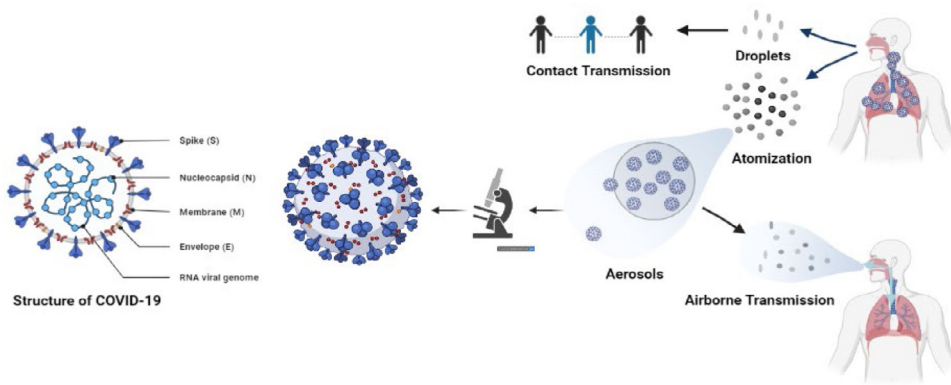
The peer-reviewed publications on Covid-19 and mask usage from 2020 to 2022 have been analysed by utilising Advanced Scopus Search Engine. The results revealed that the advancements in face masks have gained much attention during the Covid-19 pandemic. As of April 20, 2022, the total count of publications was observed to increase exponentially within the years 2020 (2873 articles) to 2021 (6686 articles). Fig. 1 represents the contribution of research and development related to facemasks from different countries, in terms of publications from 2020 to 2022. Interestingly, it has been observed that the United States is leading the table in total publication count, with more than 3500 publications followed by the United Kingdom as per the Advanced Scopus Search system.

This indicates an increasing attention in the field of face mask processing and development. Specifically, the research community was primarily focused on the origin of the Covid-19 pandemic, preventive measures, advancements in face



**Fig. 1.** Comparative study of the number of publications since Covid-19 pandemic (The data analysis of peer reviewed articles was executed by using Advanced Scopus scholarships system with the term “Covid-19” and “Face mask”)  
 (a) April 2020  
 (b) April 2021 and  
 (c) April 2022.

masks and environmental impacts of microplastic (MP) pollution. The sheer number of published studies implies that there must be some feasible approaches to properly dispose off face masks and reduce microplastic pollution. However, there is a dearth in literature for a holistic overview of personal protective equipment and its proper disposal in a sustainable manner.



**Fig. 2.** Structure of SARS-CoV-2 and its viral transmission mechanism.

## 1.2. Virus transmission mechanism

### 1.2.1. Contact transmission

When an infected individual comes into close proximity of a healthy person, direct or indirect contact transmission is possible (Fernstrom and Goldblatt, 2013). In general, indirect transmission happens when a healthy person uses an infected individual's object or comes into touch with a virus-infected inanimate surface. While, contact transmission occurs when an infected individual comes in physical contact with a susceptible host, or when pathogen infectious secretions are inhaled. COVID-19 is contagious and spreads through direct human touch, or inadequate hand hygiene or inability to follow disease control guidelines can result in self-inoculation (Kwok et al., 2015). Fig. 2 illustrates the viral transmission method of SARS-CoV-2.

### 1.2.2. Droplet transmission

Droplets with viral pathogens may be dispersed over a metre radius during sneezing, speaking and coughing. Such infected droplets collide with objects or, come into close contact with mucosa from the respiratory system, promoting the transmission of diseases. Droplet and aerosol propagation in congested areas have become a highly complex process, with limited information on the actual paths under various microclimatic conditions. The droplet and aerosol transmission mechanisms are also closely linked to the invasiveness of the sickness. Understanding these occurrences is crucial for disease management in a limited region (Jayaweera et al., 2020).

### 1.2.3. Aerosol transmission

Fine aerosol particles that remain suspended in the air for an extended period and travel at the same speed as the surrounding air might trigger various health issues in individuals. For instance, SARS-CoV-2 has a three-hour life cycle and then persists for several hours in the environment (Van Doremalen et al., 2020). Other hypotheses contend that particles with an aerodynamic radius equal to or less than 1 cm should be classified as aerosols - Gralton et al. (2011) reported the proficiency of aerosols to be airborne for an extended duration and, to reach the alveolar region (i.e., respirable portion) of the host's lungs. Inhalation of aerosols of nominal size was determined to be more probable, causing disease in the alveolar tissues of the lower respiratory tract. The survival of airborne microbes was largely affected by ambient air factors such as humidity, sunlight (or similar form of radiation), ventilation and ambient air temperature. Aerosol-based viral transmissions lose or acquire viability and infectivity depending on the corresponding environmental stress they are subjected to, before reaching a susceptible host. The specifically available genotype, the composition of bioaerosols harbouring virus with their payload, and physical conditions in the surrounding affect the tolerance of aerosols with viral presence (Schuit et al., 2020).

## 2. Face masks

Respiratory protection is one of several measures reported to decrease the transmission of infectious and viral diseases significantly. Due to increased pathogenic transmission and the necessity to safeguard the public and the health professionals, demand for medical devices and Personal Protective Equipment (PPE) has exponentially increased, with protective masks being one of the most popular. The use of face masks to inhibit respiratory illness or to prevent pollution is a well-established method (Bae et al., 2020). Leung et al. (2020) observed that wearing a mask can successfully limit the propagation of pathogenic entities from symptomatic patients, e.g., influenza, coronavirus, and rhinovirus. Government organisations and health institutions have made their use mandatory during the ongoing COVID-19 pandemic as they protect non-infected users from inhaling droplets and aerosols and infected patients from exhaling them into the

**Table 1**  
Types of face masks and their specifications.

Type Of Mask	Material Composition	Filtering Efficiency	Uses	References
N95	A non-woven polypropylene cloth with a fine mesh of synthetic polymer fibres. Composed of four layers.	95 % for particles sized 0.1–0.3 $\mu\text{m}$	Airborne particles, virus, bacteria, non-oil particles, engineered nanoparticles	Tcharkhtchi et al. (2021)
KN95	Nonwoven fabric, typically made of polypropylene. They are made up of four layers: outer, filter, cotton, and inner.	80%–95 % for particles sized 0.3 $\mu\text{m}$	Virus, germs, pollens, liquid-like sprays against non-oil particles	Yim et al. (2020)
FFP1	Multilayer mask with a filter element and an exhalation valve	$\geq 80\%$	Environmental dust mask	Lepelletier et al. (2020)
FFP2		$\geq 94\%$	Virus, bacteria, powdered chemicals, dust	
FFP3		$\geq 99\%$	Droplet aerosols, dust protein molecules, viruses, bacteria, fungi and spores, asbestos particles	
Cloth Face Mask	Cotton is the most common textile. It consists of three layers, one of which is hydrophilic.	80%–95% for particles $\geq 0.3 \mu\text{m}$	Dust, virus and bacteria	Konda et al. (2020)
SCBA	A back-plate that retains the cylinder and reduces the air pressure from high (200–300 bar) to medium (5–11 bar)	$\geq 99\%$	Emergency conditions, viruses, bacteria, smoke particles, hazardous gases	MacIntyre et al. 2015
Surgical Mask	Non-woven fabric. They are made of three layers.	60%–80 % for particles $\leq 0.3\mu\text{m}$	Virus, bacteria, pollen and dust particles	Das et al. (2021)

atmosphere (Setti et al., 2020). Numerous guidelines for the use of face masks were proposed to ensure correct usage and adequate safety. Several types of masks might be relevant for different sectors of society depending on usage, efficiency, and availability; for example, N95 respirators were suggested for healthcare professionals while surgical masks were recommended for public use. There are a variety of masks ranging from homemade masks to face shields—the most popular of which are community masks, surgical masks, and respirators (Chughtai et al., 2020). Table 1 records the different types of face masks, its material composition, uses and efficiency.

### 2.1. Homemade masks

According to the CDC and WHO (World Health Organisation, 2020), homemade face masks made of household items should only be used as a final prophylactic measure against large respiratory droplets. Homemade masks are typically manufactured without quality control using a rudimentary fabric base, mostly made of cotton and similar types of fibres. Homemade masks were recorded to be woven (cross-thread), knitted (fibres with interconnecting loops) and felted (disoriented fibres in compressed form). No well-defined protocol was observed adequately describing mask design, layer count, filtering efficiency, material to be used, or breathability rate (Clase et al., 2020). Fabrics such as nylon, cotton, polyester and silk were reported to have a relatively low filtration effectiveness of 5 to 25%, which may be enhanced without affecting flow resistance by triboelectric charge (Zhao et al., 2020). Filtration effectiveness is affected by the layer and thread count of the concerned fabric. Clase et al. (2020) reported a correlation - a filtering efficiency of more than 80% was predicted for a corresponding thread density of 118 threads. $\text{cm}^{-1}$  or more. The effective screening of respiratory droplets with a diameter of 1 to 10  $\mu\text{m}$  was observed by increasing the layer count in fabric masks. Such masks were further reported to be capable of blocking droplets of diameter 20 to 30  $\mu\text{m}$  as well (Karmacharya et al., 2021).

Several studies have demonstrated the effectiveness of cloth masks composed of four layers of 100-TPI muslin fabric, two layers of tea towels, two layers of 600-TPI cotton, two layers of cotton T-shirts, 600-TPI cotton with 90-TPI flannel and two layers of linen tea towels According to Konda et al. (2020), combining various forms of fabrics may improve the efficiency of filtration — this is largely due to the synergistic effects of two different forms of filtration. Electrostatic interactions are frequently observed in a wide variety of natural and synthetic fabrics (Perumalraj, 2015). Hence, the electrostatic interactions coupled with the process of mechanical filtration results in an improved filtration efficiency for such types of fabric masks. Hao et al. (2021) studied the filtration performance of a range of domestic fabric and fibrous materials and concluded that layers of fibrous filters might achieve levels of filtration equivalent to those of modern facemask materials.



## 2.2. Community/Non-medical masks

A community face mask is a low-cost protective gear devised from typical cotton fabric, and resides on the lower section of the user's face. Such masks were designed to act as the first line of defence, preventing droplets from circulating in the air and infecting others. The usage of handmade fabric masks has increased in light of the recent 2019–2020 COVID outbreak. These fabric masks were reported to be inferior as a prophylactic measure against COVID-19 pathogens compared to their N95 counterpart. However, they are capable of acting as a rudimentary layer of protection against aerial contaminants, such as pollen and dust particles (Das et al., 2021).

China, in particular, examined the usage of cloth masks in the community far ahead of the pandemic (Jain et al., 2020). Yang et al. (2011), performed a survey of 400 healthcare professionals working in eight hospitals in Beijing, and found that the majority (70%) of employees self-reported good mask adherence. Furthermore, washable, reusable cotton-yarn masks were the most often reported type of mask (59.8%) worn by participants, followed by medical masks (40.2%). While Jang and Kim (2015) investigated the efficacy and composition of several commercial cloth masks, they observed that nylon, polypropylene, polyurethane, polyester, polyester microfibre, and spandex are the most often utilised materials.

While, the WHO recommends a three-layered facemask with the hydrophobic middle and outer layers constructed with PE, PP (or their blends) and the hydrophilic inner layer constructed with cotton (or their blends). Sharma et al. (2020) reported that cloth face masks with multiple alternating layers made up of cotton, and any of these fabrics – silk, chiffon, or flannel, may attain a filtering efficacy of up to 90%. The filtering efficacy of the two-layered cotton fabric face mask with 240 threads.cm<sup>-1</sup> was 99.5%, comparative to N95 masks (99.9%) for particles larger than 300 nm. Likewise, Ma et al. (2020) reported a protection efficiency of 99.9% against the avian influenza virus whereas handmade fabric masks made from polyester and kitchen towels blocked 95.15% of incoming pathogens and surgical masks successfully resisted 97.14% of contaminants. At the same time, other research has indicated that a variety of additional parameters, including thread count, layer count, fabric type, and water resistance, affect the filtering performance of cloth masks (Chughtai et al., 2020).

Particle sizes of 0.3 µm and larger were used to evaluate the filtration efficiency for different forms of single-layer fabrics. The efficiency of filtration was recorded to be in the range of 5%–80% to 5%–95% for these different materials. However, a corresponding improvement to filtration efficiency was observed with the utilisation of multiple layers and the optimal efficiency was recorded with multiple materials arranged under specific combinations. For instance, the filtration effectiveness of cotton blends with flannel, chiffon and silk was more than 80% (<300 nm) and greater than 90% (>300 nm). Cotton was the popular choice for fabricating cloth-based masks – the efficiency of the cloth masks improves at higher thread counts and significantly improved the filtering efficiency. Studies report leakages produced due to improper mask fits leading to up to 60% loss of filtration effectiveness. Such findings suggest an existing dearth in literature for design studies exploring the fit and leakage issues in cloth masks. Ultimately, the combination of used materials in cloth masks has the ability to provide substantial protection against aerosol particle transmission (Konda et al., 2020).

## 2.3. Medical/Surgical masks

Surgical face masks were initially intended to trap and filter droplets carrying pathogens emitted from healthcare personnel's mouths and nasopharynxes during surgery, therefore protecting the patient. A variety of pathogens such as *Candida albicans*, *Pseudomonas aeruginosa*, *Enterococcus faecalis*, *E. coli* and *Staphylococcus aureus* were used to assess the antibacterial nature of surgical masks (Tseng et al., 2016). The biological impact of surgical masks was recorded to become increasingly significant with a subsequent rise in use time, owing to their tendency for bacterial shedding (Liu et al., 2019). The wide pore size and poor fit qualities of traditional bottlenecks their efficiency in providing the adequate protection against viral infections. Surgical face masks feature high permeability (air, water vapour), great heat and comfort attributes, electrostatic properties, and super hydrophobicity, in addition to filtering capacity (Babaahmadi et al., 2021).

The World Health Organisation in light of the recent global health crisis advised nurses, physicians, patients, and other hospital employees to use medical or surgical masks to protect themselves (Das et al., 2021). Also, surgical masks, which were solely used by medical professionals, are now worn by the general population (Gandhi et al., 2020). The melt-blown layer provides filtering capacity by melting a plastic and then blowing it from both sides onto a rotating barrel (Sureka et al., 2020). The high degree of filtration can be achieved by a very thin deposition of accumulated fibre matter from textiles, wrapped on both sides with conventional non-woven bonded fabrics. Polypropylene, polystyrene, polycarbonate, polyethylene, polyester, polyamide, polyethylene terephthalate, polyacrylonitrile, and polylactic acid can all be used to make surgical face masks. Aside from fibre selection, the manufacturing technique, web structure, and the cross-sectional shape of the fibre and its variation all have an impact on the filtration effectiveness of surgical face masks.

Surgical face masks protect healthcare personnel from droplet communication when worn within 1 to 2 m of the patient. It is expected that the threat will be reduced by at least 80% (Das et al., 2021). Surgical masks were reported to prevent the transmission of viruses, it has been found that coronavirus may live on the surface of the mask for up to a day (Chin et al., 2020). The general construction or fabrication of the mask includes an external hydrophobic layer (resistant to stains and droplets), filtration sublayers, a smooth outer layer in contact with the user's face and malleable nosepieces upon the nasal bone, and headbands/ear loops (Tebyetekerwa et al., 2020). A combination of processes such as spun bond, melt blown and electro spun are employed to synthesise the multilayer filtration structure of surgical facemasks using

non-woven materials (Khayan et al., 2021). Erben et al. (2016), informed the use of electro spun layers over melt blown or spun bond sublayers to gain the mechanical robustness essential for processing the material into a finished product. A 3-ply version of the surgical masks is formed of melt blown polymers, typically polypropylene, sandwiched by two layers of fabric (non-woven), whereas the 4-ply surgical mask contains an extra layer with an activated carbon as a filtering layer (Das et al., 2021).

Over the last decade, the scientific community has migrated towards more sustainable alternatives for medical purposes (preferably biodegradable polymers), to address the growing environmental concerns (Nair and Laurencin, 2007). Various bio-based filtering media, which include chitosan, gelatin, polylactic acid and cellulose have recently been commercialised as biodegradable facemasks. Additionally, other biopolymer combinations, such as polylactic acid/polyhydroxy butyrate, sericin/polyvinyl alcohol/clay (Cloisite 30B), cellulose/ polyethyleneimine, and Ag nanoparticles, are also used. These materials feature high filtering efficiencies and provide filtration of bacteria and other foreign particles act as a barrier against respiratory droplets carrying pathogens, particulate and bacterial filtration, and provide additional fit and comfort (Babaahmadi et al., 2021).

#### 2.4. Certified - Approved masks

Respiratory Protective Equipment (RPE) is often designed to protect the user's respiratory tract from a contaminated environment that has the potential to produce adverse health consequences. High-performance screening masks are referred to as filtering facepieces (FFP). They are often used in polluted workplaces to remove vapours, dust particles, and infectious microorganisms from the air. A complex nexus of polypropylene microfibrils is used to enable mechanical filtration and electrostatic interactions in such types of masks. Furthermore, these facemasks prevent the particulate inhalation in the form of dusts, droplets and aerosols (Tcharkhtchi et al., 2021).

FFPs can be segregated into three categories: FFP Type-1, FFP Type-2, and FFP Type-3 with four-fold, ten-fold, and twenty-fold respectively. FFP1 and FFP2 sieves a minimum of 80% and 94% of aerial particulate matter respectively. FFP3 has the most extensive list of precautions and is the only one allowed for use in UK healthcare settings. Regulations ensure respirators have a maximum of 2% overall leakage under thorough assessment with bio-aerosols. Airborne particulate matter or pathogenic entities in the range of 0.1 to 5  $\mu\text{m}$  of effective diameter can be screened with FFP3 respirators with 99% efficiency (Brochot et al., 2021).

Electrostatic media are frequently utilised in the filtration system of face mask respirators, implying that increased respiration permissibility with low cost and high filtering effectiveness should be used for this purpose (Bergman et al., 1981). According to the filtration theory, moisture increases penetration through the filtration medium, especially if the fibres of the mask are moist and the interstitial voids are already filled with liquid. Hence, users are discouraged from wearing moisture (sweat) rich facemasks (Bungău et al., 2019). Most manufacturers address this issue by covering the filter with activated carbon, which absorbs moisture and so increases the life and efficacy of the filter (Otrisal et al., 2021). This type of ultra-fine fibre significantly improves filtering efficiency while lowering permeability to near-zero levels (Subramanian et al., 2009). Concentration zones for polarity corresponding to different electrical charges, were observed to be generated by fibres in an electrostatic filter medium. In a corona discharge, this polarity is created during the web construction process (tribo-charging when multiple fibres rub together like resin wool) and fibre production (Brown, 1993). Given the nature of electrostatic filtration, when the filter comes in contact with fluids or humidity, its charge quickly decreases, reducing its efficiency and when the filter dries, it gets regained.

The National Institute for Occupational Safety and Health (NIOSH) classifies masks into three categories based on particle filtration and oil resistance efficiency as N, P, and R. Furthermore, N-type respirators are categorised into three types based on particle filtering effectiveness: N100, N99, and N95. While, N95 masks are a subset of N95 FFPs that are widely used in healthcare settings (Shakya et al., 2017). It is structured in four layers: an inner layer, a filter layer, a support layer, and a mask filter layer that extends from the outside to the inside and is equipped with a small fan used for proper ventilation and to assist in breathing reinforcement (Tcharkhtchi et al., 2021). Respirators of the R (Oil Resistant) and P (Oil Proof) kinds are classified into three subcategories respectively: R100, R99, R95, and P100, P99, P95. The corresponding capacity of filtration was assessed at 99.7% and 99.9%, respectively.

Other subtypes of the N95 respirator include KN95, valved N95 and KN90 (with and without valves). KN90 masks fitted with valves are favoured in food processing, construction, metallurgy, and non-ferrous metal processing industries. Allison et al. (2020) reported such masks as an adequate measure against oil pollutants and non-oil particulate contaminants e.g., fog, dust-sized particulate matter, and smoke. Recent studies have explored the efficiency evaluation of N95 and P100 before and after physical activity and revealed that the permeability values were almost comparable. However, the outline after exercise exhibited modification, owing to the advantage of utilising P100 masks (Tcharkhtchi et al., 2021).

#### 2.5. N95 Masks

N95 mask can be characterised as a particulate matter filtration mask meeting the N95 standard for air filtration as directed by the National Institute for Occupational Safety and Health (NIOSH). N95 standard for air filtration. They are functionally equivalent to some non-US-regulated respirators, such as the EU's FFP2 respirators and China's KN95 respirators (Otrisal et al., 2021). Under laboratory conditions, N95 masks maintain exceptionally high filtering performance



up to 11 years past their expiration date when reprocessed with ethylene oxide sterilisation. Thus, when a proper face seal is used, N95 respirators can provide great protection against airborne particles (Qian et al., 1998). Various manufacturers of N95 masks had different filtering efficiency for most of the penetrating particles ranging between 0.1 to 0.3  $\mu\text{m}$ . Filtering efficacy improves with a particle size above the specified particle size, reaching 99.5% or greater at 0.75  $\mu\text{m}$  (Swetha et al., 2020).

The N95 mask has four layers: a hydrophobic polypropylene surface, a polymeric layer constituting of cellulose with polyester, a melt blown polymer layer and a spun bound polypropylene layer. Positively-charged metal ions (such as zinc and copper) may be employed on the cellulosic layer to induce a negative electrostatic charge on the membrane and subsequently attract bacteria and viruses (Liao et al., 2021). N95 respirators have two advantages over plain fabric or surgical masks: they are more than 95% effective at removing 0.3  $\mu\text{m}$  molecules and are checked to ensure contagious droplets and contaminants do not actually leak across the mask (Swetha et al., 2020).

A valved N95 respirator allows to readily exhale air, making it more comfortable to use and preventing moisture build-up inside the mask. The problem with valved N95 respirators is that they only filter during inhalation and not exhalation. In a situation such as COVID-19, this one-way protection puts everyone around the wearer at risk. The addition of a valve in these sorts of masks hinders the containment efficiency of contaminants from the user into the environment, making them less than ideal for infection control scenarios (Eurosurveillance Editorial Team, 2020). As a result, valved respirators are no longer utilised in hospitals or other medical facilities.

The electrostatic filtering of conventional N95 masks is provided by a layer made up of a non-woven melt-blown mesh of charged polypropylene fibres. The majority of the pores in this mesh have a typical length scale of around 15  $\mu\text{m}$ , and roughly 90% of the space is void. This layer is supported and mechanically filtered and has two or more quasi-rigid layers. Polypropylene is a dielectric electret that can store a charge or have a net tiny dipole moment. Furthermore, its electrical polarisation capabilities are frequently improved by adding various additives to the polymer melt, such as magnesium stearate or  $\text{BaTiO}_3$ , to improve the electret performance. (Hossain et al., 2020). Breakthroughs in nanotechnology have offered a platform for minimising the likelihood of infectious organisms being transferred through faulty protective equipment. To achieve this critical improvement, antiviral nanoparticles such as metal and metal oxide-based nanomaterials, carbon nanomaterials, and organic nanomaterials are incorporated in fibres or non-woven fabrics that are frequently used in face protection materials (Zhou et al., 2020; Ray et al., 2020). Ren et al. (2018) suggested coating non-woven textiles with N-halamine to create fabric materials with antibacterial and antiviral properties.

## 2.6. Biodegradable face masks

Surgical face masks' protective components are durable enough for several uses; however, they are primarily designed for the disposable market. As a result, the environmental consequences of universal production on such disposable mediums must be considered. One solution to this problem might be the use of reusable/alternative, fibre-based, biodegradable precursors for the production of masks (Babaahmadi et al., 2021). Over time, masks made of biopolymeric materials disintegrate into carbon-based materials, amicable gases, and water through natural biological processes (Leja and Lewandowicz, 2010). Polymers susceptible to enzymatic and hydrolytic decomposition are two forms of biopolymers. Biodegradable polymers include natural and synthetic polymers. While, enzymatic degradation occurs in most natural biopolymers, synthetic fibres are easier to make and have better mechanical properties than natural fibres. Biodegradable polymers may act as a viable filtering media in surgical face masks (Babaahmadi et al., 2021). Novel biodegradable facemasks composed of gelatine, polylactic acid (PLA), cellulosic, proteinaceous, and chitosan-based materials have been successfully fabricated recently. Various biopolymer combinations are employed to improve filtering efficiency and functionality, Clay (Cloisite 30B)/Poly Vinyl Alcohol (PVA)/Sericin, and Ag nanoparticles (Purwar et al., 2016). Gluten, a cereal by-product with good cohesive characteristics, is ideal for the synthesis of mechanically strong fibres. Electrospinning of gluten can be conducted alone or by adding Poly Vinyl Alcohol (PVA). 99% of gold and silver nanoparticles are successfully sieved by electrospun membranes formed of 5% gluten mixed with PVA (Das et al., 2020). Ultrafine nanoweb film may be produced by treating gluten chemically — this subsequently improves the surface charging characteristic during the process of electrospinning.

## 2.7. Full-length face shield

Full-length face shields exist in a variety of shapes and sizes, but they always provide a plastic barrier to protect the face from exposure to pathogen-rich respiratory droplets and other particulate matter. The faceguard seals off possible gaps in lying in between the face shield and the forehead and thereby, ensures proper flow of air is maintained. Headbands made of elastic and a transparent shield that runs across the face (composed of polycarbonate) make up the helmet. It shields the wearer from coughing splashes and other liquid droplets. It provides virus protection along with the advantage of it being lightweight and low-cost, and is mostly employed in clinical settings (Tcharkhtchi et al., 2021). The face protection was reported to adequately block 96% of virus particles and droplets while maintaining 18 inches from the surrounding environment (Lindsley et al., 2014; Das et al., 2020).

### 3. Health impacts

Face masks have been demonstrated to decrease COVID-19 transmission and save lives. Various health organisations continue to recommend that medical staff is caring for suspected or confirmed COVID-19 patients wear medical masks or respirators that fulfil the N95, FFP2, FFP3 or any other equivalent requirements. Universal masking has also been recommended for all individuals including workers, patients, visitors, service providers, and others in all health institutions ([World Health Organisation, 2020](#)). Face masks are a potential biohazard with substantial concerns owing to improper disposal, despite their vast use and significance, as the majority of these masks are manufactured of polypropylene, polyurethane, polyacrylonitrile, polystyrene, polycarbonate, polyethylene, polyesters, etc. These polymers include a wide range of chemical compounds, including plasticisers and flame retardants, some of which have been reported to be toxic to human health. However, the risks associated with using face masks and their impact on human health are poorly documented ([Potluri and Needham, 2005](#)).

#### 3.1. Effect of Toxic Chemicals in facemask

According to a German specialist, a number of face masks, including surgical masks, have lately been found to contain harmful and prohibited substances. Modern Testing Services Global, Hong Kong and Augsburg detected high levels of potentially carcinogenic chemicals on surgical face masks, including formaldehyde, aniline, poisonous Fluorocarbons (PFCs), and others. Many scientific investigations have connected the use of formaldehyde in some N-95 and surgical masks to allergic contact dermatitis. Filtration efficiency, breathability, differential pressure, splash resistance, and microbiological cleanliness are among the current medical mask testing criteria. Non-medical masks are usually unsupervised, whereas medical masks must pass strict examinations. Testing these masks for the presence of harmful substances is not required by law ([Aerts et al., 2020](#)). The influence of hazardous chemicals used in the production of face masks on human health is addressed below.

##### 3.1.1. Formaldehyde

Formaldehyde, typically labelled as formalin, formic aldehyde, methanediol, methane, methyl aldehyde, methylene glycol, or methylene oxide, is a colourless, flammable chemical that is widely used in the agriculture, food, pharmaceutical, building materials, and apparel industries. Inhaling even low quantities of formaldehyde can induce coughing, wheezing, shortness of breath, and chest tightness, which can progress to bronchitis and pneumonia ([Raval and Sangani, 2021](#)).

Acute exposure to formaldehyde can cause lacrimation, nausea, coughing, wheezing, shortness of breath, chest tightness, stomach discomfort, and diarrhoea, which can progress to bronchitis and pneumonia. If the exposure continues, the reactions might become more severe. At greater concentrations, breathing may become difficult and severe lung damage may occur. When formaldehyde enters the body, it is absorbed and can cause lesions in several organs; if the individual is pregnant, there is a chance that the foetus will be aborted ([Raval and Sangani, 2021](#)).

Formaldehyde's potential impacts are most pronounced in tissues or organs with which it makes initial contact ([WHO, 2002](#)). Formaldehyde's harmful effects are more obvious in tissues or organs it first contacts. This includes the pulmonary, aerodigestive, oral, and gastrointestinal mucosa after inhalation or ingestion. Clinical studies and epidemiological surveys in industrial and residential contexts reported ocular and respiratory discomfort. Higher amounts can permanently affect lung function. Although epidemiological studies have not revealed a conclusive link between formaldehyde exposure and human cancer, an elevated risk of upper respiratory tract malignancies cannot be ruled out. As a result of the increased risk of nasopharyngeal cancer and leukaemia, the WHO's IARC (International Agency for Research on Cancer) has categorised formaldehyde as "carcinogenic to humans" ([World Health Organisation, 2020](#)).

##### 3.1.2. Aniline

Another important component identified in face masks is aniline (commonly referred as phenylamine, aminobenzene, or aminophenol), which is widely employed in the production of polyurethane foam, agricultural chemicals, synthetic colours, antioxidants, rubber stabilisers, herbicides, varnishes, explosives, etc ([Raval and Sangani, 2021](#)). Aniline can be harmful if ingested, inhaled, or comes into contact with the skin. Greater concentrations of aniline can damage haemoglobin, reducing the blood's ability to transport oxygen, causing difficulty in breathing and leading to death. Symptoms of aniline poisoning include headache, nausea, vomiting, dry throat, confusion, vertigo, loss of muscle coordination, weakness, disorientation, lethargy, fatigue, and coma ([Carreón et al., 2014](#)).

##### 3.1.3. Fluorocarbons

Perfluorocarbons make water-repellent coatings in commercial face masks (PFCs). It has carbon-fluorine bonds and the issue with fluorocarbons is the presence of Perfluorooctane Sulphonate (PFOS) and Perfluorooctanoic Acid (PFOA). According to the CDC and EPA, both of these carcinogens may persist in the human body for extended periods and pose health risks ([Centers for Disease Control and Prevention, 2017](#)). Large doses of PFOA have been demonstrated to affect growth and development, reproduction, and liver damage. PFOA exposure has been observed to be related to kidney cancer and testicular cancer ([Barry et al., 2013](#)). In addition, excessive PFOA exposure has been linked to pregnancy-induced hypertension, hypercholesterolemia, thyroid disease, and ulcerative colitis ([Nicole, 2013](#)).

### 3.1.4. Phthalates and Organophosphates

Since most face masks are constructed of polymers, and phthalates are often employed as polymer additives, the face mask may expose people to phthalates. However, little is known regarding the presence and potential risks of phthalates in face masks (Xie et al., 2021). Polymers such as polyester, polypropylene, polyurethane, polyacrylonitrile, polystyrene, polycarbonate, and polyethylene are used to make single-use face masks (Potluri and Needham, 2005). These polymers include a wide range of chemical compounds, including plasticisers and flame retardants, some of which are known to be toxic to human health. Commercial masks may also contain chlorinated phenols, polycyclic aromatic hydrocarbons (PAHs), and some plasticisers such as phthalates (Fernández-Arribas et al., 2021). Phthalates are basically a family of synthetic compounds that are used as plasticisers and stabilisers in a variety of consumer items (shower curtains, children's toys, cosmetics) and personal care products (fragrances, nail polishes, deodorants, and lotions) (Heudorf et al., 2007).

Earlier, phthalates were detected in cotton clothing, sanitary napkins, paper diapers, toys, and other textiles and skin-contact products (Gao et al., 2019). Widespread in personal care products, phthalates may have an effect on reproductive function (Ziv-Gal et al., 2016). Pesticides, wood coatings, adhesives, solvents, lubricants, and medical devices including tubing, blood bags, surgical gloves, and dialysis equipment all include phthalates. The vast array of products that contain phthalates results in an annual global production and consumption of phthalates of more than 18 billion pounds (Hannon and Flaws, 2015).

These phthalate exposures have been associated with human contact allergies and carcinogenic concerns (Li et al., 2019). As face masks come into close contact with the nose and mouth, allowing phthalates to be acquired through cutaneous absorption, inhalation, and ingestion. These combined exposure pathways may result in increased phthalate intakes relative to other goods. However, there is no international norm or guideline regarding the use of phthalates in mask products (Xie et al., 2021). A common organophosphate, Tri-n-butyl phosphate (TNBP) is a possible carcinogen that has been found to disrupt endocrine, reproductive, and nervous system development. Furthermore, the current study suggests that wearing a plastic mask for a lengthy period of time may result in a range of skin issues (Aerts et al., 2020; Xie et al., 2020).

### 3.2. Effect of prolonged exposure to face masks

According to a March 2020 WHO research on the prudent use of protective equipment, "the use of a single respirator for more than four hours might be uncomfortable and should be avoided". It is asserted that in previous public health situations involving acute respiratory infections, "respirators" (e.g., N95, FFP2, or other standard masks) were utilised for extended periods of time due to a lack of protective equipment. This entails continuously wearing the same respirator while caring for several patients with the same diagnosis (World Health Organisation, 2020). The median recorded tolerance for surgical masks is around 7.7 h, but the tolerance for N95 masks ranges between 5.8 and 6.6 h. The New South Wales Clinical Excellence Commission suggests removing masks after a specific time limit; wearing a mask for more than four hours is likely to cause discomfort and raise the risk of self-contamination (Clinical Excellence Commission, New South Wales Government, 2020). The CDC has set recommendations for the extended use and restricted reuse of N95 respirators; the CDC supports more prolonged usage over re-use, emphasising that respirators must remain "fit and functional" throughout extended use. According to them, employees in other sectors use N95 respirators for many hours at a time, with the respirators remaining functional for up to 8 h. In tests involving healthcare workers, respirators were worn for several hours, and the maximum usage time appeared to be limited by practical concerns rather than a two-hour limit (Planning, 2020).

Long-term mask use may have physiological and psychological consequences, as well as a negative impact on productivity. As a result, masks decrease the duration of an activity that may be continued (Shubhanshu and Singh, 2021). Particularly, persistent use of facemasks has been found to impair the cognition of around one in four health care professionals, raising apprehensions that PPE may exacerbate uneasiness and perhaps compromise workplace safety. In a study conducted in northern Europe, participants were asked to perform a familiarisation trial, followed by a control (uncovered face) and facemask (KN95, Alchemy, Shenzhen, China) test. At baseline and after 45 min of light labour, motor-cognitive performance, physiological, and perceptual parameters were assessed. Long-term use of a facemask increased dyspnea, resulting in 36% more shortness of breath than the control group. Exposure to heat, both at rest and during work, can induce hyperventilation, which reduces arterial CO<sub>2</sub> and cerebral blood flow. Masks were saturated in perspiration, making breathing even more difficult. Morris et al. (2021) suggested the change of masks at regular intervals. They outlined the need for designing a mask useable in hot settings with ample measure for ventilation and comfort of the user.

Continuous use of N95 and surgical masks for more than eight hours results in headaches, acne, skin breakdown, rashes, and diminished cognition, and impairments in vision, communication, and temperature regulation. Mechanical factors such as tight straps and the resulting pressure on superficial facial and cervical nerves, hypercapnia, hypoxemia, sleep deprivation, irregular mealtimes, and emotional stress can all contribute to headaches among healthcare professionals (Rosner, 2020). Masks reduce airflow and raise carbon dioxide (CO<sub>2</sub>) levels, leading to hypercapnia. Healthcare practitioners report hypoxemia symptoms such as chest pain and tachypnoea due to extended mask usage. A buildup of exhaled CO<sub>2</sub> between the mask and the face will result in increased lung ventilation, respiratory activity, impaired cognition, and disorientation since CO<sub>2</sub> is a known respiratory stimulant. Therefore, frequent brief breaks, neck massages, and extra hydration were suggested, especially before to the start of the shift (Johnson, 2016).

Additionally, extended mask usage may cause erythema, eruption, acne, pustules, papules, pigmentation, and contact dermatitis along the areas of contact (Das et al., 2020). The moist environment and pressure from tight masks usually clog facial ducts, increasing acne. Potentially causing urticaria and contact dermatitis is sensitivity to mask and PPE components (Al Badri, 2017). According to another survey conducted by Szepietowski et al. (2020) in Poland, 60.4% reported wearing face masks in the previous week; 19.6% had facial itching as a result of wearing a face mask; the worst degree of itching (WI-NRS) was 2.06–4.07 points (range: 0–10 points), indicating a moderate degree of itching. Respondents most frequently described the annoyance as tingling (37.4%), burning (26.3%), pinching (18.3%), or stinging (9.1%). It was discovered that people who used face masks for extended lengths of time during the day had increased irritation. As a result, it is reasonable to conclude that wearing face masks causes discomfort in individuals of all ages, which may lead to scratching and improper usage of face masks, so reducing their effectiveness and the level of protection they offer.

### 3.3. Psychological aspects

Human behaviour is also often influenced by the subjective experience of an individual. Subjective experience depends on a subject's ability to understand events in their environment in order to facilitate their fundamental needs. This is the primary reason for the intensification of individuality in the human psyche. According to self-determination, autonomy, psychological relatedness, and competence are three universal, essential demands for optimal well-being (Ryan et al., 2008). These psychological demands may be one of the pivotal factors in influencing attitudes toward mask-wearing and compliance with COVID protocols. Autonomy is one such essential psychological demand – it embodies the ability to have free will and self-control. When people lose their sense of autonomy and personal independence, they are reported to experience psychological reactance, resulting in various undesirable behaviours. The human psyche attempts to restore lost freedom through reactance in the form of noncompliance, rage, and so on. Such forms of reactive behaviour take precedence when individuals perceive a hindrance in their freedom of choice (Rains, 2013). The psychological need for autonomy motivates individuals to take necessary measures in order to restore the lost freedom. This is mainly true for COVID-19 protocols directing the use of face masks – stringent policies obligating citizens to wear a mask, may have an influence on the citizen's conception of autonomy (Scheid et al., 2020).

The use of facemasks may result in pulmonary issues, which in turn levies psychological stress on the user. The N95 filter is designed to filter out at least 95% of dust and mould from the air. However, Tian et al. (2020) reported that such filters could induce cerebral hypoxia, disorientation, chest tightness, and other symptoms under prolonged usage, owing to their dense packing. According to German labour insurance laws, workers should not use N95 masks for more than half an hour at a time. As a result, these forms of face masks are not recommended for long-term usage, especially by the elderly, children and patients with cardiovascular disease. When one wears a mask, a cavity is formed in between the mask and the user's face. The exhalation process produces oxygen-deficient air, which resides in this volumetric space between the face and the mask. This, hinders the incoming filtered air and simultaneously, dilutes the concentration of oxygen in the air inhaled. Low oxygen levels initially cause cells to become hypoxic, resulting in physiological stress. Hypoxia has been reported to cause a significant elevation in user's stress levels and can further contribute to anxiety and depression (Tian et al., 2020).

Face masks cover a large portion of the human face, which can significantly impact the social interactions and emotional expressions. Facial cues and features are the primary source of information for our personal identity, as well as additional socially essential information like trustworthiness, age and gender. Bruce and Young (1986), reported such data to be crucial in aiding speech comprehension by effective analysis of facial cues, while fine-grained information was deemed essential to read the emotional state of others via expression analysis. Carbon (2020) evaluated the use of face masks and their effect on emotional cognition – the study concluded that the usage of face masks significantly affects on everyday social interactions. Subjects were unable to perceive familiar social cues and emotions (anger, disgust, fear, happy, neutral, and sad) with the notable exception of fearful and neutral faces. Hence, face masks can make social interactions more difficult since they disrupt emotional interpretations of facial expressions (Carbon, 2020).

Furthermore, the facemask users can be lulled into a false sense of security, resulting in the decreased social distance and hand-washing complacency (Greenhalgh et al., 2020). Face mask users werereported to get increasingly irritable and self-conscious over prolonged usage, causing them to touch the mask repeatedly. This irritates the face, ears, and eyes, causing infection. When exhaled air comes into contact with the eyes while wearing a face mask, it causes discomfort and urges to touch the eyes, nose, and face. Wearing a face mask reduces the volume and quality of speech, causing people to involuntarily approach closer to one another, leading to noncompliance with social separation (Ahmad et al., 2021).

In health care settings, face coverings cause communication stress (Campagne, 2021). Masks increase perceptual distance, resulting in increased feelings of loneliness. In extreme cases it can even lead to mood problems, or influence the wearer's personality (Killgore et al., 2020). In most situations, wearing face masks alter the human stress response and raise the stress index because wearing a mask obstructs breathing and interferes with the autonomic nervous system's regulation.

Meanwhile, conflicting messages, misinformation, and a lack of medical and scientific knowledge about COVID-19 create a great deal of uncertainty, and thereby jeopardising an individual's ability to control their circumstances while feeling effective and capable. A sense of validation and reinforcement of one's behaviour and beliefs enable one to feel more competent. Hence, conforming to a subject's mask-wearing views may motivate them to incorporate such practices into their lives. Furthermore, people are more likely to feel motivated if research attention is provided to refining the wearability of masks. Issues such as increased breathing resistance, high facial temperatures and headaches leading to discomfort must be addressed to provide validation and motivation to everyday mask users (Scheid et al., 2020).

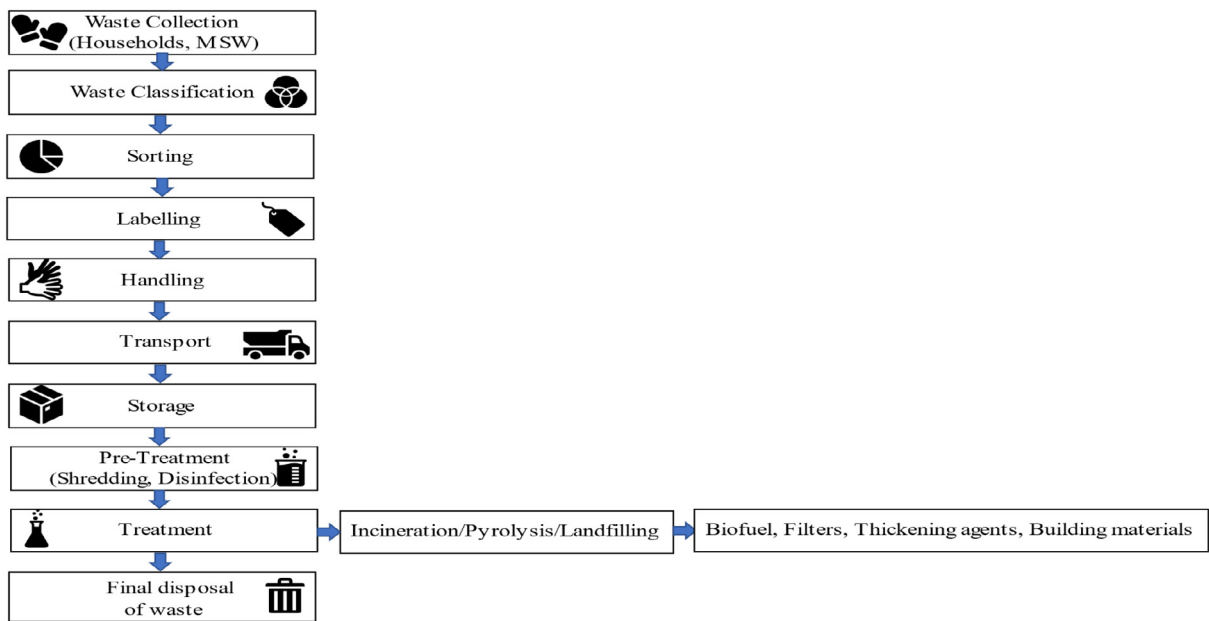


Fig. 3. Techniques for treating, processing, and disposing of discarded face masks.

#### 4. Post-usage scenario of face masks – Disposal

##### 4.1. Segregation

The COVID-19 pandemic has generated a healthcare crisis and spurred socio-economic issues worldwide. The abrupt rise in medical and household garbage has negatively affected municipal solid waste management, causing environmental problems. Another factor contributing to the proliferation of COVID-19 is poor solid waste management with high possibility that mishandling of wastes would lead to the spread of virus. This has resulted in a rise in confirmed cases and simultaneously increase the volume of medical waste connected with the pandemic at an alarming rate (Sangkham, 2020). It is widely believed that in the majority of nations, including Palestine, Vietnam, Bangladesh, Indonesia, Malaysia, India, Thailand, the Philippines and Cambodia, solid waste is disposed of in irregular landfills, causing inevitable problems and offering as the source of severe diseases and environmental issues (Ferronato and Torretta, 2019). Hence, appropriate policies for solid waste management need to be strategized and implemented at different levels of administration. Fig. 3 shows the different methods employed for the collection and treatment of disposed face masks in compliance with SDGs 3 and 12.

The COVID-19 pandemic has severely hampered the capacity to dispose of medical waste. To collect the abandoned masks, specified bins for medical waste collections were marked with points and put in public locations of cities and towns. Further, these bins were covered with double-layered medical waste bags indicated by specific colours (red, yellow) and processed as normal hospital discharge by definite employees from the waste management department (UNEP, 2020). Lastly, disinfection of the waste bag is administered using 0.5% (5000 ppm) chlorine solution before temporarily storing the waste in the disinfected bag. Peng et al. (2020) reported the inactivation of COVID-19 pathogenic entities by administering autoclaving medical waste at a high temperature ( $>70$  °C) for more than 5 min.

Hospitals and COVID-19 patient treatment locations create infectious waste that may lead to significant contamination. Such wastes must be segregated from ordinary wastes, packed, stored in a separate temporary storage facility with clearly visible warning signage, and transported to the nearby hospital for central disposal. To avoid cross contamination of wastes from general waste, waste bins in the from nucleic acid testing laboratories, observation wards, isolation wards and, clinics are put in a separate location. Medical waste with SARS-CoV-2 presence should not be retained in hospitals for more than 24 to 48 h after disposal, whereas other COVID-19-related garbage should be quarantined at home and collected 72 h later (Nghiem et al., 2020). For collection and transportation of the segregated wastes, transportation must have a sealed-off loading area with a non-absorbent surface-such vehicles should be easy to disinfect and separate from the leading vehicle. Subsequently, only specially trained workers with proper safety equipment must handle the disposal of medical waste related to COVID-19 (Rhee et al., 2020). To maintain proper hygiene, 70% alcohol solution should be used for disinfecting the vehicles before and after waste collection.



**Table 2**  
Decontamination methods used to sterilise face masks.

Decontamination Method	Equipment Required	Physical Impact on Mask	Safety Concerns	References
Ultraviolet germicidal irradiation (UVGI)	UV source – mercury lamp	N95 strength loss at 120 J/cm <sup>2</sup> . Damages the polymer and strap.	Due to the creases in masks, UV light may be blocked or distributed unevenly.	Lindsley et al. 2015
Vaporised hydrogen peroxide (VHP)	Commercially available Battelle Critical Care Decontamination System	Damaged metallic nosebands.	Organic waste can deactivate H <sub>2</sub> O <sub>2</sub> .	Torres et al. 2020
Microwave Inactivation	Microwave oven – lab grade or kitchen	N95 melting	Excessive heat (above 80 °C) damages the mask.	Polkinghorne and Branley (2020)
Moist Steam Sterilisation	Autoclave	Masks shrank and stiffened. Plastic cord slightly melted.	Moisture causes mask electrets to de-charge.	Daeschler et al. (2020)

## 4.2. Sterilisation and decontamination

To bridge the gap between the demand and the availability of N95 respirators, the Infectious Diseases Society of America has advised that personal protection equipment must be optimised. In an effort to address the limited supply of respirators, it has been suggested that they can be reused after decontamination. Changes in the respirator's appearance, structural integrity, filtering efficacy, fit, seal, and airflow resistance must be addressed for decontamination and sterilisation. Decontamination equipment, usability, cost, and maximum cycles must be evaluated. Table 2 tabulates the different forms of decontamination methods along with their associated impacts and safety concerns.

### 4.2.1. Ultraviolet Germicidal Irradiation (UVGI)

UVGI is a disinfection technology that uses UV-C light with a short wavelength (200 nm and 280 nm) to kill bacteria. It has been used to disinfect medical equipment and hospital high-touch surfaces (Casini et al., 2019). Several researchers have investigated the impacts of UVGI on N95 respirators for decontamination, with an application time of 15 mins. The majority of the focus was constrained on N95 masks and UVGI's sterilisation efficiency per cycle for such masks (Beck et al., 2018). UV-C radiation in the wavelength of 100–280 nm destroys DNA along with RNA and creates pyrimidine dimers, inactivating viruses and other microorganisms (Inagaki et al., 2020). When influenza and coronaviruses were subjected to UV doses (0.5 to 1.8 J.cm<sup>-2</sup>), there was an inactivation of almost 99.9% (Silverman and Boehm, 2020).

### 4.2.2. Hydrogen peroxide vaporisation

Hydrogen peroxide vapours have lethal properties against a broad spectrum of bacteria (Saini et al., 2020). Studies report negligible effects on the effectiveness of N95 masks after sterilising with HPV. However, it can only be used for specific N95 models that do not include cellulose. Viscusi (2007) studies used T1, T7, and Pseudomonas phage phi-6 as substitutions for COVID-19 pathogens in an investigation and found that HPV cleansing led to 100% phage extermination from one type of the N95 mask without impairing filtration function. The sterilising chamber was subjected to vacuum before being filled with hydrogen peroxide vapour. For 20 min, the hydrogen peroxide grows up to 300–750 parts per million (ppm). The de-gassing post-procedure normally takes typically four hours after the sterilising cycle is completed. As it dissolves into water and oxygen, no leftover chemical remains. Vapours are used so there is little possibility of harmful material remaining on the N95 respirator's surface. After 3–4 sterilising cycles, the N95 respirators are safe to use (Mackenzie, 2020).

### 4.2.3. Microwave inactivation

Microwave-generated steam has favorable disinfection properties. They have been proven to inactivate viruses and bacteria including coronaviruses, and are easy and inexpensive to use. The viral load on facemasks was reported to be efficiently reduced by heat treatment and microwave irradiation under an optimal period of exposure. Microwave and heat treatment was reported to successfully melt mask components successfully – the melting rate was highly influenced by the model of the mask, operating temperature, and residence time. N95 filters are primarily composed of polypropylene, sustaining a maximum operating temperature of 90°C. Consequently, adverse physical changes were observed above the maximum operating temperature. Melting was also most likely caused by high temperatures during microwave treatments. The inner nose cushion in the model 3M 1870 was recorded to be separated under microwave and heat treatments. However, the fit of the model was not hampered by any significant shrinkage and enabled the reuse of the mask (Viscusi et al. 2011).

#### 4.2.4. Autoclaving

An autoclave is generally used in primary care to sterilise surgical tools. The method of moist heat kills microorganisms by irreversibly coagulating and denaturing enzymes and structural proteins. It has been proven to work in respirators contaminated with various viruses including the H1N1 influenza (Ranney et al., 2020). Earlier investigations have suggested that under certain conditions, moist steam sterilisation can effectively decontaminate specific models of N95 FFRs. After autoclaving at 115 °C (60 min) or 121 °C (30 mins), the folded 3M 1805 and 1870/1870+ N95 models showed no visible degradation to the mask or loss of fit testing ability (Bopp et al., 2020). There was no noticeable change after autoclaving; however, the masks shrank and stiffened, and the plastic locking piece on the cord (black colour) used in the facemasks slightly melted (Kumar et al., 2021).

### 4.3. Special waste management techniques

#### 4.3.1. Waste storage

Plastic, rubber, metal, and glass make up a significant portion of the inorganic component of the majority of municipal solid wastes around the world (Kumar and Samadder, 2017). The quarantine facilities and residential areas with potentially infected patients may generate wastes with COVID-19 pathogenic presence and should be considered as an active source of contamination (Nghiem et al., 2020). SARS-CoV-2, as recently revealed, can survive for a long time on hard surfaces, including plastics (72 h), stainless steel (48 h) and paper and cardboard (24 h) (Van Doremalen et al., 2020). As a result, a 72 h collection delay is an inadequate measure against the containment of COVID-19 infection among garbage workers (Nghiem et al., 2020). Physical contact and respiratory channels are the two possible means of propagation of viral entities – hence, inadequate management may enhance the odds of COVID-19 spreading in the environment. Coughing or sneezing releases respiratory droplets into the open air. Such droplets act as a vector for the transmission of pathogens amongst a community. These vectors can lie on surfaces with the virus still active for a significant time period. As a result, an infected person's immediate environment can also be a source of transmission (Sangkham, 2020). This, in turn, may impact on the spread of the infection in metropolitan regions and similar settings due to poor municipal solid waste management (Kulkarni and Anantharama, 2020). As a result, the management of such solid wastes implemented by local governing bodies or in collaboration with the private sector should involve the supply of infectious or special waste bins in communities and public spaces for worn masks and other contagious trash (Sangkham, 2020).

#### 4.3.2. Collection and transportation

The containment and treatment of medical waste associated with the COVID-19 virus are to be handled by separate skilled individuals and automobiles unlike to those employed to collect conventional solid waste. Masks generated in residential and public areas should be double-packaged and disposed off using secure landfills or incineration. The contaminated trash is handled by designated workers, who in turn are exposed to elevated counts of occupational hazards. Hence, they should be equipped with PPEs, waterproof shoes, medical masks, protective clothing, and gloves for collecting and transferring this waste. When transporting, the concerned vehicles must be equipped with a closed loading box and maintained below 4°C (Rhee et al., 2020). Transportation vehicles are a potential source of contamination and hence must be cleansed as soon as possible. This can be achieved by thorough disinfection with a solution containing 70% alcohol, pre and post garbage collection and other end operations. Furthermore, the solution must be produced in specialised bottles allotted to the transporters and collectors. (Sangkham, 2020).

#### 4.3.3. Incineration

Incineration is a commonly used, safe, simple, and effective process for the treatment of wastes that involves burning organic waste items in both industrialised and developing countries (Ghodrat et al., 2017). The combustion of waste releases flue gas, heat and ash (solid lumps). Flue gases also contain particulate matter which must be cleansed of such particle matter before safely releasing them in the environment. Incinerators burn all organic materials at 800°C, eliminating most microorganisms while reducing solid waste volume by 85%–90%. In hospital waste incinerator treatment facilities, waste preparation, waste incineration, and flue gas purification are conducted in distinct ways. In addition, plasma incineration technology, rotary kiln incinerators, pyrolysis vaporisation incinerators, and other conventional incineration technologies have been employed thus far (Wang et al., 2020c).

#### 4.3.4. Plasma incineration

Plasma incineration is a cutting-edge method of waste disposal that transmits energy via plasma, allowing wastes to quickly disintegrate into small molecules and atoms quickly. The majority of the by-product gases produced from this process are burnt in a secondary chamber that are further purified before releasing it into the environment. Plasma incineration has a better energy efficiency than conventional incineration processes, indicating a good application prospect (Messerle et al., 2018). Since 2002, municipal-scale waste disposal plasma arc plants have been in operating in Japan and China.

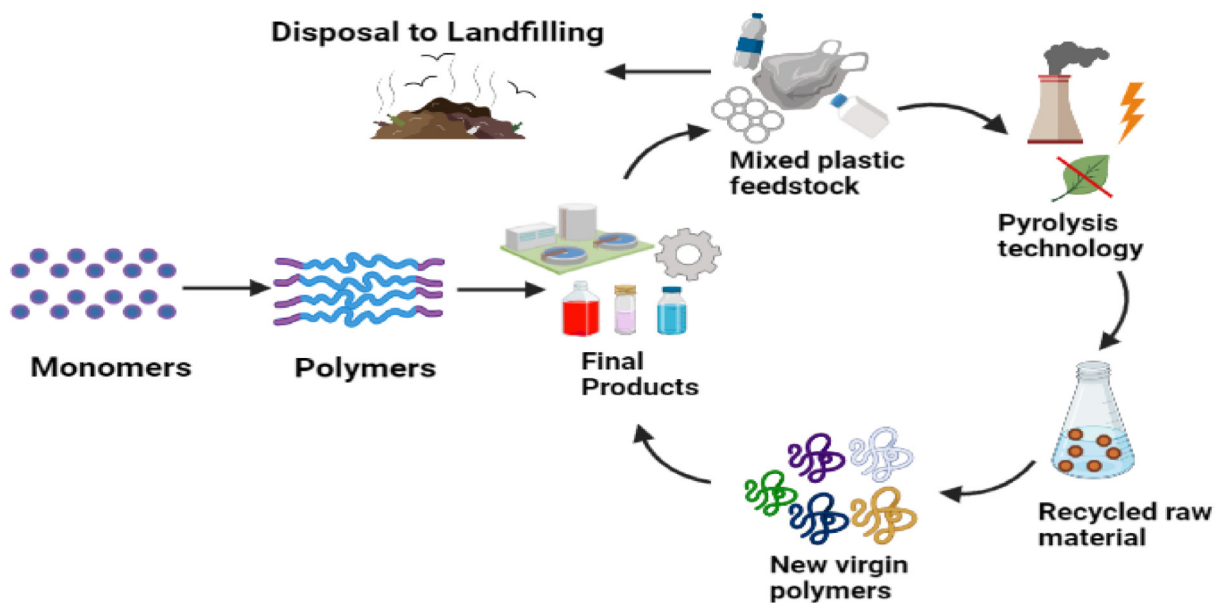


Fig. 4. Pyrolysis of polymeric materials from face masks.

#### 4.3.5. Pyrolysis

The thermochemical process of pyrolysis involves the decomposition of macromolecules in synthetic and organic plastics. It appears to be one of the most promising strategies for converting plastics to liquid fuels (Juwono et al., 2019). This solid-to-liquid conversion method exhibits a better efficiency when compared to other conventional procedures such as landfills and incineration. Several studies have concentrated specifically on the process of pyrolysis method to recover plastic-based wastes. This can be primarily accredited to the pyrolysis processes' propensity to generate fuels - Budsareechai et al. (2019) reported the application of the produced fuel to generate various forms of energy in boilers, turbines, engines and generators. Furthermore, pyrolysis is reported not to necessitate the separation of polymeric wastes from other types of wastes as a pre-processing step – this is in stark contrast compared to other forms of mechanical valorisation of waste that involves trash sorting as a necessary pre-treatment step (Quesada-Gomez et al., 2020).

The process of pyrolysis involves the treatment of plastic materials in the absence of oxygen at high temperatures between 300 °C to 700 °C, thereby enabling a thermochemical breakdown. Pyrolysis' high temperature requirement makes it easier to disinfect contaminated PPE. Pyrolysis necessitates a simple equipment design and has a low environmental impact into liquid fuel, thereby assisting in the present waste management crisis (Su et al., 2021). Using CO<sub>2</sub>-assisted pyrolysis, researchers used disposable masks to retrieve syngas and C<sub>1-2</sub> hydrocarbon (Jung et al., 2021). Torres and De-la Torre (2021) concluded that this technology appears to be promising, as it reduces CO<sub>2</sub> emissions while also providing tertiary end products.

The disposable COVID-19 face mask may be repurposed via a thermochemical technique. CO<sub>2</sub> is used as a pyrolysis reaction medium for the disposal of used facemasks. Since the face mask's primary constituents are polymers (nylon, PP, and PE), H<sub>2</sub> and a variety of HCs are obtained as the by-products from the pyrolysis process. Fig. 4 represents the recycling of polymeric materials from face masks via pyrolysis.

Jung et al. (2021) explored the process of two-stage catalytic pyrolysis of facemasks in a tubular reactor setup. The process temperature in the first stage was varied between 200 to 600 °C with an increasing heating rate of 10 °C min<sup>-1</sup> while the second stage temperature was maintained at a constant 600 °C. N<sub>2</sub> or CO<sub>2</sub> was used as a purge gas for all the setups with a volumetric input flowrate of 100 mL.min<sup>-1</sup>. The researchers suggested that carbon dioxide can be used as a mild oxidant and a purge gas to regulate gaseous effluents in a variety of thermo-chemical processes. Syngas and C<sub>1-2</sub> HCs can be produced from plastic face masks to help reduce CO<sub>2</sub> emissions (Jung et al., 2021).

#### 4.3.6. Carbonisation

Carbonisation is a standard procedure for turning waste into valuable carbon compounds that can be used in a variety of applications including environmental applications and energy conversion and storage. The process is economical in terms of energy consumption and low-effluent emissions, and it is deemed as an easy process that can yield a variety of carbon-based products as end products (Chen et al., 2020). Joseph et al. (2021) concluded that the presence of polypropylene in face masks makes it an attractive carbonisation feedstock. Furthermore, the high operating temperatures of the carbonisation process can adequately disinfect all possible contamination and pathogenic presence. The carbonisation of used face masks has recently been investigated for potential use in supercapacitors and adsorbents (Asim et al., 2021).

## 5. Environmental impacts

Polymeric materials used in face masks have been recognised as a substantial environmental source of micro-plastics and macro-plastics (Schnurr et al., 2018). They infiltrate aquatic bodies by leaching, floods, and wind dispersion, among other methods. Disposable face masks, that are composed of polymeric materials, have also been detected in the environment, firstly as litter in public spaces or in landfills, and subsequently as a new evolving source of microplastic fibres in freshwater and oceans. Insects, birds, mammals, reptiles and marine species devour or get entangled in disposed off masks and plastic wastes, posing a physical threat to aquatic life (Castro-Jiménez et al., 2019). They can obstruct the breathing anatomy in large animals and pose a hindrance to their commute (Kögel et al., 2020). This lower scavenging and mobility of the fauna, as well as food intake and consumption rates.

### 5.1. Microplastics in Water bodies

Mask waste is escalating worldwide because individuals are not using proper disposal measures for worn masks. As a corollary, it introduces a new environmental problem. Furthermore, in Sri Lanka, India and China, no adequate mask or plastic trash collection system has been identified for entire nations or parts of a region (Sangkham, 2020). This contributes a large quantity of plastic and plastic particle debris to the environment, which may wind up in streets and landfills. Furthermore, it enters the canals and reaches both fresh and salt water. This increases the presence of microplastic content in the aquatic medium (Selvarajan et al., 2020). Moreover, microplastics affect the aquatic ecosystems by absorbing dissolved organic matter to form microgels which can settle in the benthic regions of rivers and seas (Shiu et al., 2020). The production of microgel is more in marine environments because the saline water fosters its growth; it may affect filter-feeding fish and invertebrates; and, over time, it may pose a threat to humans via the food chain. Due to microbial interactions, biofilm formation can degrade the quality of water by modifying the microbiome and increasing the organic material degradation rate, resulting in a subsequent reduction in dissolved oxygen concentration (Kirstein et al., 2019).

In marine environments, Abbasi et al. (2020) observed maxima of MPs from the components of the primary mask (polypropylene, polyethylene), implying significant accumulations in a short period of time. Micro and nanoplastics may modify the physiology of aquatic species – however, Franzellitti et al. (2019) reported that the lethality of such materials is yet to be estimated accurately. Microplastics act as a carrier for heavy metals, so when fish consumes them, their gut mucosa is damaged, causing metabolic and structural issues. Plastics of micro- and nano-size may permeate biological barriers and reside within living beings (Kumar et al., 2020). Due to their fast reproduction, the process of bioaccumulation occurs in food chains. Accumulated material may be transmitted to essential organs, specifically the digestive system of the target species. Chen et al. (2017) reported that seabirds, in particular experience a blockage in their gastro-intestinal system along with internal inflammation, pseudo-satiation, and reproductive issues. The primary reason for such issues has been reported as the ingestion of plastics – Holland et al. (2016) reported that 56% of aquatic birds were found to have plastics in their stomachs. Consequently, it was also predicted that 99.9% of birds will be affected by similar gastrointestinal complications by 2050 (Aragaw, 2020).

In the long term, toxicity caused by ingesting accumulated microplastic has an impact on reproduction, survival and animal growth. Nano plastics have been reported as a source of neurotoxins in combination with genotoxins and oxidative stress in a variety of aquatic biota, including corals. Microplastics can be mutagenic and toxic to marine organisms, as well as causing hormonal disorders and immunological suppression, as they are a carrier for other hazardous pollutants such as PCBs, PAHs, and heavy metals (Chang et al., 2020).

Microplastics also get collected in aquatic creatures' gonads, feet and muscles, where they are biomagnified and passed on to humans and birds. On the other hand, it can pass through cell membranes, and lead to several immunosuppression in humans. It has also been identified as a root cause of physiological problems if retained in the blood, brain, and placenta (Häder et al., 2020).

### 5.2. Microplastics in air

Microplastics (MPs) are a leading source of environmental pollution demanding immediate attention owing to the gradual decline in human health conditions. MPs suspended in the atmosphere have the same distribution and behaviour as other airborne pollutants. Tiny filaments readily rip off garments and other fibre goods while wearing, washing, and drying, making synthetic fabrics a major source (Chen et al., 2020). It has been demonstrated that workers in companies manufacturing synthetic fibre materials (e.g., nylon, polyamide) or plastics have elevated risks of various respiratory ailments (Prata et al., 2019). During the Covid-19 pandemic, the monthly rate of consumption for masks worldwide was estimated to be around 129 billion, considering 7.8 billion inhabitants worldwide (Prata et al., 2020). Generally, a large quantity of contaminated plastics is dumped into the environment due to the inadequate protective measures taken (da Silva et al., 2020). The characterisation of MPs indicated that polypropylene and polyethylene were the most common particles found in lung tissue. In addition, the presence of microfibrils was detected in the malignant tissue of the deeper regions of the respiratory system. The fibres were measured to be a few centimetres and hence, they could bypass the filters. Additionally, the presence of such material leads to chronic and acute inflammation. Both polymers are the most frequently used types of plastics in manufacturing including face masks (Chen and Jakes, 2001; Ray et al., 2022).

### 5.3. Microplastics in soil

The presence of MPs on earth has received precedence over the presence of MPs in the atmosphere, although freshwater habitats have received far less attention. More research is needed, especially as soils have been identified as a long-term sink for MPs (Wang et al., 2020a). Disposable face masks are usually dumped or collected as plastic waste mixes. These garbage combinations are either disposed of in a landfill or incinerated. However, due to the inclusion of plastics in face masks, there is a considerable probability that such approaches may have negative environmental consequences. When mixed plastic garbage is deposited in the terrestrial system, it can clog sewage systems in cities or towns (especially in developing countries), as well as significantly impact conventional agricultural soil aeration and water percolation, reducing land productivity. Furthermore, plastic fragments from the degradation of face masks constitute a serious threat to biodiversity since they can inflict physical effects such as internal obstructions and abrasions if consumed (Du et al., 2022). The size of polymeric particulate matter varied from 0.1–0.45 mm with fragments and fibres being the ubiquitous forms. PP along with PE were the most common polymeric compositions observed. Plasticulture in agriculture, open trash dumping, road littering, tyre abrasion, and landfill are all listed as major causes of contamination in soils across the world.

However, Van den Berg et al. (2020) cited the major issue as identifying sewage sludge from Waste Water Treatment Plant applications in agricultural fields. Nizzetto et al. (2016) calculated an intake of 63,000–430,000 and 44,000–300,000 tonnes  $y^{-1}$  in European and North American soils, respectively, surpassing the MPs quantities (93,000 to 236,000 tonnes  $y^{-1}$ ) in the seas (Van Sebille et al., 2015). It was pointed out that because of MPs' hydrophobicity, their presence might cause alterations in the soil profile (Sajjad et al. 2022). Zhang et al. (2016), reported that plastic mulching was a promising method to alleviate conditions for production (e.g., weed control, evapotranspiration reduction, and temperature regulation) resulting in up to 502 kg  $h^{-1}$  films of plastic in Chinese soils. Studies discovered that the presence of MPs was found to be in areas where plastic mulching was regularly administered (Huang et al., 2020), with average concentrations in soil fields ranging from 80.3 particulate matter  $kg^{-1}$  in 5 years to 1075.6 particulate matter  $kg^{-1}$  in 24 years. These statistics identify urban and agricultural soils as a primary sink and source of MP contamination across the world, and they are to blame for the vast range of reported concentrations.

Several research identified human littering and agro-industrial operations as the major causes of plastic-based pollution, implying that management and legislative resources are urgently needed. Kole et al. (2017) evaluated vehicle tyre abrasion as one of the sources for soil contamination by MPs, with emissions averaging 6.1 million tonnes  $year^{-1}$  for tyre wear particles globally. MPs were found in road dust in three metropolitan centres in Japan, Vietnam, and Nepal, with levels as high as 39.6 particles  $m^{-2}$  (Yukioka et al., 2020). Elevated levels of MPs contamination were also detected in the loam near aquatic systems and concentrations of up to 14,712.5 particles  $kg^{-1}$  were found in coastal soils between the Bohai Sea and Yellow Sea (China) in research. Zhou et al. (2018) linked these attributes to port building, aquaculture, and tourism. Recent research in Yangtze River soils revealed higher values of contamination in sub-soils than the topsoil implying a higher propensity for retention for the former. Tiny MPs were found in most samples collected from river beds – this suggested the river water was carrying off a higher concentration of such particulate matter. These findings underscore the necessity for a more extensive study that includes a variety of soil fractions and locations in order to get more accurate conclusions regarding the sources and fate of plastic contamination in terrestrial ecosystems (Zhou et al., 2021).

## 6. Recycling

The usage of face masks and plastic gloves has increased dramatically during the coronavirus (COVID-19) outbreak. It is believed that over 700 million Africans utilise face masks on a regularly, while more than 2.2 billion Asians do so. As a result, masks are getting dumped in garbage bins or landfills. Consequently, wind and rains may easily carry the masks into city streets, rivers, and seas due to their lightweight nature. Not only that, other medical plastics are frequently thought to be contagious and hence cannot be disposed of with regular municipal garbage. The waste plastic must be decontaminated in this circumstance by breaking it down into little bits and then heating it at a high temperature. This may then be disposed of with municipal plastic garbage. This is done by classifying things that may be expired but have not been opened and are not polluted. All these processes can help to decrease waste production. Some nations, including Korea, utilise steam sterilisation before reuse, which involves heating supplies to 121 °C at 1 atmospheric pressure for 30 min. If all these things are done in a well-organised and methodical manner, the quantity of garbage produced can be minimised before it is recycled (Joseph et al., 2021). Fortunately, the ability to recycle and reuse building and demolition debris in civil engineering projects has risen dramatically. It has been proposed that using sterilised waste material in geotechnical applications is a viable method to alleviate the waste management difficulties brought by the pandemic.

### 6.1. Repurposing of face masks

The SARS-CoV-2 pandemic has resulted in a worldwide health catastrophe and subsequently endangered the ecosystem. A multidisciplinary collaborative strategy is necessary to combat the epidemic and eliminate the environmental disasters connected with the disposal of old personal protective equipment. A trend for investigating a new method of reducing pandemic-generated garbage was observed. Worn-out respirators along with other forms of waste materials



were proposed to be reused in civil work. Studies reported the use shredded face mask (SFM) as a potential additive for recycled concrete aggregate. SFM was added at varying percentages and the resultant blend was applied on road base and subbase. The experimental findings reveal that the aggregate combined with various percentages of SFM (1, 2 and 3%) met the stiffness and strength criteria for pavement base/subbase. The addition of the shredded facemask enhanced the ductility and flexibility of RCA/SFM mixes while simultaneously increasing their strength and stiffness. Increasing the quantity of SFM over 2%, on the other hand, resulted in a loss of strength and stiffness (Saberian et al., 2021).

#### 6.1.1. Filters

In wastewater treatment, plastic wastes have been utilised to make ceramic filters. Polypropylene (PP) fibres were employed as a sieving medium in order to increase filtration performance to suffice a variety of functions. Studies were conducted to explore the use of recycled polypropylene fibres in filter beds. Oil droplets were separated from oil-water combinations using reused PP fibres in the bed coalesces. Currently, enormous quantities of polypropylene-based facemasks is being disposed into the environment on a regular basis. A promising economically viable alternative is the valorisation of such materials by employing them for treating wastewater (Asim et al., 2021).

#### 6.1.2. Thickening agents

In organic and mineral media, polymers, including Polypropylene, display swelling and gel-forming activity, which permits them to operate as thickening agents. Recycled PP is being investigated as a possible thickening ingredient for lubricating greases. Martín-Alfonso et al. (2018) examined the gel-like dispersion of lubricating grease using varying quantities of reused PPs as a constituent of mineral oil. Therefore, the economic and environmental benefits of valuing PPs can significantly improve industrial uses.

#### 6.1.3. Building materials

Fibres have been used as building components to strengthen and raise structural strength since a long time (Costa et al., 2019). Many researchers have been interested in incorporating fibres derived from plastic waste into concrete. Ahmed and Lim, 2021 explored PP-based fibres and its effects on the efficiency of concrete. Adding 0.1% to 2% (by v/v%) of fibres can aid in the production of framework with improved structural strength and minimal weight, durability, fracture resistance, and effective freeze/thaw protection (Wu et al., 2020). The use of polypropylene fibres in road building and improved concrete has yielded excellent results. The single-use facemasks were used to increase the ductility, compressive strength and agility of the pavement base/sub-base (Saberian et al., 2021). Concrete strength can be improved by adding nominal quantities of SFM waste (0.2% by volume) (Kilmartin-Lynch et al., 2021). Researchers created sustainable building bricks to replace conventional masonry bricks by using 3% binders, 52% mask waste, and 45% paper waste. The addition of 0.2 of SFM debris (by v/v%) to concrete may increase its structural qualities. Previous research findings suggest another alternative for dealing with discarded PPE, particularly respirators with PP fibres. The use of these discarded materials in the preparation of concrete solves the financial element of inertia or stability, and also assures the manufacture of better versions of concrete. Nevertheless, before being used as a construction material, potentially contaminated PPE should be disinfected as part of the safety protocol (Asim et al., 2021)

## 7. Recent advancements

Alternative methods for the production of facemasks were found to be the one of the most explored avenues of research. Electrospinning has been largely regarded as an adaptable and feasible process to synthesise ultrafine fibres using polymeric melts or solutions. It has been shown to enhance biocompatibility and bio-accessibility of enzymes, active proteins, probiotics and other such hydrophobic and hydrophilic active micro- and macromolecular compounds (Xue et al., 2019). Unlike a standard PP mask, an electrospun ultrafine fibrous mask has functional ultrafine fibres directly deposited on the mask's outermost layer – the filter layer and cover layer are replaced with electrospun ultrafine fibres. It will function both as a hydrophobic layer and a particle filter while simultaneously being reused after sterilisation (Zhang et al., 2021). In addition to promising achievements in the domain of reusability, ultrafine fibres have proven to be effective in the fabrication of high-efficiency filters capable of screening particles larger than 10 nm. Studies reported the development of auto-polarised polyvinylidene fluoride (PVDF) net/nanofiber sieves with 2-dimensional nexuses and improved surface adhesion electrospinning/netting technology for electrets using a revolutionary in situ approach. The filters captured PM0.3 with remarkable effectiveness (99.99%) while preserving low air resistance (one-thousandth part of atmospheric pressure), superhydrophobicity, and needed transparency (91%) (Liu et al., 2020). Moreover, when compared to typical micro-fibrous filters, ultrafine fibre filters improve the possibility for particulate matter deposition, hence preventing the issue of particle shedding/leaking, which generates secondary pollution. As a result, the ultrafine fibrous filters can potentially sieve out microparticles and pathogenic entities while avoiding the risk of static charge build-up (Zhang et al., 2021). With the use of this technology, a broad variety of intriguing fibrous materials from the nano to micro worlds have been created, studied, and examined for use in a variety of industries, assisting in the birth and development of nanotechnologies (Armentano et al., 2021). Table 3 portrays some of the different nanomaterials adopted for use in face masks.

**Table 3**  
Comparison between different nanotechnologies of face masks.

Type of Mask	Examples	Preparation	Mechanism	References
Nanoparticle-coated	Au nanoparticle	Chemical reduction	Prevents the virus from attaching.	<a href="#">Gurunathan et al. (2020)</a>
	Ag nanoparticle	Electrochemical	Virus attachment and penetration are inhibited.	<a href="#">Deng et al. (2022)</a>
	AgO nanoparticle	Algae biosynthesised	Reduction in cytopathic effect.	<a href="#">El-Sheekh et al. (2022)</a>
	Cu nanoparticle	Coating	Destroys virus membranes	<a href="#">Kumar et al. (2020)</a>
	CuO nanoparticle	Surface modification	Degrade the entire genome and destroy the stability of the virus's coating.	<a href="#">Borkow et al. (2010)</a>
Metal organic framework (MOF)	TiO <sub>2</sub>	Sonochemical	Destroys lipid membranes of viruses and blocks attachment	<a href="#">Akhtar et al. (2019)</a>
	Zeolitic imidazolate frameworks (ZIFs)	Chemical	ZIF-8 can destroy viruses by releasing reactive oxygen species as a result of photocatalytic action.	<a href="#">Li et al. (2019)</a>
	ZIF-8 nanocrystal	Hot pressing	Dominant disinfection behaviour	<a href="#">Chua et al. (2020)</a>
Electrospun	Polymeric air filter with thermoplastic polyurethane nanofibers	Electrospinning	Capable of efficiently eliminating PM 2.5 up to 99.654% while maintaining 60% optical transparency in the material	<a href="#">Liang et al. (2019)</a>
	Polyvinylidene fluoride, polyacrylonitrile and polycaprolactone nanocomposites	Electrospinning	Withstand water cleaning and alcohol sterilisation	<a href="#">Xu Tian et al. (2019)</a>

Beyond these, future facemasks need to be antiviral, and the development of biocidal masks may significantly reduce the chances of transmission and contamination of the pathogens. To achieve so, antiviral or antibacterial compounds can be added to the surface or into the polymeric fibres. Due to their inherent broad-spectrum antibacterial and antiviral activity, durability, and capacity to be active at much lower doses, synthetic nanoparticles based on metal derivatives such as Metal Organic Frameworks (MOFs), silver (Ag), copper (Cu), or titanium dioxide (TiO<sub>2</sub>) nanoparticles have been recommended over the years as chemical disinfectants (Armentano et al., 2021). Several investigations have recently been conducted to increase the effectiveness of respirators and masks in combating diseases – Metal Organic Frameworks (MOFs) are used as filtration materials in personal devices instead of conventional textiles; they are used to synthesise PM2.5-protective face masks by developing a versatile hybrid fibre substrate. It was examined by [Li et al. \(2018\)](#) that particulate pollutants are gathered by such filters through three processes: binding to open metal sites on MOFs, reacting with functional groups on MOFs and/or polymers, and electrostatic interactions with MOF nanocrystals and simultaneously providing positive charge to polarise the PM surface due to the unbalanced metal ions and surface defects, resulting in enhanced electrostatic adsorption of PM pollutants ([Chua et al., 2020](#)). The high filtration efficacy when MOFs were applied to a polymeric base was recorded – 88.335% (PM2.5) and 89.67% (PM10) of removal efficiency, and polypropylene microfibrils altered with 2D MOFs at a low operating pressure recorded – filtering efficiencies of 92.5% (PM2.5) and 99.5% (PM10) ([Li et al., 2018](#)).

Nanofibers and nanofiber webs, along with other altered filter materials, were also one of the foci of such forms of advancements. They have microscopic voids, are light, have better permeability, and have excellent void interconnectivity. The addition of chemicals and nucleating agents to nanofibers aids in the decomposition or deactivation of impurities, lowering the danger of breathing infections and viruses ([O'Dowd et al., 2020](#)).

[Chowdhury et al. \(2021\)](#) developed nanofibers utilising insulation and a block electrospinning process; the nanofiber's orthogonal design reduced pressure on the air filter, hence boosting its filtering effectiveness – the addition of a second polymer layer can result in outstanding filtering media, hence material compositing in filter media has caught a lot of attention. The electrostatic charge retention was increased by combining different filter material layers with electret fibres, which enhanced the total filtering efficiency. [Wang et al. \(2012\)](#) constructed an ultra-lightweight binary structure of nylon 6-polyacrylonitrile nanofiber net for improved collection of tiny particles with a radius of 2.5 μm or less. Contrary to commercial fibres, the composite had a 99.99% filtration efficiency and a deep bed pattern of filtration, unlike conventional fibre's surface filtration pattern ([Wang et al., 2012](#)). A nanofiber composite comprising PP nanofibres polyvinylidene fluoride (PVDF) and cellulose acetate (CA) coating was recently discovered to fulfil the criteria of N95 facemasks ([Akduman, 2021](#)).

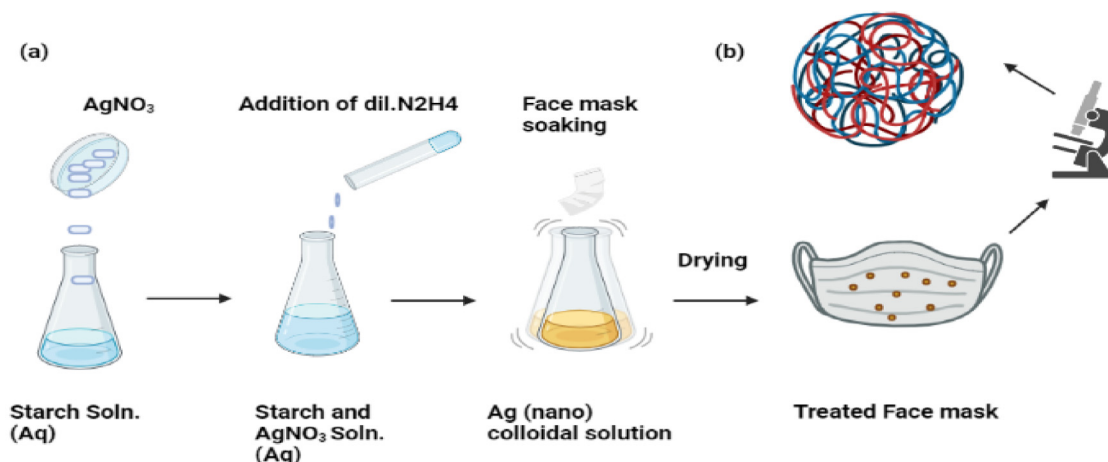


Fig. 5. Schematic representation of (a) Preparation of colloidal solution of Ag (nano) and its application on a face mask (b) Coating of Ag nanoparticles.

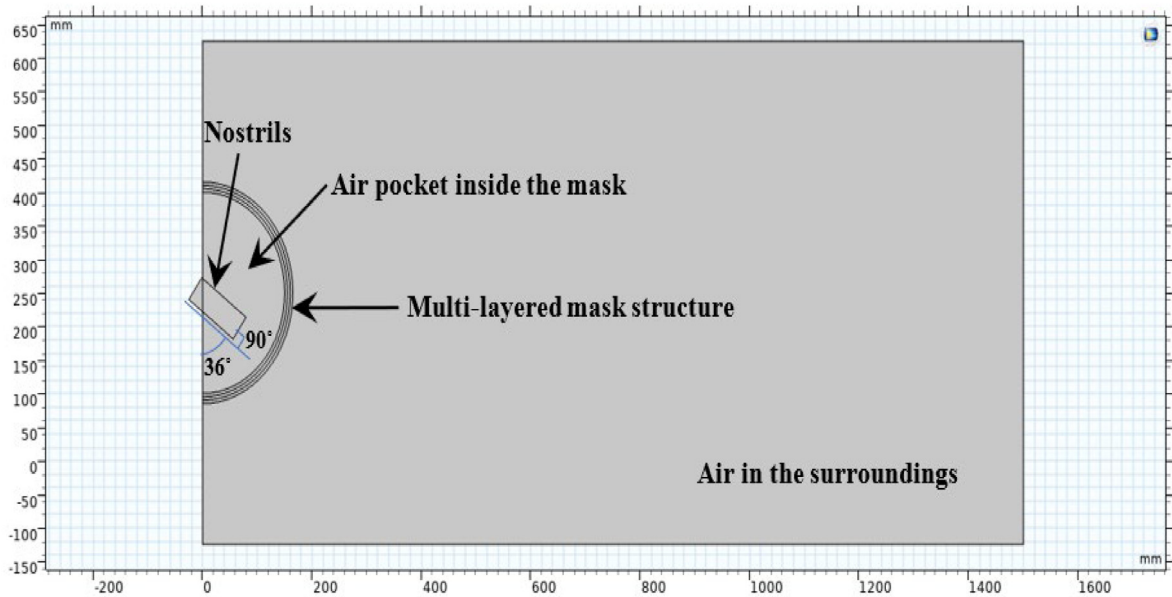
Preliminary investigations have demonstrated that silver nanoparticles and silica composite nanocoating can protect against the lethal effects of SARS-CoV-2. Campos et al. (2020) suggested adopting nanocoated masks for greater protection for both sick and non-infected individuals to avoid virus transmission as nano-sized fibres have an increased area of exposure per unit mass, and they enhance capture efficiency and other surface-dependent phenomena. Fig. 5 depicts a schematic representation of the preparation and coating of colloidal solution of Ag nanoparticles onto face masks. Bortolassi et al. (2019) examined the electrospinning production of new PAN membranes exposed to Ag, ZnO, and TiO<sub>2</sub> nanoparticles, and the performance of filtration, using NaCl filtration – the TiO<sub>2</sub>F filter had the best filtration efficiency, whereas the AgF filter had the best QF (Quality Factor). Particle agglomeration of TiO<sub>2</sub>F was observed extensively – this was largely accredited to the sizeable active surface area of the fibres and the significant interactions associated with the fibres and TiO<sub>2</sub> NPs. The AgF nanofibres were also shown to have outstanding antibacterial activity against a gram-negative E. coli solution. Several studies have been conducted to generate antibacterial filtration by coating herbal extracts on nanofibres. The antibacterial and antituberculosis activity of a polypropylene filter was recently improved by coating it with mangosteen (MG) extract (Ekabutr et al., 2018). Antimicrobial filtering effectiveness of the MG-coated filters was >95% against three pathogens, Staphylococcus aureus, Escherichia coli and multidrug-resistant TB.

To protect the wearer from virus droplets, a unique anti-influenza CuO impregnated respirator was developed. Copper oxide has been shown to have antiviral and antibacterial effects. Due to its contact-based antibacterial properties, graphene oxide has been regarded as a suitable for the development of antimicrobial surfaces (Bhattacharjee et al., 2019). Other advancements, such as thermal stability management, reusability, and self-sanitising capability, were also examined. Yang et al. (2017), developed a unique nanofibre/nanoporous polyethylene system with excellent adhesion characteristics for particulate matter and efficiency of capture. Thermal management seeks to decrease radiative dissipation in a low-temperature environment. Due to the increased rate of transmission dispersion in the body heat of humans, this material has a good radiative cooling effect. More recently, researchers from Australia's Queensland University of Technology have developed a cellulose nanofiber facemask that can filter particles as small as 100 nm and is breathable with the use of a disposable filter cartridge. In addition, LIGC Applications Ltd. of the United States has developed a respirator made of microporous, reusable, conductive graphene foam. The mask can effectively entrap bacterial matter and sterilise itself by the passage of an electrical charge (Talebian et al., 2020).

In the development of reusable, efficient, high-filtration, thermally controlled, and antiviral face masks, there is still more to be discovered. However, in the event of an unanticipated pandemic, such as COVID-19, surgical masks and respirators will always be in high demand and in limited supply. This results in a greater reliance on fabric masks, despite their limited efficiency, particularly in low-income nations. As a result, evaluating the filtration efficiencies of existing materials that potentially provide considerable pathogen protection is critical (O'Dowd et al., 2020).

## 8. Computational fluid dynamics of 1-ply and 3-ply masks with cellulose and polymer simulate air transmission during sneezing

Wearing masks and respirators increases user stress due to sheer inadequate permeability, especially for the respirator. Wearing an N95 respirator has been linked to headaches, impact on heart rate and subjective pain perception among health workers. It also affects the inhaled gas concentrations and respiratory resistances, particularly increasing carbon dioxide levels with subsequent decreased oxygen levels within the respirator, which also tends to affect breathing patterns and heart rate variability. Such instances are a consequence of the expired airflow containing a high concentration of



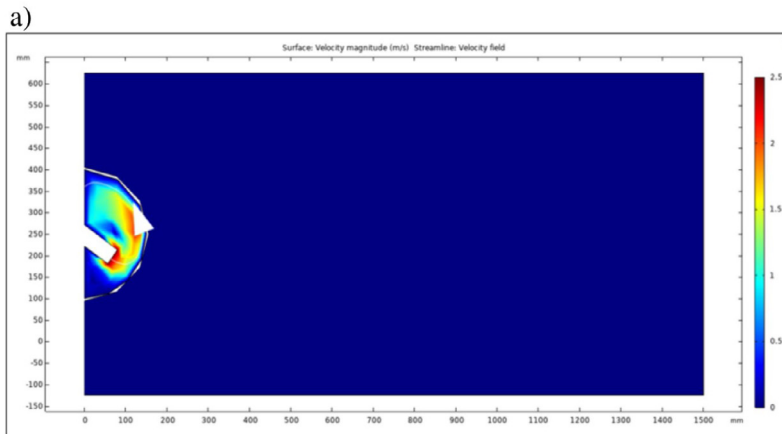
**Fig. 6.** 2-dimensional model showcasing the side view of the system with a nostril, a small air pocket inside the mask and an air space surrounding the mask.

carbon dioxide, which is trapped around the masks and re-enters the respiratory system during the next respiration cycle (Zhu et al., 2016).

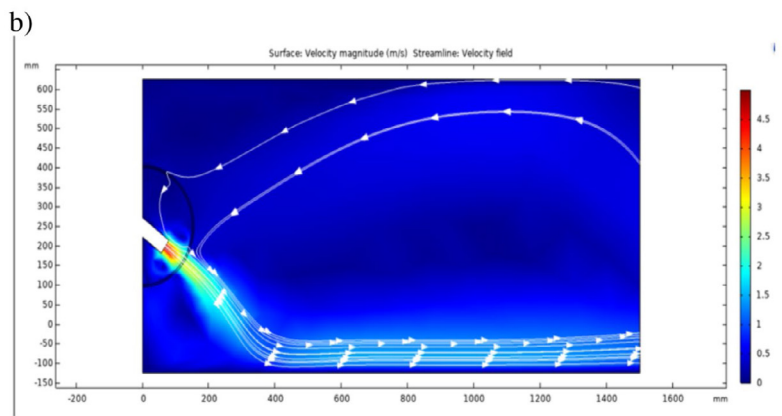
In recent decades, computational fluid dynamics (CFD) modelling has been a potential approach for examining airflow patterns in various structures (Ismail and Adewoye, 2012). The same has been extended to model the flow in the human nasal cavity and subsequently assesses its influence owing to the use of various types of masks made from various materials. Thereby, in this review, we have studied a very primitive model of a multi-layered face mask to analyse the air propagation using COMSOL Multiphysics. The 2-dimensional model showcases the side view of the system with a nostril, a small air pocket inside the mask and an air space surrounding the mask (Fig. 6). The nostril is angled at 36° based on the average angle of human nostrils with, the opening being perpendicular to its axis. The masks were designed to emulate single-ply or triple-ply manufactured of various materials like cellulose fabric, and polymer fibres. The mask's analysis was simulated for their behaviour during sneezing with an air velocity of  $5 \text{ m s}^{-1}$  exiting the nostril (the overall air velocity is observed to be between 2 to  $5 \text{ m s}^{-1}$ ). The air is intended to flow from the nostril, through the mask, and out the model's exterior boundary from the far right.

Fig. 7(a) represents an extreme case scenario where no air is allowed to flow through the mask. All the air spewed out of the nostril during sneezing is circulated within the mask itself. A single-ply mask with cellulose-derived fabric in Fig. 7(b) shows higher levels of air transmission through the mask. Most of the airflow is observed to pass through the mask with little protection offered by the mask. Fig. 7(c) showcases a triple-ply cellulose fabric mask. It can be observed that the mask offers better efficient protection due to multiple layers of fabric obstructing the flow of air through the mask. A significant amount of air circulates within the internal space of the mask, forming a vortex along with the formation of a notable vortex outside the mask, implying that the mask limits air throw velocity and that contaminated air concentrates around the mask rather than dispersing far.

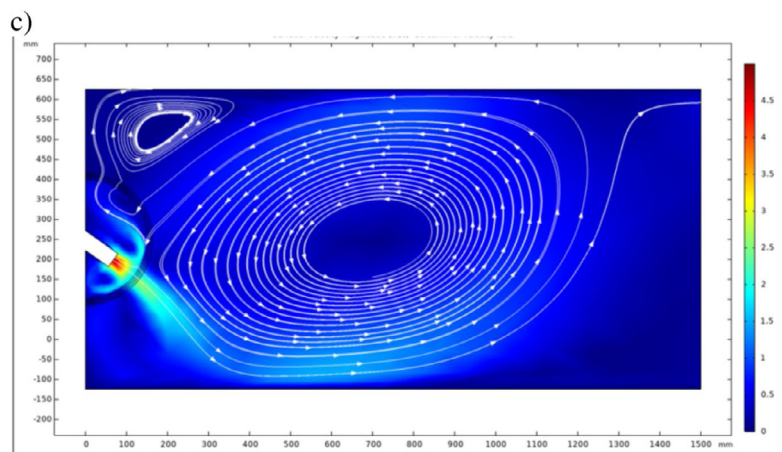
Fig. 7(d) represents the airflow characteristics with a more commonly used polymer fibre-based 3-ply mask. It can be observed that the 3-ply polymer masks provide lesser obstruction to the airflow during sneezing. The airflow was forecasted to travel a longer distance when compared to a three-layer cellulose fabric. With the replacement of the cellulose layer sandwiched between polymer layers, the airflow got subdued significantly. The three-ply mask formed of cellulose (interior layers) and polymer (exterior layers) resulted in significant obstruction of the flow, forming a strong vortex around the mask as shown in Fig. 7(e). It is highly imperative to understand the particulate flow nature with various kinds of masks. The nature of particle flow within the mask and in close vicinity to the mask is determined by the number of layers, the material utilised, the porosity, the fibre weaving direction, the binding nature between these layers, etc. In this section of the paper, a brief analysis of the particulate flow pattern within the mask and up to 1.5 m from the nostrils is carried out, considering polymer and cellulose (cotton fabric) as mask layer materials. Simulating various mask models with a single layer, three-layer masks using the manufacturing materials, single-layer mask models demonstrated a higher propagation of particulate matter with higher velocities of particles ejected from the mask, which are also immensely laminar and hence propagate in the air over a longer distance. While the flow through a three-layer mask is less laminar and, in many circumstances, turbulent, resulting in a shorter propagation distance, often less than a



Air Flow Profile: (a) with 1 Layer-Nonporous Mask



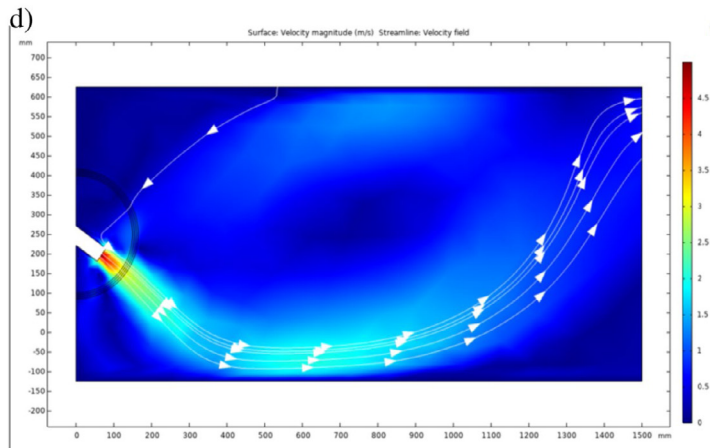
Air Flow Profile: (b) with 1 Layer-Cellulose Mask



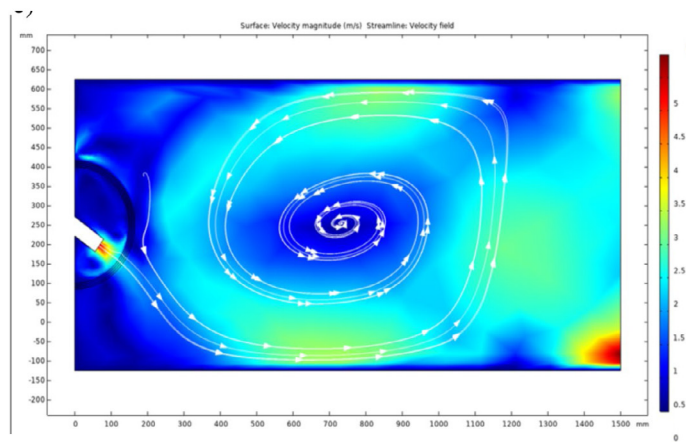
Air Flow Profile: (c) with 3 Layer-Cellulose Fibre mask

**Fig. 7.** Air Flow Profile  
 (a) with 1 Layer-Nonporous Mask  
 (b) with 1 Layer-Cellulose Mask  
 (c) with 3 Layer-Cellulose Fibre mask  
 (d) with 3 Layer-Polymer-Fibre Mask  
 (e) with 3 Layer-Cellulose-Polymer-Cellulose-Fibre..





Air Flow Profile: (d) with 3 Layer-Polymer-Fibre Mask



Air Flow Profile: (e) with 3 Layer-Cellulose-Polymer-Cellulose-Fibre

Fig. 7. (continued).

metre, thus fulfilling WHO safety regulations (Eckert, 2020). Thereby, it can be concluded that the multi-material layered combination of cellulose–polymer–cellulose efficiently inhibited particle propagation.

## 9. Conclusions

COVID-19 is being contained and reduced by a number of research communities throughout the world. Unlike earlier outbreaks such as SARS and MERS, this infection can now be controlled because of advances in technology. Quick measures such as the accurate identification of the pathogenic presence, reduced manufacturing time of detection test kits, increased counts of investigations for vaccinations or medications, and the introduction of health-care legislation in a limited time frame all contributed to this expansion (Morawska et al., 2020). One of the key research interests in this circumstance is the utilisation of novel and current technologies to employ face masks. In an effort to reduce the need for facemasks, many studies are being conducted to facilitate the decrease, reuse, and recycling of used masks. Masks produced using polypropylene are detrimental to the environment and thus, they need to be phased out in the long run (Nghiem et al., 2021). New technologies for low-cost manufacturing processes were implemented, as local businesses may assist in mask production. To increase the multifunctional performance of masks, current materials are modified as well as, mask designs are altered. New materials and technology for the manufacture of surgical masks, as well as modifications to current surgical masks, are discussed. Long-term usage of N95/N99 masks can lead to contamination since germs and viruses collect during the exposure. Many recommended modifying the N95/N99 mask to offer extra air filtration and kill germs using plasma treatment at low operating temperatures to remedy the problem (Starikovskiy and Usmanova, 2020). By minimising, aerial particulate matter or respiratory droplets from coughing or sneezing, sterile surgical facemasks can successfully aid in decreasing viral transmission. However, in the event of a pandemic, it is difficult to distinguish between

infected and unaffected patients. Worn-out surgical facemasks were redesigned using a temperature sensor material to address this issue. Wang et al. (2020b) reported the synthesis of a new form of respirator material equipped with replenishable antibacterial efficacy and rechargeable performance for filtration.

Artificial Intelligence (AI) was also a powerful tool to anticipate outbreaks using geo-mapping and to limit/avoid viral propagation. New AI techniques are being integrated with security cameras to track the use of face masks and raise public awareness (Nguyen et al., 2020). Current manufacturing materials, such as non-woven fibre-based materials, have been in commission since the early twentieth century and have been demonstrated to be still adequately viable in their usage. Material advancements have resulted in antimicrobial coatings such as graphene oxide, which can benefit both the filters utilised and the fabric, preventing infection through inhalation or consumption of pathogenic entities. Polymeric layers and nano-sized materials have shown promise in boosting the efficacy of filtration, and the usage of nanostructures can improve the mechanical strength of facemasks. Reusing these masks had little success since they were manufactured as one-use products, and forcefully extending their usage might prove detrimental. UV treatments were shown to destroy the mask's structure, whilst chemical-based sterilisation procedures increased the size of most penetrating particles in facemasks, thereby lowering their efficiency. The creation of thermochromic materials will make it easier to identify persons exhibiting probable COVID symptoms. Similarly, the synthesis of reusable materials will be extremely beneficial in the future. Current regulations, materials, and research have resulted in the development of face masks that can act as a suitable prophylactic measure during the pandemic. However, the major innovation is still necessary in order to create an effective facemask with heat regulation qualities and anti-viral properties.

### Declaration of competing interest

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

### Data availability

No data was used for the research described in the article.

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