Recent advancements in nonwoven bio-degradable facemasks to ameliorate the post-pandemic environmental impact

Junaid Khan 1, Syed Abdul Momin 1, M Mariatti 1, V Vilay 2 and M Todo 3

1 School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, Nibong Tebal Penang, 14300, Malaysia
2 Department of Mechanical Engineering, Faculty of Engineering, Sokpualuang Campus, National University of Laos, Vientiane, Laos
3 Renewable Energy Centre, Research Institute for Applied Mechanics, Kyushu University, Fukuoka, 816-8580, Japan

E-mail: mariatti@usm.my

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Abstract

Plastics have become a severe risk to natural ecosystems and human health globally in the last two decades. The outbreak of the coronavirus pandemic, which led to the manufacturing and use of billions of facemasks made from non-biodegradable and petroleum-derived polymers has aggravated the situation further. There is an urgent need to develop bio-degradable facemasks with excellent filtration efficiency and antimicrobial characteristics using scalable technology. This review article aims to provide the fundamentals of mask technology, its environmental footprint, facemask’s lifecycle assessment, conventional manufacturing routes, and state-of-the-art reports on using bio-degradable polymers for facemask applications. The article also focuses on the current challenges of the conventional facemask and the prospects of an ideal facemask that could significantly reduce the ill effects of petroleum-based polymers. The review includes concise information on the basics of polymer biodegradation and standardized tests to evaluate biodegradability. The use of currently available facemasks has been an effective measure to curb the infection rate, however, is a threat to the environment. Reusing the facemask after decontamination is not a solution from a safety perspective as cloth-based facemasks have lower filtration efficiencies which get further reduced with the washing cycle necessitating a shift towards biodegradable facemask. Systematic information is provided through this article to stimulate research on a bio-degradable facemask with excellent filtration efficiency, antimicrobial properties, and cost-effectiveness for global usage.

1. Introduction

The coronavirus pandemic has caused severe damage to health and the economy. The disease, widely known as COVID-19, causes a severe acute respiratory syndrome that primarily attacks the lungs. COVID-19 is caused by SARS-CoV-2, a lipid-based enveloped virus with spike-like projections forming a shape similar to a crown [1, 2]. The COVID-19 disease has created serious havoc with more than 10% fatality for patients with weaker immunity and 2.5 billion infections as of October 2021 [3]. The virus is highly transmissible and spreads through the patient’s derived bioaerosols that remain stable on various surfaces, causing infections [4]. Facemasks are considered one of the most effective methods to curb the disease, combined with social distancing and proper hygiene [5]. The nonwoven fabric material generally used for facemask applications consists of a compact arrangement of fibers that act as a barrier to the microbes but have sufficient porosity for breathing comfort and low manufacturing cost compared to woven fabrics.

The standardized facemask should have at least three nonwoven fabric layers to protect the wearer adequately. The filtration layer (mid) serves the primary purpose of preventing inward and outward transmission of bioaerosols. In contrast, the other two layers (inner and outer) provide fit and avoid direct skin contact with the filtration layer [6]. These nonwoven fabrics are manufactured commercially in massive
quantities using melt blown or spun-bond processes. Spun bond and melt blown are highly automated processes with set parameters that produce polymeric filaments followed by web formation and bonding [7].

The currently available face mask has more than 95% filtration efficiency, sufficient to curb infection even in high-risk regions. However, they are manufactured mainly with petroleum-based polymers like polypropylene, polystyrene, polycarbonate, polyethylene, and polyester polymers. These materials are non-degradable that significantly hampers the environment [8, 9]. The disposable facemask primarily manufactured to be used only by medical professionals and scientists has now been widely used and disposed of by the public without professional training regarding occupational hazards and safety [10].

The experts in disease control and infection were upfront about promoting facemasks in public places based on a clear rationale of inhibiting outward and inward particulate matter spread and previous experiences, in which SARS-Cov-1 was reduced by 64% by the use of facemasks at public places [11]. Facemask’s advocacy has led to a phenomenal increase in its production and use [12]. The processing and single-use disposable facemask manufactured of petroleum polymers produce vast quantities of microplastics [13]. Government authorities focus on ameliorating the infection rates and fatalities. They are apathetic about the aftereffects of the enormous plastic waste generated due to the continuous use of facemasks without considering occupational health and safety. The solid plastic waste generated is dumped without considering the fate of these plastics, which ends up polluting the natural ecosystem. The growing environmental concerns are shifting the focus of Scientist’s and Researcher’s toward eco-friendly and green routes to reduce the environmental impacts [14–20].

Plastics have brought significant comfort to our lives due to their durability, flexibility, water resistance, and cost-effectiveness [14]. The facemask prepared from these plastics has effectively reduced the transmission of the infection. A more pragmatic approach in fighting the pandemic and reducing its aftereffects involves developing an effective facemask with bio-degradable polymers. Using advanced techniques, the facemask prepared from bio-degradable polymers will have better performance than the conventional facemask and natural degradation essential to minimize plastic pollution. The importance of bio-degradable polymers can be estimated from the number of publications over the last 10 years. The Scopus database shows around 38,564 document results on this topic. The number of publications from the year 2010–2020 were taken from Scopus database when searched with keyword ‘Bio-degradable polymers’ as given in figure 1. The growing trend line demonstrates the importance of bio-degradable polymers considering the current situation and environmental awareness. Electrospinning is the most favorable technique for manufacturing facemasks filter layer with bio-degradable polymers as it has various control parameters to tune the fiber-forming properties. The importance of electrospinning and its role in bio-degradable polymers can be estimated from search results with the keywords ‘electrospinning’ within bio-degradable polymers search results, as shown in figure 1. The growing trend is obvious since electrospun nanofibers mat have significant advantages of better filtration efficiency and breathability than conventional melt-blown filter mats.

Further, regression analysis was used to determine the best fitted model for the relation of number of publication and years. Number of publications (y) was used as a dependent variable while time (in years) was used as an independent variable (x). The best model was selected based on R-squared value. According to the results the R-squared value for keywords; ‘Biodegradable polymers’ and ‘Electrospinning’ is 94.07 and 93.65%.

Figure 1. Scopus database of document results from 2010–2020 with the keywords ‘Biodegradable polymers’ and ‘electrospinning’ within biodegradable search results. The data from 2020–2030 is predicted using linear regression.
in turn demonstrating the accuracy of the model. The model equation and $R^2$ value for Biodegradable polymers and Electrospinning are given by equations (1) and (2) respectively.

\[
y = 102.99x - 205352
\]

\[
R^2 = 0.9407
\]

(1)

\[
y = 22.127x - 44367
\]

\[
R^2 = 0.9365
\]

(2)

The obtained model was used to forecast the number of publications for both biodegradable polymers and electrospinning from 2021 to 2030 as shown in figure 1. Consequently, it was observed that the number of publications is expected to increase considerably by 2030. Compared to 2010, the number of publications with keyword ‘biodegradable polymers’ may increase by 1997 documents as of 2030. While for that of ‘electrospinning’, researchers may find ~435 documents more than the number of documents published in 2010.

The rapid manufacturing of biodegradable facemask with antimicrobial properties will provide a promising solution to reduce the harmful impacts of presently available nondegradable facemask and alleviate the spread of diseases. The large-scale manufacturing of efficient and low-cost biodegradable facemask has become a hot topic in academia and industries. However, after a thorough literature review, we found that limited studies are available on the basics of the facemask technology and recent advances on bio-degradable facemasks, which is essential for future development in this research topic. The aim of this review article is to provide recent advancements in the development of facemask with biodegradable polymers. First, we introduce the fundamentals of facemask and mechanism of disease prevention. A comparison between conventional and ideal facemask is made followed by a brief discussion on environmental impact and life cycle assessment of facemask. After that, an overview of mask’s nonwoven filter layer fabrication techniques, its production speed, fibre diameter and typical cost of production is given. The most recent research for nonwoven filter layer manufacturing using biodegradable polymers and their performance as facemask is discussed in detail. Brief information on the standardized testing to check biodegradability is provided and at last, future outlook and summary is provided. We hope that this review article will provide timely information and references that can trigger future research to fabricate highly efficient biodegradable facemask.

2. Role of facemask

Facemasks play a pivotal role in minimizing the infection rate by preventing cloud formation during sneezing and coughing, which prevents the turbulent jets of infectious droplets from transmitting to individuals and the environment. Hence, maintaining a social distance of 1.5 m was proposed; however, recent reports obtained by Bourouiba [21] indicate that bioaerosols emitted by a person could travel up to 8 m. There is vast scope for improving mask performance and minimizing ill effects by fabricating antimicrobial, surface charged, scalable, and bio-degradable facemasks. Therefore, it is imperative to study the prevention mechanism and its environmental effects, as briefly described in this section.

2.1. Mechanistic information on droplet prevention

Facemasks prevent droplets from entering the wearer’s body through various mechanisms. The first most pragmatic mechanism is through interception, which blocks the droplets due to barriers offered by the randomly arranged nonwoven fibers, and most of the large-sized particles (> 600 nm) are stopped by this action [22]. The stopping mechanism for particle size in the range of (~300–600 nm) by collision or impact with the surface of the fibers after entering the sieves is highly dependent on the mass and velocity of the particles [23]. The diffusion phenomenon is based on the particle Brownian motion, which increases the possibility of particle collisions and stops it from entering the facemask surface. The last prevention mechanism is based on the electrostatic attraction between the particles and the charged surface. The schematic of these mechanisms and size comparison is depicted in figure 2.

2.2. Comparison between conventional and ideal biodegradable facemask

The lack of plastic waste management, especially in developing nations, is causing severe environmental damage. The damage is further accelerating due to the COVID-19 pandemic. Facemasks, PPE kits, and plastic syringe use have increased exponentially [24]. The United Nations declared plastic pollution a global crisis long ago; however, our reliance on plastic is rising rapidly, boosted by the current rate of COVID-19 infections [25, 26]. Even in normal circumstances, less than 10% of plastics were recycled; 12% were incinerated, and 79% was discarded in landfills or the natural environment [27]. Recycling has become even more difficult considering biohazards associated with possible virus deposition on the surfaces of plastics, facemasks, and PPE kits during
the pandemic. Considering these concerns, the plastics ends up contributing to the plastic pollution in the form of landfills, dumpsites, water bodies or littering in public places.

The production in the mask manufacturing industry has experienced a substantial upward shift in which polypropylene (PP) polymer is the most preferred material compared to other polymers due to its excellent properties and processability. These properties are perfect from the safety point of view to curb the infection; however, it has a long-term adverse effect considering the PP degradation time of 20–30 years. There are numerous reports regarding mask pollution, considering the current estimated use of over 7 billion facemasks per day around the globe[13]. Further, over 66,000 tons of contaminated plastic waste could be generated in the United Kingdom[28]. Considering a bigger scenario, the waste associated with the mask will cause severe damage to the ecosystem and living beings which needs immediate action. The current situation renders biodegradability an essential aspect of controlling mask pollution, whereas other desirable properties should be similar or better than that of the conventional mask.

Figure 3 compares the conventional facemask and an ideal facemask in terms of filtration efficiency, breathability, electrostatic charges, and biodegradability. The critical difference between the conventional facemask and an ideal facemask is the fiber diameter, which should be in the nano range for better filtration efficiency than the micro range fibers in conventional facemasks. The electrostatic charge developed in the conventional masks is transitory and lasts up to 8 h under ambient conditions. However, the present situation demands extended periods for reusability[29]. Hence, there is a need for a modification technique to develop permanent charges on the surface of the filtration medium, as demonstrated in the pictorial comparison of a conventional and ideal facemask in figure 3. Recently, Figerez et al[30], fabricated a three-layered facemask with rechargeability. Triboelectric charge generation (TEG) is one of the most valuable methods to generate an electrostatic charge on the surface of the membranes. The incorporation of nanoparticles is considered an effective way of enhancing the TEG. Graphene oxide (GO) is a potential candidate with negative charges and active surface oxygen functional groups[31–34]. The mask was made by coating a paste consisting of polyvinylidene fluoride (PVDF) and GO paste on the surface of the polypropylene filter layer by a simple solution casting method. They also demonstrated the rechargeability by simple mechanical agitation. In another study, the permanent charge on the fiber surfaces was made using chitosan nanomaterials[35]. There are also problems associated with CO2 retention of exhaled breath, creating fatigue and headache issues, and

Figure 2. Schematic of the mechanistic information of droplet prevention.
necessitating facemasks with nanopores for excellent breathability. Figure 3 also shows that, the most conventional facemasks are either sintered or accumulated, contributing to landfills. In contrast, an ideal mask fabricated using bio-degradable polymers will be a boon for society considering their natural degradation.

2.3. Environmental footprint and life cycle assessment of facemask

The COVID-19 pandemic has brought severe restrictions in movement and industrial activities. These restrictions have resulted in huge economic losses, however, has contributed to cleaner and healthier environment. There have been numerous reports indicating on reduction in CO₂, CO, NOₓ, SO₂ and various particulate matter (PM) emission across the world [36–39]. At the same time, it should be remembered that the pandemic has resulted in the additional demands for production of facemask, PPE kits, disinfectants and test kits has led to increased environmental impacts and hence its assessment and devising strategies to provide pragmatic solutions should be of prime importance. The materials used and carbon footprint of the most widely used facemask, which is N95, surgical and cloth mask is given in table 1. It can be observed that the cloth mask contributes to the highest greenhouse gas (GHG) emission than surgical and N95 masks since cloth mask is made from woven fabrics and involves a serious of steps such as carding, drawing, roving, spinning and finally weaving. These steps are completely or partially eliminated in nonwoven fabrics manufacturing and fabric is directly made from fibers. The reuse of mask could help reduce the environmental footprint; however, it is an arguable topic and needs more consideration since inadvertent reuse could lead to further transmission of

Figure 3. Comparison between the conventional and ideal biodegradable facemask.
infection. Hence effective decontamination techniques need to be developed for safe usage without compromising the filtration efficiencies \[40, 41\].

The life cycle assessment is the most effective way to determine the sustainability of the product which takes into consideration the components for product fabrication, the manufacturing method, transportation and finally its usage and disposal. A lifecycle assessment and comparison between surgical facemask and reusable cotton facemask was made by Schmutz \textit{et al.} \[45\], in which they considered reusing cotton facemask by washing whereas surgical facemask were disposed after single use. Incineration was considered as the disposal technique. Their study indicates that the surgical facemask produces lower carbon footprint as compared to cloth-based facemask, however after incineration, the surgical facemask produces higher carbon footprint since cotton incineration release biogenic CO\(_2\) emission as compared to fossil CO\(_2\) emission, since biogenic CO\(_2\) emission does not cause increase in the Global Warming potential value as it is considered that the same amount of CO\(_2\) emission during the crop’s growth phase. A similar study of life cycle assessment from cradle to grave using Embedded filter layer (EFL) reusable facemask and surgical facemask was performed by Lee \textit{et al.} \[46\] in which they showed that reusing EFL facemask can reduce the environmental impact by 30\% as compared to surgical facemasks. These studies is in agreement with report given by Allison \textit{et al.} \[42\] in which they showed that using reusable cotton-based facemask could effectively reduce the environmental impacts.

The life cycle assessment is admirable from the environmental point of view and reducing the energy impacts which is escalated due to the facemask’s demands. The fundamental reason of using a facemask is its ability to filter the aerosol containing infectious diseases. The filtration efficiencies of cloth mask are much lower than that of N95 and surgical masks. Also the filtration efficiencies of cloth based washable facemask decreases with the washing cycles \[47\]. The environmental concerns should be taken seriously without compromising the safety requirements. The facemask produced using biodegradable polymers could be an effective solution as it can significantly reduce the carbon footprint as biodegradable polymers does not require any additional disposal treatment.

### 3. Overview of the fabrication techniques

Nonwoven fabrics are the main components for facemask fabrication. There are three general techniques to form a consolidated nonwoven structure for filter media: melt-blown, spun bond, and electrospinning. Although these techniques work on different principles, the process follows the same fundamental route of forming fibers and webs using polymeric solutions followed by creating a stable structure. Table 2 presents a schematic of the different processes and properties of the nonwoven mat produced. The typical production speed, fiber diameter, and cost of production come from a study by Tuin \textit{et al.} \[48\], who used polylactic acid (PLA) fibers as a standard polymer for cost calculation. Spun bond and melt-blown techniques have served as a significant route for conventional facemask applications in which the mid-filter layer is made from melt-blown fibers as it has a smaller diameter. The top and bottom layers are made from spun-bond techniques.
| Technique   | Schematic | Process                                                                 | Control parameters                                                                 | Production Speed (m min⁻¹) | Fibre diameter (μm) | Typical Cost of production in length ($/m²) |
|-------------|-----------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------|---------------------|---------------------------------------------|
| Electrospinning | ![Electrospinning schematic](image) | Polymer solution - Electric field stretch nanofiber formation and deposition | Voltage, flow rate, collector distance, collector type (Rotating drum, plate) | 20                          | 0.08–0.7            | 2–5                                         |
| Spun bond   | ![Spun bond schematic](image) | Polymer chip melting - Spinning and stretching using spinneret to form fibers - Laying Down - Bonding | Spinning speed, speed of roller, bonding characteristics | 600                         | 10–50               | 0.3–3                                       |
| Melt Blown  | ![Melt Blown schematic](image) | Polymer chip melting - Hot air stretching to form fibers - Laying Down - Bonding | Screw extruder speed, hot air velocity, bonding characteristics                      | 300                         | 0.5–10              | 1–2                                         |
Table 2. (Continued.)

| Technique | Schematic | Process | Control parameters | Production Speed (m min$^{-1}$) | Fibre diameter (μm) | Typical Cost of production in length ($/m^2$) |
|-----------|-----------|---------|--------------------|----------------------------------|---------------------|-----------------------------------------------|

![Schematic diagram](image)
Electrospinning is emerging as a possible alternative that forms nano range diameters and charged filaments, leading to better filtration efficiencies and breathability desirable for facemask applications [49]. Various bio-degradable polymers can be processed using electrospinning techniques with multiple control parameters (flow rate, voltage, polymer concentration, and collector distance) to control nanofibrous diameter, porosity, and filter media thickness [50]. However, the lower production speed and high cost are significant setbacks and have become a topic of interest in the scientific community. The few methods that tried to overcome these limitations, including needleless electrospinning, which will be discussed later. Bio-degradable polymers with eco-friendly solvent and the continuous, scalable process will be critical parameters that need focus to manufacture cleaner and safer electrospun-based facemask technology [51].

### 4. Bio-degradable polymers for the facemask

Biodegradation is a complex process involving hydrolytic or enzymatic cleavage of polymer bonds via enzymes/chemicals associated with living micro-organisms. The process also influences oxidation, photodegradation, and hydrolysis on the polymeric chain prior to or during biodegradation [52]. Generally, polymer biodegradability depends on various factors, including distribution of functional groups, degree of polymerization, stereoregularity, and crystallinity. The micro-organism attacks the chemical bonds of the polymers and produces enzymes that change the structural and chemical properties leading to biodegradation [53, 54]. The properties of various bio-degradable polymers recently used to synthesize bio-degradable facemasks are discussed in this section. Table 3 summarizes the state-of-the-art reports on facemasks based on bio-degradable polymers filtration efficiency and breathability.

#### 4.1. Cellulose

Cellulose is one of the most abundant natural polymers that exist on earth. It is a polysaccharide with linear chains of thousands of \( \beta(1 \rightarrow 4) \) linked D-glucose units with the chemical formula \( (C_6H_{10}O_5)_{n} \). Cotton fibers are 90% cellulose, the primary piece of everyone’s clothing [63]. Besides this, cellulose and its derivatives have various applications in paper manufacturing, drug tablets, and food industries [52]. The excellent mechanical properties, biodegradability, and nontoxicity are ideal for application as a filter material. However, natural fiber forms cannot be spun into nanofibrous sheets. This is essential according to the current demand for breathability and high filtration efficiencies. Thus, electrospinning makes nanofibers using a semisynthetic yet biodegradable form known as cellulose acetate [64, 65]. Biodegradable and nontoxic filter material for facemask application was reported by de Almeida et al [49], in which cellulose acetate nanofibers were made using the electrospinning technique. The synthesized filter media showed approx. 99.99% efficiency when tested with 7–300 nm NaCl aerosol. High filtration efficiency is attributable to their smaller fiber arrangement’s and uniform diameter and randomness, which is considered suitable for filtration media [66, 67].

Cellulose acetate nanofibers production is complex, and the mechanical properties are primarily affected due to the presence of beads during electrospinning in the fibrous mats. However, adding a cationic surfactant is an effective way to reduce bead formation and the fiber diameter of nanofibrous meshes [68, 69]. In another study conducted at Lamdong Medical College (LMC), the researchers used sustainable cellulose based 7 layered filter papers to fabricate masks as a potential replacement for commercially available PP-based surgical facemasks [55]. Different filter layers have specific functions, wherein the antimicrobial properties are incorporated by Folium Plectranthii amboinicii (Lour) oil. Several researchers also attempted to impart antimicrobial activities on a cotton fabric-based facemask [30, 70, 71]. For instance, an antimicrobial mask was

| Sr No | Polymer | Filtration Efficiency (%) | Antimicrobial agent | References |
|-------|---------|---------------------------|---------------------|------------|
| 1     | Cellulose acetate | 99.99 | Surfactant | [49] |
| 2     | Cellulose filter paper | — | Lour Oil | [55] |
| 3     | Cotton polyester nonwoven fabric | — | Chinese Herbal | [56] |
| 4     | PVA-Lignosulfonate | 99.44 | — | [57] |
| 5     | Poly vinyl alcohol (PVA) | — | AgNP | [58] |
| 6     | PVA/β-cyclodextrin | 99 | — | [59] |
| 7     | Sericin/PVA | — | Organic clay | [60] |
| 8     | Polyvinyl Butyral (PVB) | 83.2 | Thymol | [61] |
| 9     | Poly(butylene succinate) | 97 | Chitosan | [35] |
| 10    | Poly lactic acid | 97.9 | Neem | [62] |
made using Chinese herbal microcapsules extracted from Scutellaria baicalensis on cotton fabric [56]. Many studies have investigated grafting to produce surface functional groups on cotton fabric followed by treatment with antimicrobial agents such as GO and pyridinium groups [19, 37, 38]. Cotton fabric-based facemasks containing antimicrobial compounds should not be used since their filtration efficiencies are extremely low due to the loose woven structure providing little or no protection [39, 40].

4.2. Polyvinyl Alcohol (PVA)
Polyvinyl alcohol is a synthetic bio-degradable polymer with excellent mat-forming properties and water dispersibility. These properties are ideal for producing nanofibrous mats using electrospinning techniques. Besides, they are cheap, nontoxic, and possess good chemical resistance and active surface functional groups. However, the membrane fabricated using PVA nanofibers lacks mechanical properties requiring additional strengthening agents. For example, a composite nanofibrous membrane was made using PVA/β-cyclodextrin (CD), which improved mechanical performance after adding β-CD [59]. The membrane also showed excellent filtration efficiency of 99% and good air permeability. Adding β-CD improved the filtration performance from 79% to 91% when tested with SO₂ gases. The improved performance could be due to empty cavities and surface functional groups.

Another study by Aadil et al [58], fabricated a PVA-lignin-silver nanoparticles (AgNP) hybrids nanofiber, which has good mechanical, antimicrobial, and filtration efficiencies ideal for filtration membranes. Figure 4 provides a schematic of the fabrication process. The reported nanofibrous membranes showed great potential in inhibiting the bacterial growth of Bacillus circulans and Escherichia coli; hence can be used to fabricate antimicrobial facemask. The antimicrobial properties of the mask can be attributed to the silver nanoparticles which shows excellent antioxidative and antimicrobial properties [72]. In another study, an efficient antimicrobial, bio-degradable filter medium was fabricated by Purwar et al [60]. They used a three-material hybrid system consisting of Sericin/PVA/Clay. In their investigation, electrospinning process was used for nanofibrous filler fabrication and the effect of nozzle and collector distance, voltage, and clay concentration were studied. They found that increasing the collector distance led to an increase in the fiber diameter. The voltage had a profound effect on the nanofiber formation. Lowering the voltage resulted in bead formation, whereas beads were not visible in higher voltage; however, the average diameter of the nanofibers was increasing, which could be due to the higher ejection of polymer solution due to higher applied voltage. The addition of clay improves the mechanical properties of polymeric materials, however it should be used in optimum quantities to balance the fiber forming abilities [73]. The clay concentration of 0.75% was optimum for particulate matter filtration and antimicrobial activity, determined using Environmental Particle Air Monitor. Cui et al [57] made a similar observation of improved filtration efficiency when they crosslinked PVA nanofibers with sodium

![Figure 4. Schematic representation for the synthesis of PVA-lignin nanofiber mat loaded with silver nanoparticles. Reprinted from [58], Copyright (2018), with permission from Elsevier.](image-url)
lignosulfonate (LS), as shown in figure 5. The filter layer can be used for personal protection since it has excellent filtration efficiency and breathability.

4.3. Polyvinyl Butyral (PVB)

Polyvinyl butyral, a thermoplastic polymer with good mechanical properties and toughness, is prepared from polyvinyl alcohol by reacting with butyraldehyde. The number of butyral groups can be controlled to improve water resistance, whereas the hydroxyl groups present in the backbone of the polymers can act as sites for crosslinking [74]. Thymol has antimicrobial properties against various gram-positive and negative bacteria and fungi [75]. Many researchers have explored the antimicrobial properties of thymol [75]. For instance, Kavoosi et al [76] fabricated a gelatin-based film with thymol for wound dressing applications. They also found that the incorporation of thymol has increased the water solubility and reduced the tensile strength of the gelatin, indicating reduced crosslinking of the polymers due to thymol. Karami et al [77], reported a similar investigation using thymol as an antimicrobial agent with Polylactic acid (PLA), poly(ε-caprolactone) (PCL), and their blends (PLA 50: PCL 50) using an electrospinning technique [77]. They also observed decreased polymer solution viscosity, indicating reduced crosslinking due to thymol [76–78].

A bio-degradable facemask with excellent antimicrobial activity and mechanical properties was fabricated by Lu et al [61] using PVB polymer and thymol as an antimicrobial agent by simple blending using ethanol as solvent and vertical electrospinning technique. The conventional electrospinning techniques are horizontal and vertical (shaft and converse type), as represented schematically in figure 6. Yang et al [79] studied difference between different electrospinning techniques, and they observed significant variations in the fiber diameters and their distribution. The shaft type vertical spinning gives the thinnest fibers, whereas the converse electrospinning arrangement gives the thickest. The horizontal electrospinning setup has a diameter in between the shaft and converse type. Gravity plays a significant role in strengthening the electrical field, leading to more stretching (thin fibers) in the shaft type setup and less stretching (thick fibers). However, due to the higher electric field and gravity, a higher standard deviation in the fiber diameter occurred in shaft type electrospinning than the converse and horizontal electrospinning setups. The vertical electrospinning technique also has advantages of needle movement and speed control, leading to more uniform and higher surface area coverage than the horizontal electrospinning technique.

Lu et al [61] fabricated a facemask using PVB/thymol via a vertical electrospinning technique. They tested it with Automated Filter Tester according to the National Republic of China Standards. Figure 7 presents the graph of filtration efficiency and pressure difference with spinning time. The particulate filtration efficiency increased from 38.6% for 1 h. spinning time to 83.2% for 6 h. spinning time. More time leads to more deposition of randomly arranged nanofibers, increasing the particulate barrier. The increase in the barrier is good for the
filtration efficiency and protection; however, it comes with a cost of increased pressure difference, which should be minimal for the breathability and comfort properties of the mask. The filtration efficiency and breathability of the mask were satisfactory and within the standard specification of CNS 14774, demonstrating protection and breathability. The facemask also demonstrated excellent antimicrobial activity of 99.40%, extremely significant considering the current situation.

4.4. Poly (butylene succinate)
Polybutylene succinate, or PBS, has emerged as one of the most promising bio-plastics due to its excellent biodegradability, melt processability, and chemical resistance [80]. The most famous PBS production technique is polycondensation of succinic acid (or dimethyl succinate) and 1,4-butanediol. These monomers can be obtained from petroleum-based fossils or renewable resources and have applications in compostable bags, nonwoven garments, sheets, foams, mulching films, and catering goods [81]. Recently, Choi et al [35] made a bio-degradable, efficient, and breathable facemask filter medium using PBS. They made the fibers using electrospinning in the micro and nano ranges, with varying times for different thicknesses and evaluated their filtration performance. The electrospinning setup is represented schematically in figure 8(a). Nano and microfibers have shown uniform fiber diameter without any evidence of beaded structure. They performed electrospinning at different times and measured the filter media thickness.

Figure 8(b) graphs the relation between thickness and spinning. The nanofibers’ thickness increased with a longer electrospinning duration, and the microfibers’ higher thickness had the same time duration as the nanofibrous mesh. The nanofibrous mat had superior filtration efficiencies than microfibers for all thickness, with the best filtration efficiency of 90% for 10 gm⁻² thick nanofibrous mat (see figure 8(c)) due to the physical sieving mechanism. Electrostatic attraction of particulate matter (PM) is one of the most promising mechanisms for lower size particulate matter prevention. Many commercial masks use electrostatic attraction temporarily formed with the help corona charging setup [71]. A permanent charge and antimicrobial property were
incorporated on PBS electrospun polymers by dip-coating chitosan (CsW) nanomaterial [82, 83]. The filtration efficiencies of nano and microfibers before and after CsW coating is given in figure 8(d). The filtration efficiency improved after CsW coating, showing electrostatic deposition of PM. The maximum value of 97% efficiency was reached for 10 μm thickness. The nanofibrous filter layer showed higher pressure drop than microfibers, which could be due to smaller voids in the nanofibrous structure compared to the graph of figure 8(e), which was contradictory considering nanofibers meshes are more porous compared to microfibers [35, 70, 84]. However, this contradictory behavior can be ascribed to the smaller pore size nanofibers, which are more susceptible to blocking due to the chitosan coating contributing to increased pressure difference. The thickness of the filter media needs to be optimized to maintain the minimum pressure drop with good filtration to maintain
comfortable breathability to the wearer. The fabricated facemask degraded within 1 month in composting conditions, showing great potential as a viable replacement for petroleum-based facemasks.

4.5. Polylactic acid (PLA)
Polylactic acid (PLA) is a bio-degradable polymer obtained from lactic acid during the fermentation of crops [52]. PLA is the most famous bio-degradable polymer owing to its biocompatibility, processability, and stiffness. The PLA can be processed using various techniques, such as injection molding, cast filming, blow filming, fiber spinning, and thermoforming [52, 85]. Patil et al [62] made a fully biodegradable three-ply facemask using a PLA nanofibrous filter layer, top and bottom functionalized cotton, and PLA as a filter layer with antimicrobial properties imparted using natural substances, as represented schematically in figure 9. The outer layer was treated with C6 fluorocarbon to impart hydrophobic properties, which was 153°, indicating superhydrophobic characteristics when checked with a static contact angle goniometer. The PLA nanofibers were manufactured using the needleless electrospinning method (NLES), as shown in figure 10. NLES can be used to fabricate scalable quantities of nanofibers and hence could help produce advanced nanofibers based on highly efficient facemasks to ameliorate the pandemic instead of using conventional electrospinning technique as it is not viable for large scale production [86].

In NLES, the polymeric jet initiation occurs by a self-organized process occurring at the surface of the free liquid compared to the capillary forces in the conventional electrospinning process. The NLES is a complex process, and it is difficult to control the nanofibers directly produced from an open liquid surface. The rotating electrode is partially dipped inside the polymeric solution. The electrode rotation causes agitation leading to the formation of conical spikes, which are stretched due to the high electric fields and deposited on the take-up
cylinder [87]. The mask fabricated showed a low-pressure differential of 35.78 Pa cm$^{-2}$. Many studies have reported the antimicrobial activity of various substances due to their chemical and structural properties. The most common antimicrobial agents are derived from natural sources [71]. A recent study by Park et al [88], found that simply depositing nano dry salts (NDS) on the nonwoven structure of the mask can also help to inactivate the coronavirus. The antimicrobial activity of these substances can be predicted using computational analysis of phytochemicals against bacteria and virus targets based on the interaction at the ligand and the protein at the molecular level. Molecular docking and conceptual density functional theory have proved the antimicrobial activity of various traditional phytochemicals, which can help restrict the spread of COVID-19 [89]. The computational study gave further encouragement to use natural substances as potential antimicrobial properties. The PLA mask was blended with Azadirachta Indica (10 wt% with respect to PLA) and Eucalyptus Citriodora (10 wt% with respect to PLA). The antimicrobial test was performed using the Bureau of Indian Standards for medical textiles. The mask incorporated with phytochemicals showed 97.9% bacterial filtration efficiency. The PLA-based facemask was also tested for its biodegradability using cow dung slurry. It showed promising biodegradability due to the action of various micro-organisms, leading to hydrolytic cleavage of ester bonds and breakage of macromolecular chains, as checked by weight loss measurements [90, 91].

5. Testing for polymer degradation

Polymer biodegradation is a natural phenomenon that involves the action of the complex biogeochemical process [52, 53]. The biodegradation conditions that occur naturally are callous to imitate in the lab conditions considering a large number of variables which include biotic (microbial activity) and abiotic (UV, temperature, moisture, and pH) components [92–94]. The complexity in the natural degradation process has resulted in an anomaly in the degradation reported in the lab and natural conditions. Hence, testing in the natural environment is necessary before the polymer is considered biodegradable. However, testing in natural conditions requires a longer duration, which is unsuitable for carrying out research in normal circumstances and should be considered in the final testing stage [95].

The biodegradation process can be divided into three stages: (i) abiotic deterioration, (ii) bio-fragmentation, and (iii) microbial assimilation. The first stage of polymer deterioration involves a loss in the polymer’s structural and physical properties by the action of the abiotic condition such as light and heat [95, 96]. The initial breakdown rate is affected by many factors, including the polymer’s chain length, crystallinity, size, shape, geometry, molecular weight distribution, surface porosity, and water diffusivity in the polymer matrix. In the bio-fragmentation stage, the micro-organism acts on the smaller fragments of the polymers and further degrades them into microplastics by the action of enzymes. The polymers with more active functional groups are vulnerable to microbial attack than non-reactive linear chain polymers [97]. The final biodegradation stage is the fundamental reason for biodegradation as polymers are the carbon source that acts as a feedstock for micro-organisms. The simple reaction illustration is given in equation (3). The micro-organism utilizes the carbon
Table 4. Standardized testing for biodegradation and their specifications. Adapted from [94].

| Standardized Test   | Degradation Environment          | Temperature       | Test duration | Validity criteria                                                                 |
|---------------------|----------------------------------|-------------------|---------------|-----------------------------------------------------------------------------------|
| BS EN ISO 14851:2004| Sludge, compost and/or soil       | 20–25 (±1)        | Max. 6 months | Greater than 60% degradation of reference material; BOD of negative control must not exceed a specified upper limit. |
| BS EN ISO 14852:2018| Sludge, compost and/or soil       | 20–25 (±1)        | Max. 6 months | Greater than 60% degradation of reference material; CARBON DIOXIDE evolved from negative control must not exceed a specified upper limit. |
| ISO 18830:2016      | Sediment or sediment and seawater| 15–28 (±2)        | Max. 24 months| Greater than 60% degradation of reference material; BOD of negative control must not exceed a specified upper limit. |
| ISO 17556:2012      | Adapted or non-adapted soil      | 20–28 (±2)        | Max. 6 months | ≥60% degradation of reference material. The measured CO2 or the BOD values from the blanks at the end of the test are within 20% of the mean. |
| ASTM D6691-09       | Preselected strains or seawater   | 30 (±1)           | Max. 3 months | ≥70% degradation of reference material                                              |
| ASTM D7991-15       | Sediment and seawater            | 15–28 (±2)        | Max. 24 months| ≥60% degradation of reference material                                              |
| NF U52-001          | non-adapted soil                 | —                 | —             | ≥70% degradation of reference material. Standard deviation of replicates <20%.        |
| UNI 11462:2012      | non-adapted soil                 | 21–28             | Max. 3 months | ≥60% degradation of reference material. Standard deviation of replicates <10%.        |
source for their growth and energy needs and releases carbon dioxide or methane depending on oxygen availability. Hence, the easiest way to determine the biodegradability of the polymer is the release of CO$_2$. In contrast, other metabolites (e.g., alcohols, fatty acids, aldehydes, and methane, etc) can be determined using gas chromatography with mass spectrometry (GC-MS)\cite{98, 99}.

\[
\text{C}_{\text{polymer}} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{C}_{\text{biomass}}
\]

(3)

The residual polymer’s molecular weight changes and distribution after biodegradation can be analyzed using gel permeation chromatography (GPC)\cite{100}. Various organizations use standardized tests to evaluate the biodegradation or compostability of polymeric materials, as given in table\ref{table4}. These standardized tests give the procedures, conditions limits, and results\cite{101, 102}. ASTM D6400 is one of the most well-known standard specifications for compostable materials for municipal and industrial composting facilities. Material can be considered biodegradable if it fulfills the satisfactory requirements of disintegration, biodegradation, aquatic safety, and terrestrial safety in a controlled composting lab environment. These requirements can be evaluated from weight reduction, analyzing the evolution of CO$_2$, CH$_4$, biological oxygen demand (BOD), or the ratio of BOD/theoretical oxygen demand, and observing the change in the surface morphology and molecular weight measurements\cite{103}.

6. Future outlook and summary

Facemasks, intended for medical professional use, are now ubiquitously used by the masses owing to the COVID-19 pandemic. The elevated use of a single plastic facemask is causing severe damage to the ecosystem. There is a dire to derive a method for rapid manufacturing of bio-degradable facemask at a low cost. Previous researchers have made many attempts to fabricate facemasks using bio-degradable polymers; however, these processes need to be optimized further for consistent filtration efficiencies, longevity, and scalability. More research must also focus on developing antimicrobial and antiviral properties in the filter layer to avoid cross-infection.

This review aims to provide comprehensive information regarding the fundamentals of the mask structure, its mechanism for disease prevention, and the most conventional manufacturing techniques and their parameters. The primary difference between the presently available and ideal facemask to eliminate the ill effect of microplastics, environmental footprint and lifecycle assessment of facemask is given. The details regarding the state-of-the-art reports on facemask using bio-degradable polymers and their fabrication process are discussed. The filtration performance and antimicrobial characteristics for each fabrication technique, along with basics of biodegradation and standardized tests, are also mentioned.

Mass vaccination programs are already in full swing; however, the role of the mask will still be prominent considering the current state of virus mutations. Scalable bio-degradable polymers-based facemasks with permanently charged surfaces for high filtration efficiency and antimicrobial and antiviral properties are an urgent necessity in the present scenario and the future. Hence, a collaborative strategy partnering with industries, health professionals, and materials scientists are required to design an advanced facemask to ameliorate the present and after effect of the pandemic.

Declaration of competing interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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Data availability statement

No new data were created or analysed in this study.
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