Nanofibers enhanced with plant extracts: A novel approach to combat microorganisms for use in face masks

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ABSTRACT

The review highlights the progress in face mask technology, specifically the use of electrospun nanofiber membranes, which are lightweight and feature tiny pores that ensure high filtration efficiency. These masks are gaining popularity for their ability to effectively block infected aerosols and protect against environmental pathogens. There is an increasing demand for masks that not only filter airborne particles but also have antiviral and antibacterial properties, particularly in response to new pathogens that can lead to pandemics. Traditional masks often fail to filter out nano and micro-scale particles and can pose risks of pathogen transmission when disposed of improperly. While Non-natural antimicrobial agents can enhance mask effectiveness, they may also introduce harmful side effects. The review suggests that incorporating natural plant extracts into nanofibers can provide a dual benefit: maintaining structural integrity while offering antibacterial properties, making them a safer option for mask development. This review aims to assist engineers, scientists, and entrepreneurs in creating innovative face masks.

Keywords: face mask, electrospinnig, nanofiber, antibacterial, plant extracts, pathogens

١. INTRODUCTION

Airborne pollutants pose serious health risks, leading to various diseases. Particulate pollution, especially particulate matter (PM ٢.٥), along with bacteria and viruses, significantly impacts public health, causing an estimated ٤.٢ million premature deaths annually, as reported by the World Health Organization (WHO). Masks serve as physical barriers that obstruct the ingress of mucosal and salivary droplets into the nasal and oral cavities. Mask usage is typically seen as a low-risk and cost-effective strategy for disease mitigation among the general populace, aiding in source control from asymptomatic individuals inadvertently spreading the virus. Thus, wearing masks is vital for personal protection and effectively controls respiratory infections [١]. Besides the advantages of face masks in diminishing aerosol transmission of pathogens, the act of breathing mechanically enhances penetration during repeated inhalations, causing the mask to serve as a collector of viruses, especially when its exterior is exposed to contaminated droplets. The filter layer of typical single-use face masks (SFM) mostly consists of non-biodegradable, petroleum-based polypropylene melt-blown fabric, which captures ultrafine particles by electrostatic adsorption. Therefore, the filtration efficiency decreases continuously because of the humidity change caused by the moisture breathed out by wearers. Membrane filtration, particularly using electrospun nanofiber membranes, offers a promising solution for air filtration. Electrospinning is one of the most widely documented methods for manufacturing nanofibers. Its capacity for efficient scalability and straightforward technology transfer for large-scale production is the reason. Optimisation is straightforward, and diverse fibre types with varying properties can be electrospun for applications including wound dressing, nerve cell regeneration, and filtration. The generated fibres are appropriate for their intended applications. Electrospinning is acknowledged in the literature as a straightforward, efficient, and portable polymer processing technique for producing polymeric nanofibers with diameters spanning from micrometres to nanometres, while allowing for the regulation of surface properties including surface area, pore size, and pore volume for various applications. These membranes have advantages over traditional microfiber filters, including higher surface area, porosity, and customizable pore sizes. Masks made from these materials effectively block viruses and reduce the spread of aerosol droplets. In contrast, conventional filter materials like glass and melt-blown fibers can be less environmentally friendly. Thus, there is a growing interest in developing natural polymer nanofiber filters to improve air quality while minimizing environmental impact [۱- ۵].

The incorporation of antibacterial characteristics into electrospun nanofibers via medicinal plant extracts is a novel approach for improving personal protective equipment (PPE). Electrospinning produces nanofibers with a high surface area, allowing plant extracts to be embedded or coated onto the fibers, providing natural antimicrobial properties [۶].

۲. Structure of a face mask

Personal protective masks often comprise many fundamental components that function together to provide safety. The design and composition may differ based on the mask type and its intended purpose [۷]. The fundamental elements often present in personal protective masks are as follows: (i) External layer (protective layer): The exterior layer is generally composed of a non-woven fabric or a comparable substance. It functions as the primary line of defense, serving as a barrier against bigger particles, liquids, and droplets. This layer inhibits the ingress of environmental pollutants into the mask. (ii). Intermediate layer (filter layer): The filter layer is an essential element that captures minute particles, including dust, pollen, bacteria, and viruses. These particles are categorized into three categories based on size: macroparticles (more than ۶۰۰ nm), microparticles (about ۳۰۰–۶۰۰ nm), and nanoparticles (less than ۳۰۰ nm). It is typically composed of high-density materials, such as melt-blown polypropylene. The complex web-like configuration of this layer forms a barrier that efficiently filters airborne pollutants, safeguarding both the user and others nearby. (iii) Inner layer (shell layer): The inner layer directly contacts the wearer's face. It is generally composed of a soft and comfy fabric, such as cotton or a synthetic combination. This layer fulfills several functions. It offers a soft and soothing sensation on the skin, absorbs moisture from the wearer's respiration, and minimizes friction or irritation [۸, ۹]. (iv) Nose Wire: Numerous masks feature a nasal wire or a metallic strip along the superior edge. This component enables the wearer to mold the mask over the nose, creating a secure and tailored fit. The nose wire mitigates air loss from the upper portion of the mask, hence enhancing its overall efficacy [۱۰]. Ear loops or straps: Personal protective masks typically feature ear loops or straps that anchor the mask securely. These loops or straps encircle the ears or head, ensuring the mask remains correctly positioned throughout use. Adjustable ear loops or straps facilitate a secure fit and enhance comfort [۱۱]. (vi) Exhalation Valve: Certain masks, especially those utilized in industrial contexts or for specific applications, may feature an exhalation valve. This valve facilitates expiration by opening during the wearer's exhalation. It decreases humidity within the mask, enhancing respiratory comfort. Nonetheless, masks equipped with exhalation valves are inappropriate for scenarios when the safeguarding of others is paramount, as the valve permits the release of unfiltered air [۱۲].

۳. Nanofiber-based face masks

Nanofibers' thin fiber diameter, small pore size, high porosity, and large specific surface area make them useful in a variety of applications in the domains of filtration, energy and medical dressings [۱]. Nanofibers are incredibly well-suited for applications like water and air filtration, membranes, protective gear, and drug delivery systems because of their high surface area-to-volume ratio, low weight, and adjustable surface qualities. Additionally, nanofibers provide ways to precisely alter the surface, improving properties including biocompatibility, water solubility, and bio-recognition. These characteristics put polymer nanofibers at the forefront of biotechnology and healthcare applications. Most significantly, they overcome the limitations of traditional melt-blown nonwoven materials, which rely on electrostatic adsorption for filtration, by primarily relying on physical interception (small pore size) between the fibers to achieve filtration. Nanofiber membranes can maintain high filtration efficiency over extended periods of time and under extreme conditions of use. In addition, they have low density, low piezoresistive resistance, and high efficiency, among other advantages. As a result, nanofibers have become the most potent and promising candidates in the field [۳]. The nanofiber scale, especially that of ultrafine fibers, has also been shown to have a substantial impact on filtration performance in a number of investigations. Studies have shown that fibers show a slipping effect when the fiber scale is less than ١٣ nm, which reduces or eliminates filtering resistance. Highly effective and low-resistance (٩٩.٩٢٪ and ٦٩ Pa) polyvinylidene fluoride (PVDF) nanofiber antifogging window screens with a ٢٠–٣٥ nm scale and high transparency (−٨٠٪) were created by Xiong ٢٤. This was achieved by electrospinning a very diluted PVDF solution with high conductivity [١].

Zhang [١٣] and Liu [١٤] used friction electrostatic technology to successfully create two-dimensional spider web nanofibers with a diameter of about ٣٠ nm. This method produced a porosity of ٩٢.١٪, a resistance of just ٧٣.٥ Pa, and a removal effectiveness of up to ٩٩.٩٩٦٪ for PM ٠.٣. However, the wider usage and development of synthetic polymers are limited by the use of costly ingredients and the requirement for posttreatment of these materials after use.

٤. Electrospun polymer nanofibers

Nanofibers can be fabricated using various methods, including electrospinning, centrifugal spinning, meltblown technology, phase separation, and template synthesis. Among these, electrospinning is the most widely used due to its ability to produce continuous nanofibers with diverse surface topographies and morphologies. The electrospinning process in which a polymer solution is charged by an electric field. The polymer solution is flowed at high voltage through a syringe. The polymer solution is removed from the tip of the needle to form nanofibers continuously due to the high voltage [١٥]. Electrospinning is simple, cost-effective, efficient, and reproducible, allowing for the use of both synthetic and natural polymers [١٦]. It can create ultra-thin, flexible nanofibers with diameters from tens to hundreds of nanometers, offering high surface area for improved filtration and breathability—key factors for comfortable mask production [٧, ١٧].

An electrospinning apparatus usually is comprised of a syringe pump, a capillary needle (the spinneret), a high-voltage power sup-ply and a metal collector. Figure ١ shows the electrospinning scheme and the microscopic image of the nanofibers.

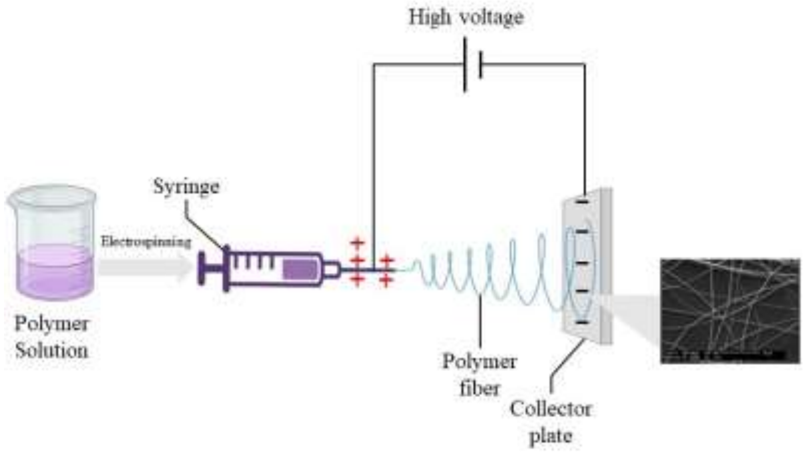

Figure ١. *The electrospinning scheme and the resulting nanofibers*

٤.١. Methods of electrospinning

Bioactive substances can be incorporated into electrospun nanofibers by two methods. In one approach, active compounds are introduced into the solution prior to electrospinning, subsequently yielding nanofibers that incorporate the active agents. In the alternative method, nanofibers are initially synthesised using electrospinning, followed by the incorporation of active and medicinal substances into their surface via complimentary and surface modification techniques. The initial method involves incorporating medicinal compounds into the electrospinning fluid and encapsulating them within fibres, so facilitating sustained release while inhibiting premature discharge, which has garnered significant interest. Three strategies for electrospinning include mix electrospinning, co-axial electrospinning, and emulsion electrospinning [١٨].

The emulsion and coaxial methods of electrospinning have garnered increased interest owing to their capacity to encapsulate therapeutic agents within electrospun nanofibers. In the blend electrospinning technique, the electrospinning solution comprises a combination of polymer and bioactive agents, whereby the bioactive molecules are dissolved inside the polymer solution. This form of electrospinning significantly contributes to the research. Core-shell fibres produced through co-axial electrospinning exhibit a significant capacity for encapsulating pharmaceuticals and biological agents. Their structural design effectively prevents direct exposure of biological molecules to the external environment, which is essential for preserving the biological activity of unstable drug agents. Co-axial electrospinning employs several syringes. Typically, active pharmaceutical compounds are encapsulated within the core, while the shell serves a protective function and facilitates the controlled release of biomolecules. Emulsion Electrospinning is a technique for manufacturing core-shell nanofibers that does not necessitate specialised needle tuning. This method depends on forming an emulsion inside a singular solution, followed by the incorporation of pharmacological substances, resulting in the formation of a particulate solution. In the electrospinning process, these pharmacological compounds are integrated into the fibre core, resulting in the formation of core-shell nanofibers [۱۹]. Figure ۲ shows the different electrospinning methods for loading drugs into nanofiber.

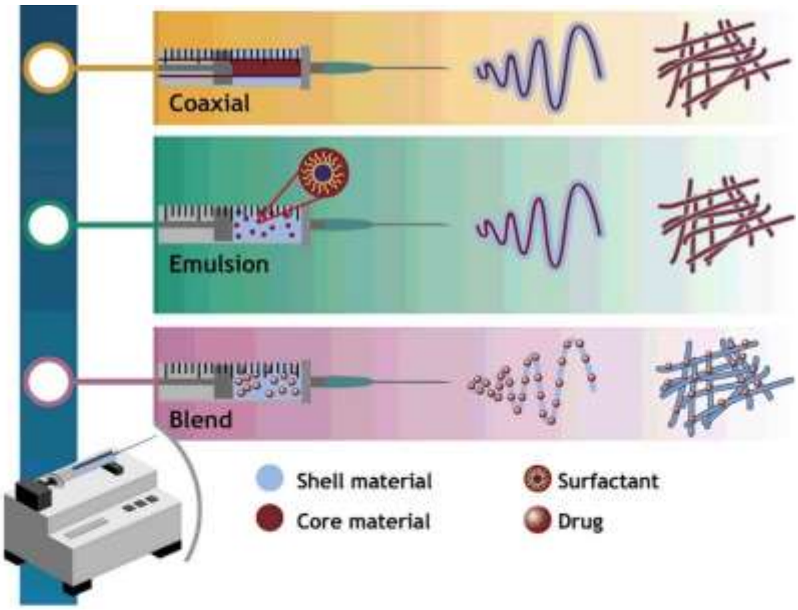

Figure ۲. *Different electrospinning methods for drug loading on nanofibers, including blend electrospinning, co-axial electrospinning and emulsion electrospinning* [۱۸]

۵. Classification of polymers used in electrospinning

In this section synthetic and natural polymers that have been used in electrospinning are listed in Figure ۳.

Figure ۳. *Classification of polymers used in electrospinning*

۵.۱. Synthetic Polymer

Plastics' durability makes them suitable for packaging, construction, and hygiene products, but they're not easily biodegradable and resistant to microbial degradation. With rising oil costs, interest in biodegradable polymers has increased. Biodegradation transpires by enzymes or chemical reactions, with biodegradability determined by the polymer's source, structure, and environmental factors [۲۰]. According to the aforementioned information Synthetic polymers utilized in electrospinning are often categorized into biodegradable and non-biodegradable classes based on their functional applications. The often utilized biodegradable polymers include polyethylene oxide (PEO), polyurethane (PU), poly(lactic-co-glycolic) acid (PLGA), polylactic acid (PLA), polycaprolactone (PCL), and polyvinyl alcohol (PVA) [۱۶]. Moreover, prevalent non-biodegradable polymers include polyvinylidene fluoride (PVDF), polycarbonate (PC), polyvinyl chloride (PVC), polystyrene (PS), polyacrylonitrile (PAN), and polyamide (PA) [۲۱, ۲۲]. This section offers an overview of the synthetic polymers referenced.

۵.۱.۱. Polyethylene oxide (PEO)

Polyethylene oxide (PEO) is a hydrophilic polymer that can integrate with natural active constituents of herbal medicine to enhance characteristics. Nonetheless, elevated water solubility impedes practical usage. To address this issue, the use of additional polymers and cross-linking agents can enhance the material's functionality and application, facilitating optimal release rates and concentrations of active chemicals [۱۶]. Oana et al. [۲۳] incorporated chitosan (CS), which was blended with various active components. The CS/PEO nanofibers infused with Propolis-Calendula officinalis extract exhibited an enhanced hemolysis index, non-toxicity, and notable free radical scavenging and antibacterial efficacy against *Staphylococcus aureus*. Zahedi et al. [۲۴] used coaxial electrospinning technology, utilizing aloe extract/PEO as the core and PCL/chitosan/keratin nanofibers as the shell. The shell's protection permits the incorporation of the herbs into the membrane.

۵.۱.۲. Polyurethane (PU)

Polyurethane (PU), a biocompatible hydrophobic polymer, is widely used in medical applications due to its superior biocompatibility and flexibility [۱۶, ۲۵]. It has also been used as a biomaterial for bone and cartilage repair since the late ۱۹۹۰s [۲۶]. The efficacy of moisture control, together with its favorable barrier and mechanical qualities, has been investigated in face masks [۱۶]. A study revealed that, despite a lower initial weight, the filtration effectiveness and quality factor of four layers of polyurethane nanofiber filter media surpassed those of a three-layer N۹۵ mask. The electrospun polyurethane nanofiber media exhibit satisfactory filtration efficiency and quality factor values for filtering applications. Moreover, the production of nanofiber media with specific characteristics (such as nanofiber diameter and homogeneity) for application in respiratory protection filters can be achieved by refining the electrospinning process [۲۷].

۵.۱.۳. Polylactic acid (PLA)

Polylactic acid (PLA), developed in ۱۹۳۲ by Wallace Carothers, is a sustainable, biodegradable substance derived from renewable plant materials like corn starch. Its quick prototyping, excellent biodegradability, and biocompatibility make it a prime material in medical applications like tissue engineering and drug delivery systems [۷, ۲۱]. Owing to the superior characteristics of PLA, researchers formulated a poly (L-lactic acid) (PLLA) polymer. Like polylactic acid, it possesses excellent mechanical and biodegradable characteristics [۲۷]. Upon utilization, these masks can be entirely decomposed by microorganisms in the environment, leading to the production of carbon dioxide and water, hence avoiding environmental pollution [۲۸]. Consequently, PLA is advantageous for personal protection and conforms to environmentally sustainable procedures, aiding in environmental preservation, a vital element of sustainable mask design [۷]. Salami et al. [۲۹] employed poly("-caprolactone)/poly(vinyl alcohol)/collagen (PCL/PVA/Col) to encapsulate the Momordica charantia extract. Post-incorporation, the wettability of the nanofibers enhanced, although the shape, porosity, water vapor permeability, and swelling parameters remained mostly unaffected. In vitro findings indicated that the synthesized nanofibers inhibited bacterial penetration. A study involved blending polylactic acid (PLA) and black pepper essential oil (BP-EO) in an acetone solution, electrospinning the mixture into nanofibers, and subsequently coating them with medium molecular weight chitosan (CS). The findings indicate that the CS coating enhances the fiber's hydrophilicity and creates a biocompatible hydrophilic layer for efficient treatment. Simultaneously, it augments the antibacterial efficacy of the essential oil independently [۳۰].

۵.۱.٤. Poly(lactic-co-glycolic) acid (PLGA)

Poly(lactic-co-glycolic acid) (PLGA) is a polymer formed from the uneven polymerization of lactic acid (LA) and glycolic acid (GA) [۳۱]. The superior controllable degradability and adjustable physicochemical properties render PLGA a suitable candidate for electrospun fibers [۲٦, ۳۲]. Polylactide-glycolide (PLGA) is extensively utilized in tissue engineering due to its affordability, distinct structure, dependable mechanical characteristics, and degradation kinetics, along with its excellent biocompatibility and biodegradability [۱٦]. Aksit et al. [۳۳] chose PLGA/gelatin polymers and incorporated varying quantities of Hypericum capitatum var. capitatum (HCC) extract, a traditional herb, to fabricate antibacterial membranes. The elevation of HCC concentration resulted in a reduction of fiber diameter and enhanced the hydrophilicity and breakdown rate of the membrane. It also demonstrates antimicrobial properties, non-toxicity, biocompatibility, and cell adhesion.

۵.۱.۵. Polycaprolactone (PCL)

Polycaprolactone (PCL) is an organic polymer synthesized using the ring-opening polymerization of caprolactone monomers. PCL is a biocompatible material that has received Food and Drug Administration (FDA) approval. The presence of ester groups imparts degradable characteristics to PCL. PCL can undergo hydrolytic cleavage, resulting in oligomeric pieces that are subsequently phagocytosed and digested by macrophages [۲٦, ۳٤]. Currently, the exceptional characteristics of PCL, including its processability, favorable mechanical properties, biodegradability, and biocompatibility, render it appropriate for diverse tissue engineering applications, including bone, cartilage, nerve, cardiovascular tissue, and skin [۳۵, ۳٦]. PCL nanofiber fabrics can be manufactured with significantly reduced pore diameters for use as filtration devices, contingent upon the production process. The attributes of PCL fabrics offer significant qualities including filtration, hydrophobicity, and flexibility. The incorporation of antimicrobial nanoparticles into PCL for targeting specific microorganisms renders the use of PCL in face masks highly adaptable [۳۷]. The disintegration rate of PCL is far slower than that of other biodegradable synthetic polymers, rendering PCL an optimal choice for long-term drug delivery systems, such as contraceptive implants [۳۸].

۵.۱.٦. Polyvinyl alcohol (PVA)

Polyvinyl alcohol (PVA) is a biodegradable polymer utilized by bacteria as a carbon and energy source. PVA is harmless and biocompatible, rendering it an excellent solution for the production of many products, including plastic films [٣٩]. Polyvinyl alcohol (PVA) is a colorless, tasteless, water-soluble semi-crystalline polymer [١٦]. Wang [٤٠] created a friction-based self-charging medical mask with hydrogen-bonded reinforced polyvinyl alcohol (PVA). This method successfully resolved the challenges associated with the charge storage capacity and self-charging efficiency of PVA. Conventional polypropylene-based medical masks demonstrate substantial charge dissipation with prolonged usage. Wang [٤١] synthesized Ag NCs/CS/PVA nanofibrous mats using electrospinning, demonstrating filtration efficiencies of up to ٩٨٪ and exhibiting superior antibacterial characteristics. Hartatik [٤٢] used an electrospinning process to fabricate collagen−CS/PVA composite nanofibrous materials exhibiting high filtration efficiency and superior bacteriostatic characteristics against *Escherichia coli* and *Staphylococcus aureus*.

٥.١.٧. Poly(vinylidene fluoride) (PVDF)

Flexible electroactive materials are crucial in electronic applications, including sensing, actuation, and energy harvesting. Poly(vinylidene fluoride) (PVDF) has garnered significant research interest owing to its exceptional pyroelectric, piezoelectric, and ferroelectric properties, in addition to its comparatively high dielectric permittivity. The formability, flexibility, and biocompatibility of PVDF enhance its suitability for diverse innovative applications [٤٣]. A study examined a high-performance composite filter medium exhibiting moisture electroactive antimicrobial properties, achieved by integrating electrospun poly(vinylidene fluoride)/polystyrene (PVDF/PS) nanofibers with Ag/Zn modified cotton fabrics via magnetron sputtering. The diminutive pore size, elevated porosity, and low basis weight of PVDF/PS nanofibers guaranteed superior air permeability and filtration efficacy. The Ag/Zn@cotton layer offers substantial structural stability and an effective contact sterilization capability [٤٤].

٥.١.٨. Polycarbonate (PC)

Among numerous potential engineering materials, polycarbonate (PC) occupies a pivotal place due to its distinctive mechanical and physical qualities. It is a substance characterized by superior heat resistance, resistance to acids and alkalis, impact strength, rigidity, toughness, and consistent performance in elevated temperature environments. The aforementioned characteristics of PC render it an appropriate material for filtration, biomedical applications, electronics, protective apparel, and numerous more contemporary uses [٤٥]. Being an amorphous material, it can retain a significant residual charge after electrospinning. The fabrication of antimicrobial filtration membranes from polycarbonate was achieved using electrospinning, including quaternary ammonium salt into the polymer matrix [٤٦].

٥.١.٩. Polyvinyl chloride (PVC)

PVC is among the most prevalent and economical synthetic polymers available in the market. The history of PVC commenced in the early ١٨٧٠s with the initial polymerization of vinyl chloride, yielding the first polymer. Nonetheless, the substance derived from the polymerization of vinyl chloride exhibited rigidity and brittleness. Consequently, it was unsuitable for industrial manufacture. In ١٩٢٦, American chemists found the method to plasticize PVC, leading to the commercialization of numerous PVC-based items thereafter. Currently, its demand is surpassed only by that of polyethylene and polypropylene, which are the materials with greater market demand. In ٢٠١٨, the worldwide demand for PVC was approximately ٤٤.٣ million tons and is projected to rise to nearly ٦٠ million tons by ٢٠٢٥ [٤٧, ٤٨]. PVC is used in many different fields, such as in the construction industry (pipes, windows, carpet, plumbing, etc.), electrical and electronic industry (instrument components, housing, sheaths for cables and wires, etc.), automotive industry, food packaging, medical equipment, and many others. PVC nanofibers have been used as a material for environmental applications (water filter, air filter, separator for water and oil), energy storage systems, anti-corrosive material, protective clothing, and so on [٤٨].

٥.١.١٠. Polystyrene (PS)

Amorphous polystyrene (PS) is a transparent, colorless, and lustrous substance, making it one of the most valuable plastics. It possesses exceptionally high electrical resistance and minimal dielectric loss.

Furthermore, it is rigid, inflexible, and exceedingly fragile. Nonetheless, variations like high impact polystyrene (HIPS), a copolymer combined with an elastomeric polymer such as polybutadiene, are frequently utilized. In this context, a brittle PS may generally be rendered somewhat flexible through fiberization. Polymer fibers have been fabricated by electrospinning and conventional techniques including melt, wet, and dry spinning [٤٩]. Polystyrene (PS) is a frequently electrospun polymer, renowned globally for its superior physical qualities and affordability. Polystyrene is one of the materials presently utilized in surgical masks and, to a lesser degree, in other face coverings. It has exhibited remarkable filtration efficiencies of up to ٩٩.٧٦٪ and ٩٩.٩٩٪ for particles measuring ٠.٣ µm and ١ µm in diameter, respectively [٥٠].

٥.١.١١. Polyacrylonitrile (PAN)

Polyacrylonitrile (PAN) is a synthetic thermoplastic polymer characterized by a melting point of ٣٠٠ °C and a glass transition temperature of around ٩٠ °C, with a linear structure. This polymer, produced through the progressive polymerization of acrylonitrile, has widespread uses in textile fibers, hollow fibers, and membranes. A study examined the efficacy of PAN-graphene oxide membranes in air filtration and the collection of suspended particles, demonstrating a removal effectiveness above ٩٩٪ after ١٠٠ hours [٥١]. The amalgamation of PAN with Moringa gum to fabricate nanofibers exhibiting healing and antibacterial properties constitutes one of the applications of PAN in biomaterials [٥٢]. A composite of PAN and bovine serum albumin, along with hybrid nanofibers, has also been documented in wound dressings [٥٣]. A layer of PAN nanofibers was functionalized with metal nanoparticles, including gold, silver, and copper, to act as an antibacterial agent in respirators [٥١, ٥٤].

٥.١.١٢. Polyamide (PA)

Polyamide (Nylon) is an economical polymer composed of amide groups interspersed with methylene sequences, which can be electrospun exhibiting favorable mechanical, thermal, and chemical properties. It is a biodegradable and biocompatible synthetic polymer exhibiting excellent mechanical capabilities, which are further augmented by hydrogen bonding. To improve the biodegradability of polyamide, it was combined with chitosan, which possesses antibacterial and antiviral properties in addition to its biodegradability, biocompatibility, and nontoxicity. Electrospun nanofibers derived from polyamide (PA) have already been utilized in several applications [٥٥, ٥٦]. PA exhibits an exceptional capacity for fiber formation. In contrast to other polymers like polyethylene oxide and polyvinyl alcohol, PA exhibits resistance to both water and humidity. PA is soluble in formic or formic/acetic acid solutions, promoting environmentally friendly processes compared to other solvents like dimethylformamide (DMF), which is hazardous as per EU directive ٦٧/٥٤٨/EEC. PA ٦ and PA ٦/٦ are the most extensively researched polyamide variants; yet, the discourse regarding their applicability in filtering is quite constrained. Recent results indicate that electrospun nylon-٦ nanofibers demonstrate polyamide (PA) as a notably appealing material for filtration applications [٥٦, ٥٧].

٥.٢. Natural polymer

Natural polymers in electrospinning are gaining attention for their biocompatibility, biodegradability, and sustainability. They are mainly divided into two types: polysaccharides and proteins [١٦]. Polysaccharides are the homopolymers or copolymers of monosaccharides. In nature, polysaccharides can be found in many organisms, including polysaccharides of algal origin (e.g. alginate), plant origin (e.g. cellulose and starch), microbial origin (e.g. dextran), and animal origin (e.g. chitosan and hyaluronic acid) [٥٨]. They are environmentally friendly, derived from renewable resources. Proteins are essential amino acids in the human body, offering high biocompatibility, making them important for various medical applications. Proteins like collagen, silk fibroin, corn protein, and keratin are valued for their structural properties and applications in tissue regeneration, face masks, and biomedical uses [١٦, ٥٩].

٥.٢.١. Animal Polysaccharide

Chitosan (CS) and hyaluronic acid (HA) are two animal-derived polysaccharides being researched for use in creating nanofibers. Chitosan is a naturally occurring, cationic polysaccharide found in the shells of crustaceans, insects, and fungi, such as crabs and shrimps. It is derived from chitin through a deacetylation process and is a key component of dermal tissue, consisting mainly of N-acetylamino and D-glucosamine [۲٤]. Chitosan (CS) has been extensively used in biomedical applications due to its numerous beneficial properties, including high absorption, cost-effectiveness, biodegradability, Immunostimulatory properties, non-toxicity, Antibacterial properties, Anti-inflammatory- properties, Remodeling behavior [٦۰, ٦۱]. Hyaluronic acid (HA) is a negatively charged linear glycosaminoglycan consisting of repeating disaccharide units. It is a vital component of intracellular, extracellular, and pericellular matrices, found in joints, cartilage, and skin. HA is essential for transporting nutrients to help cells degrade products [٦۲].

Electrospinning technology is challenged by the insolubility of hyaluronic acid (HA) in organic solvents and the properties of its aqueous solution. Snetkov's research group [٦۳] addressed these issues by creating HA-curcumin electrospun fibers with antibacterial, anti-inflammatory, and anti-tumor properties. They formed a metachromatic complex between HA and curcumin in a water-organic medium, which stabilized the electrospinning process and improved the fibers' characteristics.

۵.۲.۲. Plant Polysaccharide

Plant polysaccharides, particularly cellulose, are extensively used in electrospinning, with pectin and starch also serving as carriers. Cellulose, the primary component of green plant cell walls and the most abundant natural biopolymer, is a linear homopolymer of β-(۱-٤)-glycosidic bond-linked D-anhydroglucan. It is valued for its excellent thermal and mechanical stability [٦٤, ٦۵] Nanotechnology advancements have enabled the use of nanocellulose in electrospinning, with sizes ranging from nanometers to microns depending on its ۱D, ۲D, or ۳D structure [٦٦, ٦۷].

Cellulose acetate (CA), a widely used derivative of cellulose, is non-toxic, cost-effective, easy to prepare, hydrophilic, and biocompatible. It dissolves easily in various organic solvents, making it an ideal material for electrospinning [٦۸]. Electrospun nanofibers offer key benefits like loadability, controlled release, and high practicality [٦۹]. Gum Arabic (GA) is a branched, negatively charged polysaccharide [۷۰]. In contrast, Bell pectin (BFG) is a non-ionic polysaccharide made of arabinose, galactose, rhamnose, and glucuronic acid, with D-galactose enhancing water solubility and retention. Its galacturonic acid content allows property modification, and it serves as a gelling agent and adhesive [۷۱]. Carrageenan (CG) is a sulfated polysaccharide that forms hydrogels but has limited stability and durability, often requiring blending with other polymers [۷۲]. Starch is a popular natural polymer in biomedical engineering and biodegradable plastics due to its biocompatibility, biodegradability, and low cost. However, its brittleness and limited processability are improved by combining it with other polymers [۱٦].

۵.۲.۳. Algal Polysaccharide

Alginate (Alg), a polysaccharide from brown algae, is composed of D-mannuronic and L-guluronic acid units. Its immunoregulatory, antioxidant, anticoagulant, and anti-tumor properties make it valuable in biomedicine, including drug delivery and regenerative medicine [۷۳]. It is highly biocompatible, non-toxic, easy to process, and exhibits excellent film-forming capabilities [۷٤].

۵.۲.٤. Fungal Polysaccharide

Fungal polysaccharides, often bacterial-derived, are valued for their unique properties and applied in nanofibers. Dextran, a biocompatible, biodegradable, and water-soluble polysaccharide, is affordable, readily available, and easy to use. Hybrid nanofibers hold potential for use in bioactive delivery systems and antibacterial food packaging. Xanthan gum, an extracellular polysaccharide from Xanthomonas, contains glucose, mannose, and glucuronic acid. Its gel-like, stress-sensitive properties and high viscosity under low shear stress, driven by hydrogen bonding, make it suitable as an encapsulation matrix [۷۵].

۵.۲.۵. Collagen

Collagen, a key protein comprising ۳۰٪ of animal body weight, is vital for tissue structure, organ support, and cell function regulation. With properties like ductility, bioabsorbability, non-toxicity, antimicrobial activity, and compatibility with copolymers, collagen is an ideal material for nanofibers.

However, its drawbacks include processing challenges, high purification costs, and disease transmission risks [٦٣].

٥.٢.٦. Gelatin

Animal collagen can be hydrolyzed acidically or alkalinely to produce gelatin. It is also the most prevalent element in skin and bone. It is nearly identical to collagen in terms of composition and biological properties [٧٦]. The nanofiber membrane made by electrospinning technique has the benefits of tiny pore size, high surface area, and physical stability. It also has outstanding biodegradability, biocompatibility, and non-immunogenicity. Due to its inherent protein structure and several functional groups, gelatin can also be readily cross-linked and utilized as a targeted drug delivery vehicle [٧٧]. Gelatin has weak mechanical strength, degradability, and water resistance despite having strong functional qualities [٧٨]. A combination gelatin derived from freshwater fish skin and hog collagen was selected by Yao et al [٧٩]. On the one hand, fish gelatin has a reasonably good thermal stability and can help lower costs and certain infectious disorders [١٦].

٥.٢.٧. Silk fibroin

One of the strongest and most resilient biomaterials is silk fibroin (SF), a naturally occurring structural protein that is frequently isolated from silk worms. A disulfide link at the C-terminus connects the heavy (H) and light (L) chains that make up this important protein component [٨٠]. Silk fibroin is a great option for biomedical applications because of its versatility and ease of low-cost manufacture. In addition, it possesses low immunogenicity, anti-inflammatory properties, permeability, good cell adhesion, unique biocompatibility and biodegradability, and the capacity to regulate growth factor release [٨١]. Additionally, SF has predictable biodegradation rate and acceptable mechanical properties when compared to regularly used biopolymers like collagen and gelatin [٨٢, ٨٣].

٥.٢.٨. Zein

Zein, a hydrophobic plant protein and the primary storage protein in maize, is rich in amino acids such as leucine (٢٠٪), glutamic acid (٢١–٢٦٪), alanine (١٠٪), and proline (١٠٪). It exhibits excellent biodegradability, biocompatibility, flexibility, microbial resistance, non-toxicity, and antioxidant properties. Studies using suspension and double-nozzle electrospinning demonstrate its controlled release, biocompatibility, and antibacterial capabilities. Additionally, its outstanding film-forming and gas barrier qualities make it a suitable material for edible active food packaging applications [٨٤].

٥.٢.٩. Keratin

Keratins serve as structural proteins in many organisms. Their high stability and unique physicochemical properties are due to disulfide bonds between cysteine residues and various intra- and intermolecular bonds among amino acids [١٦]. Zahedi et al. [٢٤] employed coaxial electrospinning technology using aloe extract/PEO as the core and PCL/chitosan/keratin nanofibers as the shell. The protective shell enables the incorporation of aloe vera into the membrane. Aloe vera gel, consisting of ٩٩٪ water, is a therapeutic herb with strong antibacterial properties. The addition of keratin enhances adhesion and slightly boosts tensile strength.

٦. Herbal medicines loaded into electrospun nanofibers

There is an increasing interest in utilising the electrospinning technology for the fabrication of nanofibers incorporating active pharmacological components, including botanical medicines. Research has been conducted to integrate medicinal plants with nanofibers for medical applications. Plants can be utilised in the manufacturing of nanofibers as extracts, essential oils, and pure active compounds. Integrating nanofibers with plants amalgamates the structural physical features of nanofibers with the chemical and antibacterial attributes of plants. Certain plants may be appropriate for face masks composed of electrospun nanofibers. In the following, several examples will be mentioned [١٩].

٦.١. *Aloe vera* (*AV*)

Aloe vera (*AV*), often called the "Plant of a Million Benefits," has gained worldwide recognition for its diverse therapeutic and nutritional applications in cosmetics, food products, and pharmaceuticals. The fleshy leaves of the *AV* plant contain a rich array of bioactive compounds, including polysaccharides, antioxidants, vitamins, minerals, enzymes, lignin, saponins, salicylic acids, and amino acids. These components contribute to *AV*'s numerous beneficial biological properties, such as antifungal, antibiotic, antibacterial, antiviral, anti-inflammatory, and anti-swelling effects. In a study, The choice of *AV* as a key component in poly vinyl pyrrolidone(PVP)/CNF composite was driven by several factors that make it particularly suitable for facial mask applications [٨٥, ٨٦]

٦.٢. *Thymus Vulgaris L.* (*Thyme*)

Thymus Vulgaris L. (*Thyme*) grows in many parts of the world and has been known since history as a health-promoting plant. The main components of *Thyme* extract are the monoterpenes thymol and carvacrol, which gained popularity as antimicrobial agents. Depending on the type of extraction and the plant material, further components include phenolic acids like rosmarinic acid, gallic acid, caffeic acid, vanillic acid, syringic acid, and chlorogenic acid, as well as the flavonoids luteolin and apigenin. These compounds are known for their antimicrobial properties and are involved, for example, in pharmaceutical, cosmeceutical, medicinal, and dental applications. Some of those include antimicrobial food packaging, oral and skin care products, wound, plaque- and biofilm-preventing treatments, as well as personal protective equipment (PPE) [٨٧].

Lu et al. [٨٨] developed a Thymol/polyvinyl butyral (PVB) composite nanofibrous membrane with various optimization conditions for antibacterial mask applications. Thymol/PVB nanofibers may serve as an alternative membrane layer, anticipated to work as a multifunctional antibacterial mask against bacteria and viruses. Bacterial filtration efficiency and pressure differential demonstrate superior performance compared to the commercial mask. The quantitative antibacterial activity test utilizing the JIS L ١٩٠٢ absorption method indicates that an increase in Thymol concentration correlates with enhanced antibacterial activity of Thymol/PVB nanofibrous membranes.

٦.٣. *Glycyrrhiza glabra* (*G. glabra*)

Glycyrrhiza glabra, a medicinal herb, has been used since ancient times for its bioactive substances, including sugars, glycyrrhizin, and polyphenols. Its main component is *glycyrrhizin*. It is relatively heat stable and inhibit against the growth of cytopathology for various DNA and RNA viruses and is used to manage cough, pharyngitis, splenic disorders, allergies, hepatic issues, ulcers, and renal conditions. It is also used to treat early Addison's disease, cough suppression, and liver disease [٨٩].

Chowdhury et al. [٩٠] have proposed the potential of the licorice root membrane as a nanofiber that can be used in the production of a face mask. The porosity of the proposed mask is less than the size of COVID ١٩, thus, it is believed that this mask can help to prevent the spread of the virus.

٦.٤. *Oregano*

Oregano is a prevalent herb extensively found in the Mediterranean region and Asia. The entire grass can yield fragrant oil, specifically *oregano* essential oil (OEO). The primary constituents of OEO are carvacrol and thymol, which exhibit potent biological activity, including anti-inflammatory, antibacterial, and antioxidant properties [٩١]. Goncalves Cattelan et al. [٩٢] discovered that OEO exhibits an inhibitory effect on numerous bacteria and possesses a wide range of antibacterial capabilities. Lambert et al. [٩٣] discovered that OEO enhanced the permeability of the cell membranes of *S. aureus* and *P. aeruginosa*. Dutra et al. [٩٤] discovered that OEO can efficiently inhibit Alicyclobacillus, potentially due to the robust antioxidant properties of its constituent components. Consequently, OEO may serve as a potent natural antibacterial agent.

A study by Khan et al. in ٢٠٢٠ developed and assessed the antibacterial efficacy of PLA/Silk fibroin nanofibers infused with varying concentrations of OEO against pathogenic strains of *S. aureus* and *E. coli*. The results indicated that all nanofibers containing different concentrations of OEO exhibited antibacterial activity, whereas the blank PLA/Silk fibroin nanofibers showed no activity [٩٥].

٦.٥. *Moringa*

The *Moringaceae* family of flowering plants has a single genus, *Moringa*, which has been utilized for generations to treat wounds and different diseases, including diabetes and colds. Several phytoconstituents in *Moringa* species comprise alkaloids, saponins, tannins, steroids, phenolic acids, glucosinolates, flavonoids, and terpenes. The diverse array of phytochemicals in this species is beneficial for numerous therapeutic purposes [٦].

Fayemi et al. [٩٦] investigated polyacrylonitrile (PAN) nanofibers including varying amounts of *Moringa* leaf extracts. The antibacterial efficacy against *S. aureus* and *E. coli* was evaluated using the agar diffusion method, revealing a significant antibacterial effect with a ١٥ mm inhibitory zone for *E. coli* and a ١٢ mm inhibitory zone for *S. aureus*, utilising the maximum concentration of PAN nanofibers infused with *Moringa* leaves (٠.٥ g).

٦.٦. *Garlic*

Garlic is a bulbous blooming plant classified within the genus Allium. Allicin, the principal phytochemical in *Garlic*, has numerous biological activities, including antibacterial, antioxidant, antibiotic, anticancer, and antiviral effects. *Garlic* comprises organosulfur chemicals that are soluble in both water and oil [٦].

In a study, Edikresnha et al. effectively encapsulated *Garlic* extract and glycerin within PVP/CA nanofibrous mats exhibiting antibacterial properties. The antibacterial efficacy of the *Garlic* extract remained intact post-encapsulation in the fibers, as demonstrated by the in vitro antibacterial assay. Polyvinylpyrrolidone (PVP) and cellulose acetate (CA) were the foundational components of the composite fibers, which functioned as the hydrophilic matrix for encapsulating *Garlic* extract, with glycerine used primarily to enhance the mechanical properties of the composite fibers [٩٧].

Table ١ provides an overview of some of the plants used in electrospinning, their properties and components and carrier polymers.

Table ١. Some of the plants used in electrospinning, their properties and components and carrier polymer

Plant name	Component	Properties	Carrier polymer	Ref.
Aloe vera	Soluble sugars, anthraquinones, polysaccharides, sterols, amino acids, salicylic acid, vitamins, proteins, minerals	Antifungal, antibiotic, antibacterial, antiviral, anti-inflammatory, and anti-swelling	PVP	[١٦, ٨٥]
Thymus Vulgaris L.	Thymol, carvacrol, phenolic acids, flavonoids	Antispasmodic, anti-inflammatory, emmenagogic, antibacterial, antifungal, antiviral, antiparasitic, and antioxidant	PVB	[٨٧, ٨٨, ٩٨]
Glycyrrhiza glabra	Sugars, glycyrrhizin, polyphenols	Antiallergic, antibacterial, antiviral, anti-inflammatory, and anticarcinogenic	PVA	[٨٩, ٩٠, ٩٩]
Oregano	Carvacrol, thymol, rosmarinic acid (phenolic compounds)	Anti-inflammatory, antibacterial, antioxidant	PVDF	[١٦, ٩١]
Moringa	Alkaloids, saponins, tannins, steroids, phenolic acids, glucosinolates, flavonoids, and terpenes	Antibacterial, antioxidant, antibiotic, antifungal	PAN	[٦, ٩٦, ١٠٠, ١٠١]
Garlic	Allicin, flavonoids, phenolics, organosulfur, vitamin C	Antibacterial, antioxidant, antibiotic, anticancer, antiviral	PVP	[٦, ٩٧, ١٠٢]
Curcumin	Curcumin, demethoxycurcumin (DMC), bisdemethoxycurcumin (BDMC)	Anti-oxidant, anti-cancer, analgesic, relieving anxiety, angiogenesis, nerve healing	PVA	[٦, ١٦, ١٠٣]
Nigella	Thymoquinone (Essential Oil),	Analgesic, anti-inflammatory,	PVA	[٦, ١٦]

sativa (seed)	carbohydrates, proteins, alkaloids, vitamins, minerals	anticancer, antibacterial, antifungal, antioxidant		
Cinnamon	cinnamaldehyde, eugenol, camphor, benzaldehyde, cinnamic acid, coumarin, cinnamyl acetate	Antibacterial, anti-tumor, antioxidant	PEO	[٦, ١٦, ١٠٤]
Green tea	Polyphenols, amino acids, alkaloids, sugars, proteins, pectin, aromatic substances, enzymes, organic acids	Antibacterial, anti-inflammatory, antioxidant	PEO	[١٠٥, ١٠٦]
Matricaria chamomilla	Flavonoids, camphor, camphene, pinene, ١,٨-cineole, and bisabolol oxide	Antibacterial, anti-inflammatory, antiseptic, antispasmodic, antioxidant	PS	[١٠٧, ١٠٨]
Lavandula angustifolia	Terpenoids, polyphenols, coumarins, sterols, tannins	Antimicrobial, anti-inflammatory, antioxidant	PVA	[١٩, ١٠٩]

٧. Conclusion

Infectious diseases continue to pose significant threats to global health. While face masks have proven to be effective in preventing the spread of these diseases, the environmental impact of disposable masks and the need for more effective, reusable options have become increasingly pressing. Electrospinning technology offers a promising avenue for developing advanced face masks with enhanced antimicrobial properties. By integrating plant extracts into nanofibers, the power of nature can be harnessed to create innovative solutions that are both sustainable and protective. However, further research is needed to fully understand the safety, efficacy, and long-term impact of these nanofiber-based face masks. It is crucial to explore potential synergistic effects with other antimicrobial agents, optimize drug release profiles, and develop scalable manufacturing processes. By addressing these challenges, the way can be paved for the widespread adoption of these advanced face masks, contributing to a healthier and more sustainable future.

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