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Review

Biodegradable Electrospun Membranes for Sustainable Industrial Applications

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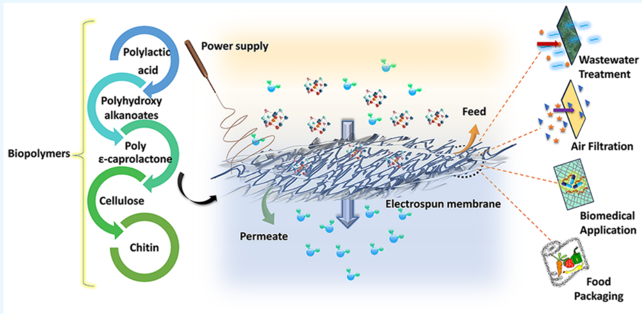
ABSTRACT: The escalating demand for sustainable industrial practices has driven the exploration of innovative materials, prominently exemplified by biodegradable electrospun membranes (BEMs). This review elucidates the pivotal role of these membranes across diverse industrial applications, addressing the imperative for sustainability. Furthermore, a comprehensive overview of biodegradable materials underscores their significance in electrospinning and their role in minimizing the environmental impact through biodegradability. The application of BEMs in various industrial sectors, including water treatment, food packaging, and biomedical applications, are extensively discussed. The environmental impact and sustainability analysis traverse the lifecycle of BEMs, evaluating their production to disposal and emphasizing reduced waste and resource conservation. This review demonstrates the research about BEMs toward an eco-conscious industrial landscape for a sustainable future.



1. INTRODUCTION

In the era of rapid industrialization and growing environmental concerns, the development of sustainable materials has become imperative. Industrial processes generate a significant ecological footprint, with various sectors contributing to pollution, resource depletion, and waste generation.[1] The quest for eco-friendly alternatives has prompted researchers and industries to seek innovative solutions to alleviate the environmental impact while maintaining economic viability. Among the array of advancements in materials science, the utilization of biodegradable membranes has emerged as a promising approach to address this challenge.[2] Membrane technology has significantly advanced and is extensively applied across various industrial processes such as wastewater treatment, desalination, surface water treatment, gas separation, as well as food and beverage processing.[3−5] More recently, membranes have garnered attention in specialized biomedical diagnostics and therapeutic applications, along with energy conversion processes, like fuel cells and alternative batteries, which have progressed from laboratory investigations to commercialization.[6] There is ongoing exploration into the development of novel membranes to enable additional separations, particularly in the chemical and pharmaceutical sectors. Across these diverse applications, membrane technology offers significant advantages, including high selectivity, reduced energy consumption, the potential for more compact systems with a smaller footprint, the opportunity to replace severe chemical treatments, and the ease of scalability.[7]

In recent years, electrospinning has garnered attention as a straightforward method for producing submicrometer-sized polymer nanofibers, a challenge with conventional mechanical fiber techniques. The technique's advantages include the capability to create extremely thin fibers with large surface areas, easy functionalization for various purposes, superior mechanical qualities, and user-friendly application.[8] Electrospun membranes, formed through the electrostatic fiber-forming process, exhibit unique properties such as high surface area-to-volume ratio, tunable pore size, and exceptional mechanical strength.[9−11] Their versatility makes them valuable in diverse industrial applications, including filtration, separation, tissue engineering, drug delivery, and environmental remediation.[11,12] The integration of BEMs addresses sustainability concerns, offering tailored solutions to industrial challenges while minimizing the environmental impact. Crafted from biodegradable polymers, these membranes contribute to sustainability by breaking down into harmless compounds under environmental conditions, reducing nonrecyclable waste, and minimizing long-term ecosystem impact.[13] This aligns with the imperative for sustainable practices in industries

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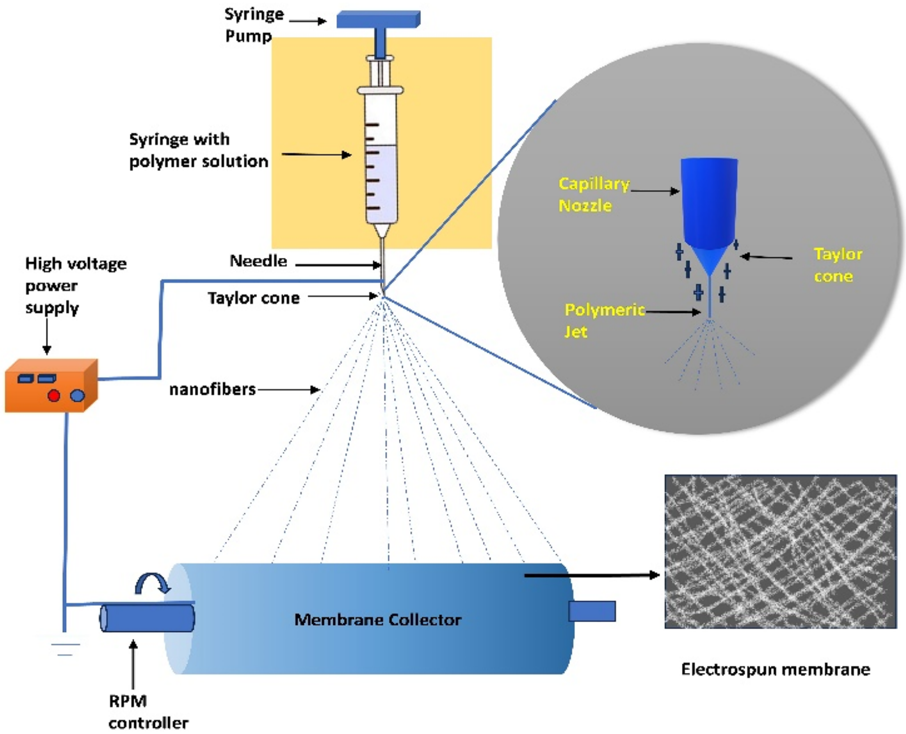

Figure 1. Fabrication of electrospun membrane.

dominated by nonbiodegradable materials.[14] Advancements in membrane science focus on achieving long-term sustainability and consistent performance throughout the membranes' lifespan.[15] The direction in membrane technology supports eco-friendly practices such as avoiding hazardous solvents, adopting renewable resources, and promoting membrane module reuse.

BEMs have emerged as a revolutionary solution across various industrial sectors due to their exceptional eco-friendliness and sustainability. Among the noteworthy biopolymers utilized in the electrospinning process are poly(lactic acid) (PLA), an immensely popular choice recognized for its remarkable biocompatibility and robust mechanical properties.[16] Additionally, polyhydroxyalkanoates (PHAs) have gained prominence for their intrinsic biodegradability and flexibility, while cellulose, an abundant and renewable biopolymer, is in demand for its exceptional biocompatibility.[17] Chitosan stands out for its unique properties, including antimicrobial attributes and accelerated wound-healing capabilities.[18]

These electrospun membranes have found their function in an array of applications. They are adept at fine filtration, efficiently purifying air and water, making them particularly fitting for scenarios where traditional synthetic membranes may fall short in environmental friendliness.[19] Their efficacy extends to controlled drug delivery, acting as high-porosity scaffolds in tissue engineering and providing controlled-release solutions in agriculture for products like fertilizers, pesticides, and herbicides, thereby minimizing environmental impact.[20,21] Additionally, they play a pivotal role in the packaging industry, reducing plastic waste with sustainable alternatives.[22] In the biomedical field, these membranes contribute to advancements in implantable devices and dressings due to their biocompatibility and eventual biodegradability.[23,24] Furthermore, they are essential in environmental remediation, aiding in the removal of contaminants from water and air and thus contributing to environmental conservation. In addition, BEMs offer environmentally conscious solutions, significantly reducing ecological footprints while innovating across diverse industrial and biomedical domains.[25]

In today's world, sustainability has become a paramount concern across industries. Sustainability, as a guiding principle, encourages us to balance the present needs while safeguarding the capacity for future generations to fulfill their own requirements.[26] The ongoing depletion of natural resources, environmental degradation, and the increasing awareness of the finite nature of resources of our planet have brought sustainability to the forefront of industrial practices.[27] As a result, there is a persistent need for innovative and environmentally friendly materials that can contribute to a more sustainable future. Reducing the environmental footprint of industrial processes is crucial for sustainability, considering the adverse effects of traditional materials derived from fossil fuels. Such materials contribute to pollution and waste, emphasizing the need for alternatives.[28] Biodegradable materials play a pivotal role in this quest by naturally breaking down and returning to the environment in a nontoxic form. This stands in contrast to nonbiodegradable materials that persist in the environment, causing harm and accumulating as waste. Their ability to mimic natural processes aligns with circular economy models, promoting resource efficiency and waste reduction.[27,29]

This review explores the fascinating realm of BEMs, offering a comprehensive overview of their production techniques, properties, and diverse industrial applications. Electrospinning, a versatile and scalable fabrication method, has witnessed a surge in popularity due to its ability to produce nanofibrous membranes with tailored characteristics, making it an excellent candidate for sustainable industrial applications. When combined with the intrinsic biodegradability of certain

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polymers, it holds great potential for transforming industries into more environmentally friendly and sustainable entities.

2. ELECTROSPINNING TECHNIQUE

Electrospinning is a simple and adaptable method that requires utilization of electrostatic repulsion among exterior charges to draw nanofibers continuously from a viscoelastic liquid. Using a diverse range of materials, such as polymer compounds, ceramics, tiny molecules, and their mixtures, this process has been successfully used to create nanofibers tens of nanometers in diameter. Besides producing smooth-surfaced solid nanofibers, the electrospinning technique can be modified to produce a variety of secondary arrangements, particularly those containing a core sheath and porous and hollow structure.[30]

2.1. Principle of Electrospinning. The fundamental arrangement for electrospinning is simple and easy to understand. The electrospinning device was mainly composed of four key components: a high-voltage power supply, a syringe pump, a spinneret, and a collector plate. The concept of electrospinning is that during the electrohydrodynamic process of electrospinning a tiny liquid drop is ionized to create a jet, which is subsequently expanded and elongated to produce ultrafine fibers.[30] When a small amount of viscoelastic liquid is pushing out from the spinneret, the surface tension causes the liquid to extend from the spinneret, forming a hanging droplet. The droplet's surface will shortly be submerged in charges of the same sign as it is connected to a high-voltage electrical source. The spherical shape will become unstable because of the repelling force between these same charges, overcoming the surface tension. The droplet of liquid will turn into a conelike form known as a Taylor cone from which a charged jet will eject when the repellent force is sufficiently strong enough to conquer the surface tension. Because of the combined influence of the electric field and the repulsion between surface charges the jet first extends in a straight path toward the ground collector and keeps getting smaller in diameter until it begins to bend, and then it quickly changes and accelerates rapidly in a "whipping" manner.[31] Consequently, the jet's diameter gradually reduces as the solvent evaporates over time. On the grounded collector, solid continuous nanofibers are deposited as a result of the solvent evaporation from the viscoelastic solution of polymer.[30,8] In this process, the nonwoven fibrous mat is randomly oriented to deposit ultrathin solid nanofibers on the collector. Figure 1 depicts the fabrication of the electrospun membrane.

2.2. Parameters Governing the Electrospinning. Good electrospinnability is the ability of a viscoelastic liquid to spin smoothly, uniformly in size, and without beading on strings. This capacity to spin repeatedly in the presence of an applied electrostatic field is referred to as good fiber production.[32] A number of variables referring to the polymer (solvent selection, surface tension, molecular weight, conductivity, and viscosity/concentration), polymeric solution, processing conditions, and environmental circumstances (temperature and humidity) influence the electrospinning of a polymer solution as well as the structure and form of the resulting polymer nanofibers.[33]

2.2.1. Physicochemical Parameters. A good electrospinning solution requires the following two general conditions: first, the polymer must have sufficient molecular weight and second is the presence of an appropriate solvent for dissolving the polymeric material. Since there is less chain entanglement when the molecular weight is lowered, beads rather than fibers are often obtained.[31] The majority of polymer solution characteristics, including viscosity, surface tension, conductivity, and dielectric capacity, are influenced by the polymer molecular weight. In the end, the shape of the electrospun fibers is affected. In general, a polymer with a higher molecular weight achieves the desired viscosity for the generation of fibers.[34] The Taylor cone from which the charged jet emerges is affected by the concentration of the polymer in the electrospinning fluid. While the concentration of the polymeric solution is low, surface tension and the electrical field that is applied cause the braided polymer chains to break into pieces before they reach the place of the collection.[35,36] With increasing concentration, the viscosity of the polymeric solution increases, promoting chain tangling inside the polymer chains. Uniform beadless electrospun nanofibers are the end product of these polymeric chain entanglements that overcome the surface tension.[37] There is a threshold concentration for each polymer at which uniform beadless fibers developed. Above this crucial concentration, polymer solidification at the end of the needle tip hindered the passage of the polymer solution through the needle, which eventually generates defective or beaded nanofibers.[38] Furthermore, the Taylor cone fails to form at lower polymer concentrations, which leads to the deposition of many droplets onto the collector's surface. Since the concentration impact of a polymer solution is strongly related to its viscosity, surface tension, and rheology, it is important to use the ideal solution concentration in order to produce uniform fibers. Also, thicker fibers are generally produced more readily when viscosity and surface tension are decreased, but instead of lowering the polymer concentration, this can be performed by adding a surfactant.[31] If the viscosity is too low, then no fiber will be generated. On the other hand, if the viscosity of the solution is too high, ejecting it from the spinneret will be difficult.

Since completely insulating solutions are unable to transmit charges from their center to their surface, they are challenging to electrospin because of their electrical conductivity. When charges from the surface cannot accumulate on a conducting droplet, it is difficult to create a Taylor cone or initiate bending instability if the polymeric solution is highly conductive.[39] The dielectric value of the solvent controls the efficiency of the electrostatic repulsion between the surface charges on the jet. The voltage being applied to generate a continuous flow increases when the dielectric constant rises.[40]

2.2.2. Processing Parameters. The intensity of the jet's interactions with the surrounding electric field, as well as the charges carried by the jet and the strength of electrostatic repulsion between the charges, are all directly determined by the applied voltage. To produce an electric field, a steady DC high voltage source is typically given to the spinneret. The spherical polymeric drop expands into a Taylor cone when a current is supplied through an external high voltage source, which results the production of nanofibers. Due to differences in surface charge, different polymers have varying critical voltage ranges. An extended jet formed by high applied voltage forms nanofibers with lesser diameters. The two main factors causing the formation to bead at higher voltage are an increase in velocity of the jet and a decrease in the Taylor cone size.[8] It was also observed that when the applied voltage increased the nanofibers' diameter increased. It was determined that increasing the jet length with the voltage that was applied was the cause of this diameter increase.[41]

With the critical flow rate of a polymeric solution, homogeneous beadless electrospun nanofibers could be

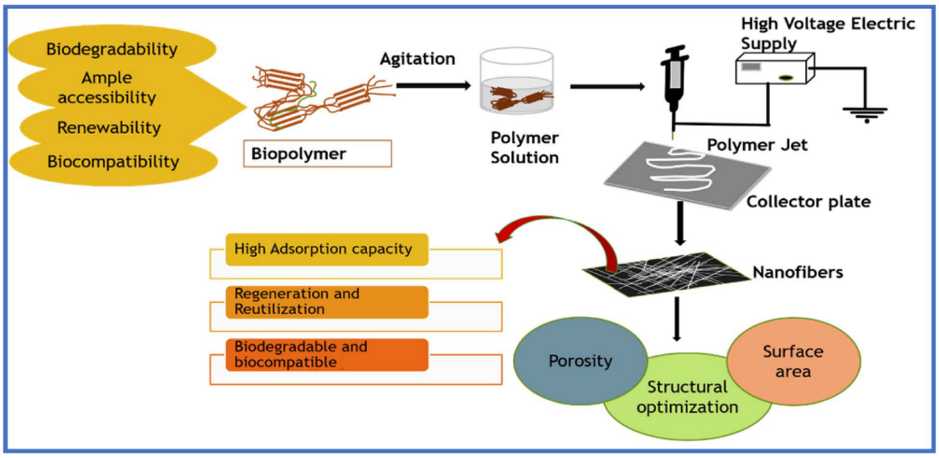

Figure 2. Preparation of electrospun membranes from biopolymers. Reproduced with permission from ref 63. Copyright 2023 Environmental Science Advances.

generated. Based on the polymer system, this critical value fluctuates. Beyond a threshold number, increasing the flow rate causes bead production in addition to a rise in pore size and fiber diameter because of the nanofiber jet's inadequate drying throughout its path between the metallic collector and the needle tip.[42] Since variations in rate of flow of polymer solutions impact the formation and structure of nanofibers, it is important to maintain a minimum flow rate to ensure equilibrium among the departing polymeric solution and also the replacement of that solution with a fresh one during the production of jets.[42]

The polymer system also affects the gap between the collector and the metallic needle tip. The diameters of the nanofibers decrease with an increase in the tip-to-collector distance; yet, short-length nanofibers are generated beyond a critical distance. Decreasing tip-to-collector distance results in beads and large-diameter nanofibers which restrict the ability of the solvent to evaporate from the polymer jet.[37] The geometry and composition of the collector are two crucial factors that influence the morphology of the electrospun fibers. A variety of collectors are utilized, including wire mesh, pins, parallel bars, rotating rods, rotating cylinders, aluminum foil, conductive paper, conductive cloth, and liquid nonsolvents like methanol and ammonium hydroxide.

2.2.3. Ambient Parameters. The rate at which the solvent evaporates and, consequently, the rate at which the jet solidifies are influenced by the relative humidity. Reduced relative humidity increases the creation of fibers that are thinner and exhibit a more dried surface.[43] The solvent will evaporate quickly if the level of relative humidity is excessively low, which will prevent the jet from extending. However, if the level of relative humidity reaches a critical level, then water vapor from the surrounding air can enter the jet and alter the nanofiber morphology. It is possible to create porous nanofibers by adjusting the humidity. With this approach, two solvents were employed to create porous nanofibers, and the porosity in the materials results from the different rates at which the solvents evaporate.[44] A predominant factor in the formation of ultrafine fibers is the surrounding temperature. The production of thinner fibers is facilitated by an increase in temperature since it lowers the polymer solution viscosity and surface tension. But, the process of evaporation of the solvent will also accelerate at higher temperature, thereby restricting the capability of jets to extend.[31]

3. BIODEGRADABLE MATERIALS FOR DESIGNING ELECTROSPUN MEMBRANES

Electrospinning is shown to be the most promising production technology for biodegradable biopolymers or biocomposites that replicate the collagen nanofibers of the extracellular matrix as a replacement for wounded tissue.[20] Due to an enormous surface-to-volume ratio and wide range of potential synthetic and natural, biodegradable, or nonbiodegradable polymers, the electrospinning process has been shown to be an excellent method of fabricating drug delivery systems. Thus, the primary goal of research on drug delivery is to customize the regulated drug release and polymer breakdown rate. Electrospun scaffolds can include a variety of drugs, including proteins, DNA, and RNA, as well as antibiotics and anticancer medicines.[20,32] Even the successful electrospinning of living cell suspensions has been achieved. Electrospun scaffolds have been used in many different tissue applications, such as vascular, bone, neural, and tendon/ligament, because of the flexibility in material selection and potential to modify the scaffold properties.[45]

Electrospinning is a skillful technique used to produce nanofibrous materials with various applications, including membranes, biomedical devices, and environmental protection, among other areas.[20] When it comes to creating BEMs, researchers often use natural polymers derived from renewable resources. Figure 2 represents the fabrication of an electrospun membrane from a biopolymer. BEMs are ideal for applications in various fields due to their tunable porosity, large surface area, and controllable fiber diameter.[21] The inherent material characteristics, surface chemistry, and hierarchical fiber morphologies of biopolymers enable effective and eco-friendly physical, chemical, and biological pollution filtration. They are appealing as sustainable, biocompatible green filters since they are biodegradable. Natural materials, biosynthetic polymers, and chemically synthesized polymers are examples of green and sustainable polymer materials that adhere to the idea of green electrospinning and promote environmentally friendly and sustainable development. Some common natural and polymeric biodegradable materials employed for electrospun membranes are mentioned here.

3.1. Biodegradable Natural Materials. A variety of distinctive polymer macromolecules are cellulose, starch, chitosan, and proteinaceous substances like silk fibroin and

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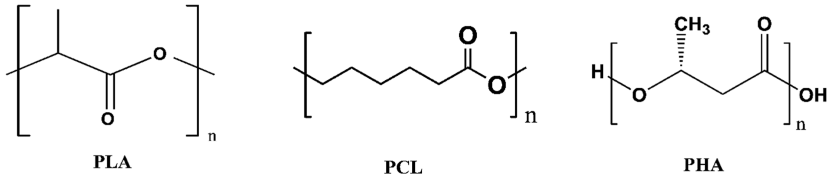

Figure 3. Structure of biodegradable polymers.

soy proteins, etc. They have the advantages of environmental sustainability, broad availability, easy decomposition by microorganisms, eco-friendliness, and biocompatibility. They are cost-effective, widely available in nature, and easily produced with workable surface chemistry and functionality.[46] Furthermore, a majority of biodegradable natural polymers are obtained from natural waste such as chitin after proper processing and can become significant chemical raw materials.[47] For filtration applications, they are appealing substitutes for traditional synthetic materials.

Cellulose is the most prevalent biodegradable polymer in nature and provides a renewable resource. It can be found in a wide variety of sources, including the cell walls of plants and wood as well as microorganisms like bacteria, algae, and fungi. It is very stiff and has strong hydrogen bonds between cellulose molecules. Cellulose's nanoscale structures, such as its nanofibrils and nanocrystals, provide a special set of characteristics like strong elasticity, low thermal expansion, flexible surface chemistry, transparency, and anisotropy.[48] Cellulose acetate (CA), the most well-known derivative of cellulose, is excellently soluble and biodegradable and exhibits group activity, making it a perfect material for the production of electrospun nanofiber membranes. For instance, Chattopadhyay et al.[49] prepared CA filters by an electrospinning process with a range of fiber thicknesses and diameters. The outcome demonstrated that during the electrospinning process acetylation of cellulose nanofibers enhances their interaction with the polymer solvent. Starch is one of the most significant renewable resources in sustainable civilizations due to its incredible potential for electrospinning to produce nanofibers. Through the use of CO_2 and water during plant photosynthesis, it is derived from a vegetable source. Commercially, starch is made from tubers like cassava and potatoes or cereals like wheat, maize, and sorghum.[50] Jaiturong et al.[51] demonstrated the production of pure waxy rice starch nanofibers using the electrospinning technique and also disclosed that this process did not alter the material's chemical structures.

In nature, chitosan (CS), which is present in molluscan organs, fungi, insects, and the shells of crustaceans, is the second most prevalent biopolymer after cellulose. It usually originates from chitin (CT) that has been deacetylated. It is extensively utilized in the industries of agriculture, environmental protection, medicine, and other disciplines as a type of green and biodegradable substance. CS is a low-cost and nontoxic biopolymer with high hydrophilicity and antimicrobial properties.[52] Therefore, CS-based materials have drawn attention from researchers in a variety of domains, including energy utilization, air filtration, medicinal applications, wastewater treatment, and bone tissue engineering. For instance, Cooper et al.[53] demonstrated the electrospun CS-poly(ε-caprolactone) (PCL) composite nanofibrous membranes for antibacterial water filtration, utilizing chitosan's inherent antibacterial properties.

A naturally occurring biomaterial, silk, is made by insects, such as silkworms, moths, and spiders. In recent years, tissue engineering and other biomedical domains have made extensive use of silk nanofibers produced via an electrospinning technique.[54] The silk protein nanofiber membrane has a high skin affinity and can be utilized as a personal air purifier or for comfort. Thus, there is a lot of promise for producing a green, multipurpose air filter based on silk protein. Electrospinning was used to create a series of silk fibroin (SF) nanofiber membranes for the first time by Wang et al.,[55] and their filtering ability for particulate matter (PM) was examined. The outcome shows that SF nanofiber air filters had higher filtering effectiveness at a lower basis weight when compared to standard commercial air filters. Sericin is an additional biopolymer that can be spontaneously obtained from silk by heating it in an alkaline solution. Because of their high water solubility, membranes containing only sericin are weak, brittle, and highly swellable. To solve the issues, sericin is combined with other polymers.[56]

3.2. Biodegradable Polymer Materials. Biodegradable polymer materials refer to a kind of polymers that, when subjected to the operations of microbes or other natural processes, can naturally break down and degrade into components that are beneficial to the environment, such as water, CO_2, and biomass. They are a significant replacement for traditional, nonbiodegradable plastics. They include microbial polyesters, polyamino acids, and microbial polysaccharide and are produced by fermenting different carbon sources. As a result, they have good optical, biodegradable, and biocompatible qualities;[47] e.g., poly(lactic acid) (PLA), poly(ε-caprolactone) (PCL), and polyhydroxyalkanoates (PHAs) are all biodegradable polymers.

3.2.1. Poly(lactic acid) (PLA). PLA is a biodegradable and compostable polymer derived from sustainable resources such as cornstarch or sugar cane, making it an environmentally friendly alternative to traditional petroleum-based plastics. PLA as a kind of polyester is obtained from lactic acid through aerobic fermentation of carbon-containing substances including glucose and lactose using bacteria and fungus such as lactococcus, pediococcus, lactobacillus, and streptococcus.[57] The chemical structure of PLA is shown in Figure 3. PLA can be electrospun into fine fibers with good mechanical properties, making it suitable for various applications. PLA is a biocompatible thermoplastic polymer as it is well-tolerated by living tissues. This makes it suitable for use in biomedical applications such as tissue engineering and drug delivery systems. The polymer can be tailored to degrade at a specific rate, allowing for the controlled release of drugs or therapeutic agents over time. PLA electrospun membranes are used in filtration applications such as air and water filtration. The fine fibers provide a high surface area for effective filtration of particles and contaminants. PLA can be blended with other biodegradable polymers or modified to enhance its properties,

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such as its degradation rate, mechanical strength, or surface characteristics, to meet specific application requirements.

3.2.2. Poly(ε-caprolactone) (PCL). PCL as the petroleum-based linear polymer has been the subject of substantial research due to its recognition as one of the few entirely biodegradable and biocompatible polymers. PCL is a polyester series polymer that consists of repeated units of hexanoate units which is synthesized by polycondensing 6-hydroxyhexanoic acid.[58] The chemical structure of PCL is shown in Figure 3. PCL has a good electrospining ability, which makes it a popular choice for creating membranes with a high surface area. PCL can be blended with other polymers or functionalized with additives to tailor its properties to specific applications. For instance, it can be combined with other polymers to improve its mechanical strength or to add functionalities such as antibacterial properties. Consequently, PCL is typically utilized to release various biologics and other therapeutic substances under controlled conditions in order to treat cancer. With the biological ability to lyse biofilms, PCL is combined with α-cyclodextrin to form a hydrogel, which is then administered to the liver to treat resistant liver cells. Further investigation of PCL's potential in anticancer therapy is currently underway.[59]

3.2.3. Polyhydroxyalkanoates (PHAs). PHAs are a type of linear and thermoplastic polyester that is noncytotoxic and is produced by a variety of bacteria (Gram-positive and -negative) through fermentation in the presence of abundant carbon and nitrogen sources. Furthermore, physicochemical characteristics of PHA range from high elasticity to hardness, making it appropriate for a variety of application requirements.[60] PHAs are hydrophobic, totally isotactic, water insoluble, and unaffected by hydrolytic breakdown. Monomer components, chain length, side group spacing, and ester linkage all affect the mechanical characteristics of PHAs.[61] The chemical structure of PHA is shown in Figure 3. PHA polymers break down into water and CO_2 in an aerobic environment, but they are converted to methane by microbes in anaerobic environments such as soil, sewage, lake water, and seawater.[62] In addition to that they are biocompatible, biostable, nontoxic, nonallergenic, and nonimmunogenic and have adjustable properties. While simulating the composition and functionality of a cell's original extracellular matrix, electrospinning nanofibers between 10 and 10,000 nm in size can enhance PHA's mechanical qualities and reduce its crystallinity. For this reason, PHA electrospinning nanofibers as designed scaffolds have been employed extensively as carriers for drug delivery applications as well as tissue engineering scaffolds in the areas of cardiovascular, vascular, nerve, bone, cartilage, and skin.[60]

4. INDUSTRIAL APPLICATION OF BEMS

BEMs stand at the limelight of sustainable innovation, offering versatile solutions across a spectrum of industrial applications. Their unique properties make them invaluable in addressing insistent challenges and advancing eco-friendly practices. This exploration looks into key sectors where these membranes play a transformative role, showcasing their potential in revolutionizing water and wastewater treatment, providing sustainable solutions in food packaging, contributing to breakthroughs in biomedical applications, offering eco-conscious practices in agriculture and horticulture, and enhancing air filtration systems. The biodegradable nature of these membranes not only aligns with the global shift toward sustainability but also presents innovative approaches to longstanding industrial challenges. BEM offers diverse and innovative solutions across several industrial sectors, demonstrating their versatility and potential for sustainable applications.

4.1. Wastewater Treatment. Water is one of the most essential sources of life and faces quality challenges due to population growth, urbanization, and industrialization.[63] Traditional water treatment methods are often inefficient and costly. Various water purification technologies, including distillation, chemical disinfectants, and membrane filtration, have been utilized. Among these, membrane filtration has a lot of advantages such as scalability, low power consumption, chemical-free operation, and low operational temperature.[64] Membranes act as semipermeable barriers, allowing specific molecules to pass while hindering others. Nanotechnology, particularly electrospun nanofibrous membranes, offers a sustainable and efficient solution.[65] These membranes, made from affordable and durable polymeric materials, operate without chemical accumulation. Due to our environment sustainability, BEMs excel in water treatment by serving as efficient filtration materials.[66] Their nanofibrous structure allows for precise control over pore sizes, enhancing the filtration efficiency in water treatment plants. These membranes can be employed for wastewater treatment, separating pollutants and facilitating the removal of contaminants, contributing to the purification of water before discharge or reuse.[64] The electrospun nanofibers produced, featuring customizable wettability, a high length-to-diameter ratio, and a specific surface morphology, demonstrate effectiveness in eliminating both organic and inorganic contaminants from wastewater.[67]

Biopolymers are attracting industrial interest as potent adsorbents, owing to their abundant availability and ability to eliminate contaminants across various concentrations. The incorporation of amine, hydroxy, and carboxyl functional groups in polysaccharides and polypeptides enhances their suitability as adsorbent membranes, especially for the adsorption of heavy metal ions.[68] Chitosan and cellulose, known for their biocompatibility, nontoxicity, disinfection capacity, and effective adsorption behavior, are particularly prominent in water treatment research.[69] Various studies have investigated the adsorption of heavy metals, dyes, pharmaceutical wastes, and toxins through the use of biopolymers in wastewater treatment. The primary removal mechanism employed by electrospun biopolymers is adsorptive removal, utilizing either physisorption or chemisorption, depending on the specific characteristics of the adsorbent and adsorbate. This efficacy is credited to the interconnected pore structures, high aspect ratio, specific surface area, and adjustable properties such as surface roughness of electrospun biopolymers.[63] The application of BEM in wastewater treatment is shown in Figure 4.

4.1.1. Oil–Water Separation. Oil–water separation is a crucial process in various industries, including environmental remediation and wastewater treatment. Traditional methods often involve the use of chemical agents or physical barriers, but an innovative approach involves the use of BEM which is shown in Figure 5. This technology holds promise for efficient and sustainable oil–water separation in various industries and environmental applications. Liu et al. developed a hierarchical PLA membrane for oil/water separation, exhibiting superhydrophobicity and superoleophilicity.[70] Similarly, Cheng et al. developed biodegradable superhydrophilic membranes with

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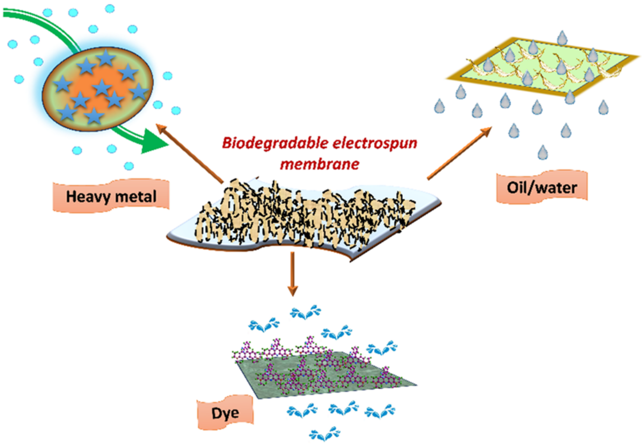

Figure 4. BEM membrane for wastewater treatment.

PLA nanofibers and poly(ethylene oxide) hydrogels, demonstrating ultrafast purification of oily water. The nanofiber membranes exhibit a separation efficiency exceeding 99.6%, providing a promising eco-friendly solution for waste membrane treatment.[71] Zhang et al. achieved superhydrophilicity and underwater superoleophobicity in biodegradable electrospun PLA membranes.[72] Eang and team designed biodegradable superhydrophobic PLA nanofibers for effective oil/water separation, demonstrating high oil absorption rates and multiple adsorption−desorption cycles.[73,74]

Duman et al. pioneered superhydrophobic membranes, specifically electrospun PVA and agar/PVA. Their membranes, developed through electrospinning and glutaraldehyde cross-linking, demonstrated outstanding water contact angles, oil absorption, and selective separation of toluene and chloroform from water.[75] Reshmi et al. developed a superhydrophobic, superoleophilic electrospun nanofibrous membrane using beeswax and polycaprolactone. With a water contact angle of 153° ± 2° and high oil sorption capacity, the membrane achieved 98.1% separation efficiency in gravity-driven oil−water separation and proved to be recyclable after 15 cycles. This innovative beeswax-based membrane shows promise for industrial oily wastewater treatment and oil spill cleanup.[76] So, BEM represents a promising and environmentally friendly solution for oil−water separation. Their unique structure, created through electrospinning with materials such as PLA or PHA, enables efficient capture and separation of oil from water. The hydrophobic nature of the membrane ensures water permeability while repelling oil, and its biodegradability aligns with sustainable practices. This innovative technology holds great potential for addressing the challenges of oil−water separation in diverse applications, offering an efficient and eco-friendly alternative to traditional methods.

4.1.2. Heavy Metal Separation. Biopolymers possess a diverse array of functional groups, endowing them with a notable affinity for heavy metals. These biopolymers are directly subjected to electrospinning processes, yielding nanofibers tailored for the adsorptive elimination of contaminants from wastewater.[76] The mechanism of BEM for removing heavy metal ions involves physisorption and chemisorption, either individually or in combination, as shown in Figure 6. Physisorption involves the capture of toxic pollutants on the surface or within pores, propelled by intermolecular forces such as van der Waals or electrostatic interactions.[63] This may result in a multilayer configuration influenced by temperature and pressure. The adsorbent's specific surface area plays a crucial role in physisorption capacity, prompting studies to incorporate functional materials into electrospun fibrous membranes to enhance surface area. In heavy metal separation, Yang et al. synthesized amino-functionalized chitosan-based electrospun membranes for efficient removal of Cr^{4+}, Cu^{2+}, and Co^{2+} with maximum adsorption capacities of 138.96, 69.27, and 68.31 mg/g, respectively.[77] Zia et al. developed chitosan-grafted porous P-

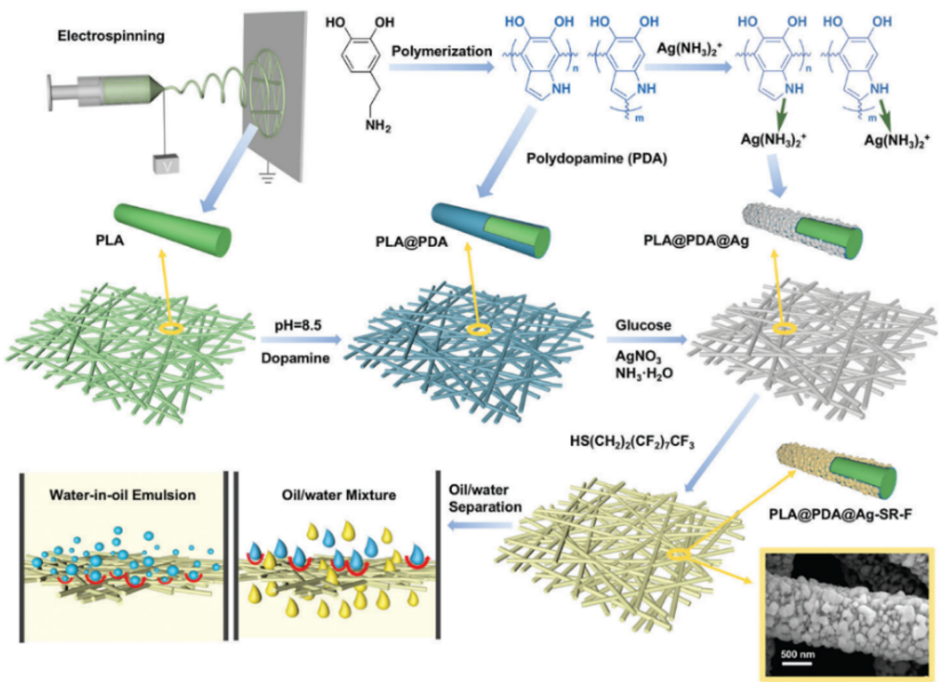

Figure 5. PLA-based BEM for oil−water separation. Reproduced with permission from ref 70. Copyright 2018 New Journal of Chemistry.

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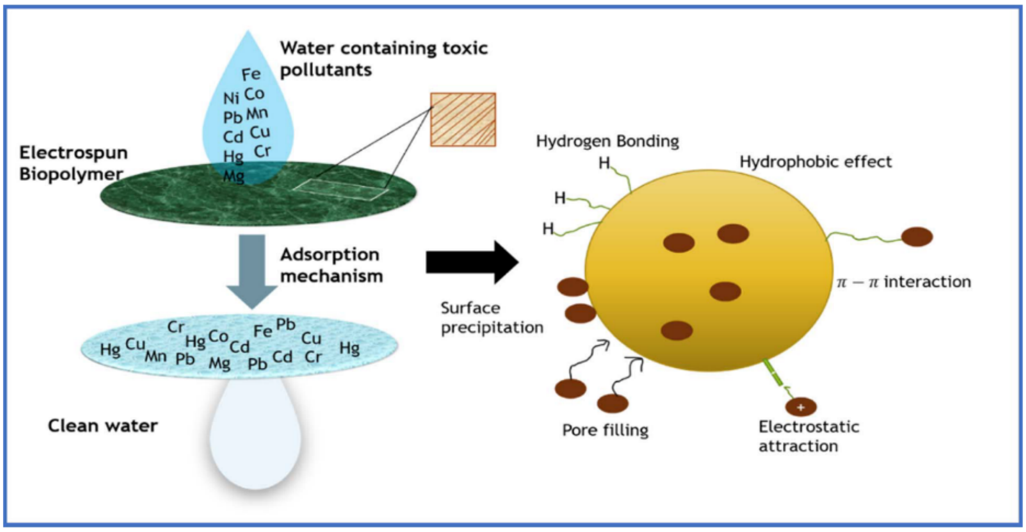

Figure 6. Adsorptive mechanism of heavy metal separation by using BEM. Reproduced with permission from ref 63. Copyright 2023 Environmental Science Advances.

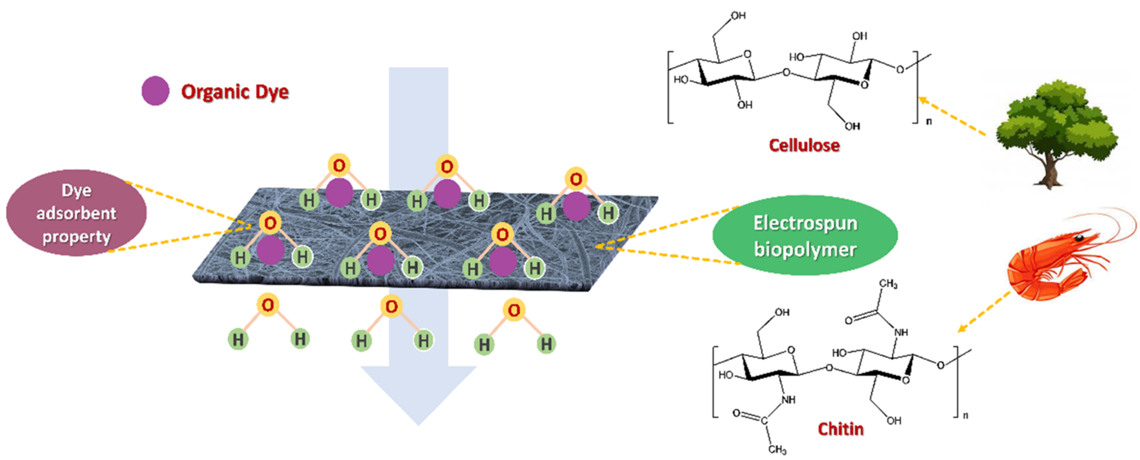

Figure 7. Removal of organic dye using a biopolymer-based electrospun membrane derived from sustainable sources of raw materials.

PLLA nanofibrous membranes with a maximum adsorption capacity of 270.27 mg/g for Cu^{2+} ions.[78] Similarly, Wu et al. prepared an electrospun nanofibrous membrane that exhibited high adsorption and separation performance for Cu^{2+}, Ni^{2+}, Cd^{2+}, Pb^{2+}, methylene blue (MB), and malachite green (MG), with retention rates exceeding 80% and adsorption capacities ranging from 13.27 to 34.79 mg g^{-1}.[79] In a study of PVA/protein nanofibers, adsorption efficiently removed NSAIDs and carbamazepine from wastewater. The chemisorption process followed the Freundlich adsorption isotherm, with a maximal adsorption capability of 31.25 to 333.33 mg g^{-1}.[80] A separate investigation suggested the development of cellulose-based composite nanofibers using electrospinning, combining CA with organically modified montmorillonite. This was followed by a deacetylation process, aiming for the selective removal of Cr^{6+} ions from aqueous solutions. The findings hold promise for the large-scale adsorption of heavy metal ions in wastewater treatment.[81] Examining various electrospun membranes, including amino-functionalized chitosan and chitosan-grafted porous P-PLLA, we were fascinated by their demonstrated high adsorption capacities for heavy metals. We speculate that BEM represents a promising, sustainable, and confidently effective solution for the separation of heavy metals in industrial wastewater treatment.

4.1.3. Removal of Dyes and Organic Pollutants. In the contemporary landscape of environmental awareness and sustainable technologies, the separation of dyes and organic pollutants has become a focal point for addressing the challenges posed by industrial activities. The discharge of wastewater containing diverse synthetic dyes and organic pollutants is a significant contributor to the environmental effect, necessitating effective and eco-friendly separation strategies. In this context, the integration of BEM emerges as an innovative solution that combines advanced membrane technology with environmental responsibility.

Dyes are classified as ionic or nonionic, with nonionic dye adsorption involving chemisorption and ionic dye removal utilizing physisorption and ion exchange.[82] Common materials for water dye removal include graphene oxide, β-cyclodextrin, magnetic nanoparticles, and polydopamine. Electrospun nanofibers serve as effective supports, reducing agglomeration and increasing surface area for improved adsorption efficacy and speed.[82] Ao et al. introduced a cellulose composite membrane for simultaneous biodegradable dye removal through a dip-coating process. The membrane, coated with a cellulose

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hydrogel layer incorporating citric acid, demonstrates efficient dye separation and enhanced mechanical properties.[83] Zia and group developed a porous PLA nanofibrous membrane coated with chitosan cross-linked with 3-aminopropyltriethoxysilane for strong adsorption of MB and rhodamine B in wastewater. Optimal conditions yielded removal capacities of 86.43 mg/g for rhodamine B and 82.37 mg/g for MB.[84] Hosseini et al. created efficient and reusable electrospun nanocomposite membranes for cationic dye removal, exhibiting superior performance and enhanced thermal stability.[85] Figure 7 illustrates the sustainable foundations of the BEM. The marked sources of cellulose and chitin represent the eco-friendly nature of these membranes, as cellulose is derived from renewable plant-based sources, while chitin is sourced from discarded crustacean shells. This conscious selection of raw materials contributes to the overall sustainability profile of BEMs, aligned with environmentally responsible material choices. The schematic representation of dye separation through BEM is shown in Figure 7.

Fan and his group developed a cross-linked electrospun nanofiber membrane (β-CD/CS/PVA) for simultaneous removal of organic and heavy metal micropollutants, demonstrating high efficiency in static and dynamic adsorption experiments.[86] Paradis-Tanguay et al. synthesized biodegradable chitosan/poly(ethylene oxide) (PEO) nanofibers for the removal of the anti-inflammatory drug ibuprofen, achieving 70% removal within 20 min.[87] In summary, these BEMs, with selective separation capabilities, offer promising and eco-friendly solutions for efficiently removing dyes and organic pollutants in water treatment, aligning with sustainability goals.

4.2. Biomedical Applications. In the field of biomedicine, electrospinning is a flexible and popular method for producing nanofibrous membranes. In the realm of biomedical applications, BEMs demonstrate significant advantages over other nanofiber membranes. The inherent biocompatibility of BEMs, coupled with their intrinsic degradability, positions them as favorable materials for various biomedical purposes. Their tunable mechanical properties offer versatility in designing scaffolds for tissue engineering, while the capability for controlled drug release systems underscores their applicability in pharmaceutical contexts. This comprehensive overview highlights the distinct benefits of BEMs, emphasizing their potential to outperform conventional nanofiber membranes in biomedical applications. The unique combination of biocompatibility, degradability, and mechanical tunability positions BEMs as promising candidates for innovative solutions in the biomedical field. Some biomedical applications of electrospun membranes are discussed below including a representative figure shown in Figure 8.[149]

4.2.1. Drug Delivery System. The elevated surface area and porous structure of the electrospun membranes facilitate the sustained release of drugs, making them suitable for applications in drug delivery systems. Various medical needs have been achieved through electrospinning of different artificial biopolymers. Targeted drug delivery through electrospun nanofibers capitalizes on smaller sizes and appropriate coatings to enhance drug absorption at the intended site. A variety of medications, including proteins, anticancer drugs, antibiotics, DNA, and RNA, have been loaded onto the electrospun nanofibers.[88] Drug discharge can occur sequentially via diffusion and degradation of the delivery system. The goal is to customize the regulated drug release and polymer degradation rate. In vitro treatment of C6 glioma with electrospun PLGA-based micro- and nanofiber implants delivering paclitaxel showcased continuous release for over 60 days.[89] Electrospinning techniques, including integrating drugs within nanofibers and coating drugs on their surface, produce scaffolds as nanocargo carriers. Antibiotic-loaded electrospun fibrous scaffolds are explored for preventing postsurgical abdominal adhesions and infection.[90] Electrospinning enables the incorporation of multiple drugs into a single membrane for combination therapies. Taepaiboon et al. combined four NSAIDs into electrospun PVA nanofibrous mats, achieving high drug encapsulation (81−98%) and varied release percentages at 24 h.[91] Verreck et al. explored the use of water-soluble medicines combine with hydrophobic polyurethane electrospun nanofibers for topical medication delivery.[92] Ongoing research is crucial for developing innovative techniques to meet the growing demand for diverse drug delivery systems.

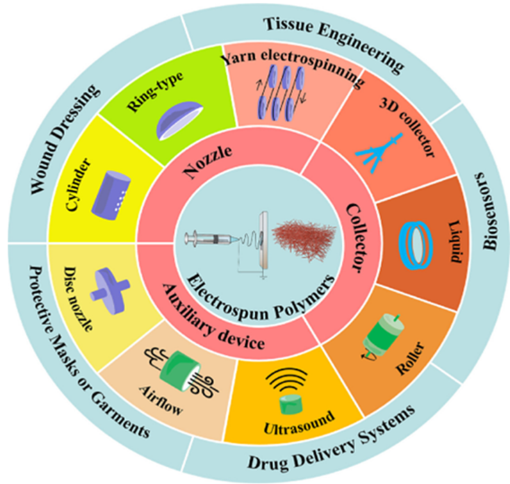

Figure 8. Electrospun membrane for biomedical applications. Reproduced with permission from ref 149. Copyright 2023 Reactive and Functional Polymers.

4.2.2. Tissue Engineering. Considering the area of tissue engineering, the most appealing characteristic of electrospinning has been demonstrated to be its ability to replicate the nanoscale fiber texture of the extracellular matrix (ECM). Because of their unique properties, fibrous scaffolds that are both biocompatible and biodegradable are often selected over conventional scaffolds for tissue regeneration for which the usage of nanofibers made by electrospinning in tissue engineering is growing day by day.[54] Chitosan, known for its biological compatibility, biodegradability, and mechanical qualities, has been extensively studied as an electrospinnable tissue engineering matrix. Chemical modifications have been explored to obtain soluble derivatives, overcoming challenges in electrospinning pure chitosan fibers.[69] Zhang et al. investigated nanohydroxyapatite/chitosan fibers for bone tissue engineering, demonstrating enhanced bone marrow mesenchymal stem cell proliferation compared to membranous hydroxyapatite/chitosan scaffolds.[93] The incorporation of cellulose acetate improved the biomaterial scaffold structure, with a focus on porosity management and surface modification. Pant et al. synthesized a polyamide-6/calcium lactate mineralized scaffold through electrospinning, demonstrating potential for bone formation in biomimetic simulated body fluid tests.[94] Kim et al. developed a highly porous 3D nanofibrous fibroin scaffold with 94% porosity, showing

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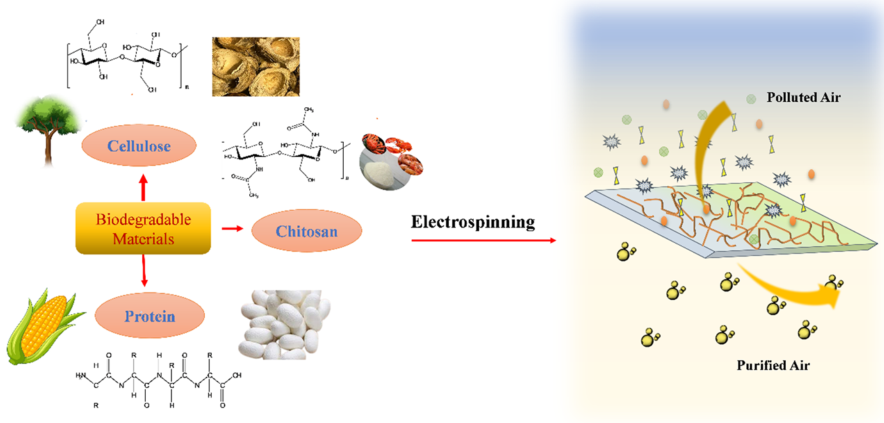

Figure 9. BEMs for the air filtration application.

improved cell adhesion and proliferation for bone regeneration compared to a 2D scaffold.[94] Sinusoidal fibers created by melt electrospinning exhibited promise in cardiac tissue regeneration.[95]

4.2.3. Wound Healing. Electrospun nanofibers are being studied as wound dressing material. The movement and penetration of repairable cells can be improved by constructing nanofibers to give topographical and biological signals. The use of cellulose-based materials as woven cotton gauze dressings is well-known, owing to their superior hemostatic and adhesive barrier properties. Also, electrospinning cellulose and its derivatives have opened up a broad range of new possibilities, ranging from regulated drug delivery to mimicking the extracellular matrix (ECM) that can help to increase the efficacy of scaffolds for tissue engineering and wound dressings.[96] CA has also been utilized to modify the adhesion characteristics of fiber mats used in wound treatment. In an investigation by Vatankhah et al.,[97] adjusting the ratio of CA and gelatin in the electrospun fiber mat composition allowed them to change the adhesion properties. By preventing draining in the location of the wound and promoting cell infiltration, a 3D scaffold could be utilized in a wound dressing. In order to integrate surface chemistry and topography with the intended spatial indications, a 3D scaffold made of silk fibroin and a PCL nanocomposite fibrous matrix was created by Lee and co-workers for an artificial dermis application.[98]

4.2.4. Protective Masks or Garments. The excellent filtration effectiveness, low weight, and nanoscale porosity of BEM materials have drawn specific attention to masks and garments crafted from them.[99] Through electrospinning a nontoxic polyvinyl butyral (PVB) polymeric matrix with the natural phenol monoterpene Thymol that serves as an antibacterial ingredient, Lu et al. established an inexpensive method for creating masks that more efficiently fulfill the demands of the pandemic situations.[100] Xu et al. also created a specific type of face mask by electrospinning Nylon-6 (PA) nanofibers onto polyethylene (PE) meltblown nonwovens, which have superior filtration capabilities and radiative heat dissipation effects.[101] Regarding garments for protection, electrospun polymeric nanofibers have garnered a great deal of curiosity. An appropriate choice for the defense sector's manufacturing of protective clothing is polyacrylonitrile (PAN) nanofibers, which can be conveniently tailored with chemical reagents and exhibit good fiber production.

4.3. Air Filtration. Air pollution is the greatest threat to the environment. PM and hazardous gases are one of the main sources of air pollution, endangering people's health and safety. Ambient pollutants, such as PM2.5, PM10, and bacteria, are the most common air pollutants. The primary sources of PMs are chemical pollutants, such as sulfate, chloride, nitrate, iron, calcium, organic carbon, and elemental carbon. These pollutants are mainly released by burning coal, burning vehicle exhaust, industrial emissions, and burn farming.[102] Therefore, the creation of effective and antibacterial materials for air filtration has emerged as a pressing issue.

Air filtration is the most promising and effective method to remove particle matter and enhance the quality of air. The application of electrospun nanofiber membranes in the field of air filtration appears to be highly promising because of its porous structure, small diameter of the fiber, high specific surface area, excellent filtering effectiveness, minimal pressure drops, adjustable morphology, good mechanical strength, and multifunctional fiber surface.[103] The air filter membranes have a major role in the filtration process, which establishes the filtration efficiency and result.[47] Thus far, a number of polymers, including polyacrylonitrile, poly(ethylene oxide), polyurethane, PVA, PLA, polycarbonate, polyamide, and polyimide, have been successfully synthesized into nanofibrous membranes through electrospinning and assessed for air filtration, as shown in Figure 9. For ultrathin particle pollutants, the majority of these electrospun polymer membranes exhibit exceptional filtering performance.[102] However, the majority of electrospun membranes provide a challenge to biodegrade and result in secondary environmental degradation. With the benefits of being widely available, environmentally sustainable, biocompatible, and biodegradable, natural polymers are gaining attention as viable alternatives to conventional synthetic polymers in the production of air filtration medium. Souzandeh et al.[104] described a high-performance, environmentally friendly cellulose/protein gelatin composite air filter with nanofiber structure. This work created a multihierarchical, multifunctional composite air filter with exceptional mechanical qualities by using cellulose tissue (CT) as a mechanically supported substrate and covering it with an electrospun protein gelatin nanofiber coating. High-performance protein nanofibers were wrapped around the two sides of the composite structure in the CT configuration, which was its intermediate configuration. Xie et al. prepared zein-based composite nanofibers

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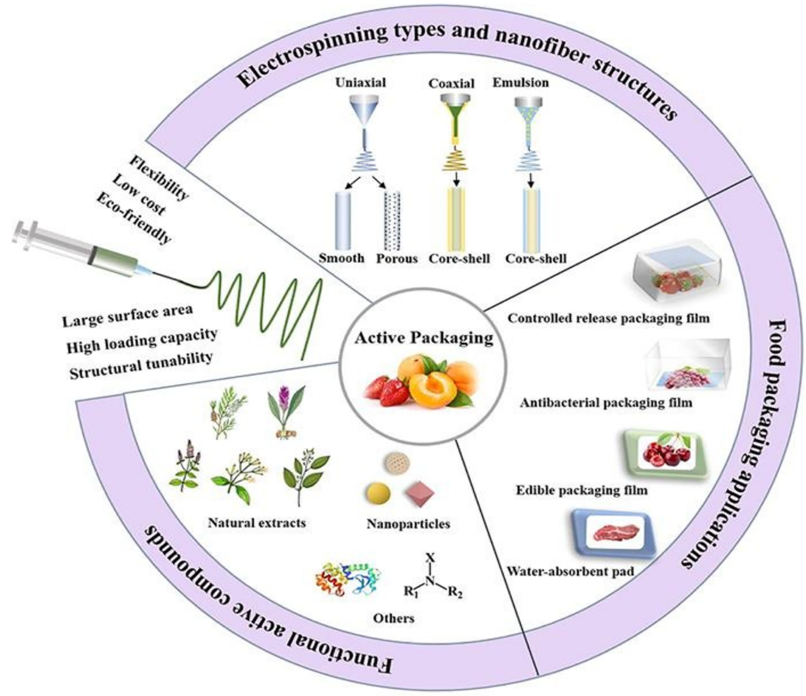

Figure 10. BEM for food packaging application. Reproduced with permission from ref 150. Copyright 2022 Food Chemistry.

loaded with curcumin by electrospinning using a PVA polymer.[105] All of the modified nanofibers had filtering efficiencies of >98% when it came to particles bigger than 0.5 μm in diameter. The tightly packed nanofibers with the loaded curcumin displayed high adherence to cellulose paper towels used as air filter substrates and great moisture resistance due to their interaction with protein molecule chains to form a network structure. In order to manufacture zein-based composite nanofibers with good moisture resistance for air filtration, this work presents a novel electrospinning technique.

Applications for biopolymer-based materials in filtration, as well as other applications, are numerous. The functional groups of biopolymers offer beneficial surface chemistry that can be utilized unaltered or further refined for targeted, intended uses to enhance filtering.[46] The abundance of fully biodegradable functional groups and low cost of the typical biobased polymers have proved their economic potential for industrial usage. Electrospun membranes find applications in automotive air filtration systems, helping to improve air quality inside vehicles by capturing PM and pollutants. These membranes are also used in heating, ventilation, and air conditioning systems to enhance filtration efficiency. In pharmaceutical manufacturing, healthcare facilities, and clean-room environments, electrospun membranes are used to maintain sterile conditions and prevent the spread of airborne pathogens.

4.4. Food Packaging. To promote food safety and ensure that everyone has access to safe food, food preservation is very much crucial. Food safety practices not only prevent the transmission of harmful microorganisms but also contribute to maintaining the overall quality and freshness of food. Implementing food safety measures helps to minimize the environmental impact of unsafe food production and distribution practices, as food items spend a significant amount of time within packaging while in transit from the farm to the table. Using efficient food packaging materials is one of the most effective strategies to avoid outbreaks of food borne disease and decrease food deterioration and waste.[106] Food packaging is therefore essential to increase the product's shelf life without sacrificing its quality. Good packing materials not only prevent microorganisms and minimize food losses but also safeguard and provide food that is safe and nutritious.[107]

Petroleum-based synthetic polymers are extensively utilized as food packaging films because of their cost-effectiveness and advantageous mechanical and gas barrier characteristics.[108] However, these materials have biodegradability issues, and the discharge of micro- and nanoplastics from the overuse of synthetic polymers is raising concerns about the environment. Thus, it is crucial to figure out how to create biodegradable packaging materials with good mechanical properties, flexibility, thermal stability, and water and gas vapor barrier qualities.[109] Therefore, in terms of long-term environmental sustainability, petroleum-based products should be replaced by biopolymers, which originate from renewable sources with such properties.

Electrospinning is increasingly used in food packaging due to its ability to create uniform nanofiber structures. These nanofibers serve multiple purposes, including protecting food from oxidation, moisture, and light, eliminating taste or odor interference, aiding in cell and enzyme immobilization, releasing bioactive compounds, enhancing probiotic viability, and creating functional foods.[110] Combining proteins and polysaccharides in electrospun nanofibers offers eco-friendly packaging materials with biocompatibility, biodegradability, and cost-effectiveness, using materials like starch, zein, gelatin, polyhydroxy butyrate, polyhydroxy butyratevalerate, and poly(lactic acid).[111] Incorporating antibacterial agents, such as carvacrol, thymol, and nisin, into electrospun fibers enhances their suitability for food packaging, promoting safety and quality.[112] Recent research has brought attention to diverse areas such as multistructured electrospun nanofibers for air filtration, core–shell microparticles in biomedical applications, photothermal nanomaterial-mediated photoporation for intracellular delivery, stimuli-responsive nanobubbles in biomedical contexts, and innovative nanofibrous membranes for the simultaneous treatment of complex wastewater.[113−120]

Using biopolymer nanofibers or coatings with antimicrobials, electrospinning has proven to be an effective technique for producing active packaging materials. It is a simple, efficient, and economical way to make fibers with a high surface-to-volume ratio and porosity that slow the initial release of compounds that are entrapped and allow them to release gradually into the food chain. The advanced functionality of biopolymeric nanofibers in active packaging is shown in Figure 10.[150]

Our research group has made notable strides in the development of diverse polymeric membranes tailored for various industrial applications. These membranes have proven effective in the areas like gas separation,[121] food packaging,[122] enantiomer separation,[123,124], biomolecule separation,[125] biomedical application, and wastewater treatment.[126−128] Building on these works, our ongoing research focuses on the utilization of electrospun membranes for numerous industrial applications. This innovative approach holds promise for unlocking new possibilities and enhancing the sustainability and efficiency of processes across different sectors. Table 1 represents a comprehensive overview of different biodegradable materials used in electrospun membranes alongside their respective industrial applications.

Table 1. BEM Materials and Their Industrial Application

BEM material	Industrial application
PLA nanofiber membrane	Oil/water separation[70,73,71]
PVA and agar/PVA	Oil/water separation[74]
Chitosan-based membranes	Heavy metal separation (Cr^{4+}, Cu^{2+}, and Co^{2+})[77]
Chitosan-grafted porous poly(L-lactic acid) (P-PLLA)	Separation of Cu^{2+} ions[78]
PVA/protein nanofibers	Removal of NSAIDs and carbamazepine from wastewater[80]
Cellulose-based composite nanofibers	Removal of Cr^{6+} ions[81]
Chitosan/poly(ethylene oxide) nanofibers	Removal of the anti-inflammatory drug ibuprofen[87]
PCL nanofiber membrane	Antibacterial water filtration[53]
PHA nanofiber	Drug delivery and tissue engineering scaffolds[60]
CA nanofiber	Tissue engineering and wound dressings[96]
PLA membrane (coated with chitosan)	Removal of MB and rhodamine B in wastewater[84]

5. PROPERTIES AND PERFORMANCE

BEMs are a class of materials renowned for their diverse properties and possess a unique amalgamation of attributes, including impressive mechanical strength, tailored chemical properties, and inherent biodegradability.[129] This combination of properties makes these membranes exceptionally versatile and crucial in industrial sectors. Their mechanical strength, achieved through a specialized nanofibrous structure derived from the electrospinning process, equips them to endure various mechanical stresses.[130] Further, their chemical composition and inherent biodegradable nature contribute to their compatibility with a wide range of substances and their capacity to break down naturally over time, significantly reducing the environmental impact. These properties collectively position BEMs as promising materials, essential for addressing multifaceted challenges and seeking sustainable solutions across diverse industrial landscapes.[131] Furthermore, a critical aspect involves comparing the performance of biodegradable materials with their traditional nonbiodegradable counterparts in specific applications, marking a crucial step in evaluating their practical utility and significance in various industrial contexts.

BEMs offer exceptional mechanical attributes, including remarkable tensile strength derived from their nanofibrous structure achieved through electrospinning.[132] This strength makes them indispensable in applications such as filtration systems, protective clothing, and tissue engineering scaffolds for tissue regeneration and enduring mechanical stresses and pressures.[133] BEMs also exhibit remarkable flexibility and elasticity, crucial for adapting to various shapes, particularly in biomedical settings, and their ability to revert to their original shape enhances durability.[130] Electrospinning parameters, like polymer concentration, solution viscosity, and spinning parameters, can be fine-tuned to adjust mechanical characteristics.[134] These versatile mechanical attributes, including tensile strength, flexibility, elasticity, and tunability, make BEMs suitable for a broad spectrum of applications across industries, from healthcare and environmental remediation to protective textiles, highlighting their resilience and adaptability.[130] The ability to fine-tune these properties expands their potential applications, offering versatile solutions to diverse challenges.

Chemical properties of BEMs form the keystone of their versatile applications in diverse industries. These properties encompass the chemical composition of materials, their interaction with diverse substances, and their inherent capacity to degrade in an eco-friendly manner.[135] These membranes are primarily composed of biodegradable polymers derived from natural resources. Moreover, their compatibility with various substances is crucial in numerous applications. Membranes crafted from biodegradable polymers (PCL, PLA, PHA) interact favorably with drugs, chemicals, or environmental contaminants, making them ideal for applications such as drug delivery systems and water filtration. Additionally, the inclusion of biodegradable polymers, such as chitosan and cellulose derivatives, further enriches the diversity of these materials. Chitosan, derived from chitin, is biocompatible and degrades through enzymatic hydrolysis, proving beneficial in wound healing and tissue engineering.[136] Cellulose derivatives, such as CA, contribute eco-friendly and biodegradable characteristics to membranes, particularly in water filtration and pharmaceutical applications due to their exceptional resistance and strength.[137] The diverse range of biodegradable polymers significantly broadens the scope and potential applications of BEMs, offering tailored solutions in the healthcare, environmental, and packaging sectors. Their chemical stability ensures that they interact favorably with the substances they contact with, making them suitable for use in drug delivery systems, water filtration, or controlled release applications. For example, in water treatment, electrospun membranes made of biodegradable polymers effectively filter contaminants due to their chemical compatibility and structural design, reducing environmental pollution. Furthermore, the biological properties of BEMs, including their biocompatibility, support for cell growth, and controlled drug release capabilities, make them highly advantageous in various

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biomedical applications. The inherent biodegradability of these materials is another significant chemical property.[135] Unlike nonbiodegradable counterparts, these membranes break down into nonharmful components when discarded, reducing the strain on landfills and ecosystems. This feature aligns with sustainability goals, contributing to environmental conservation and reducing the accumulation of long-lasting waste.

6. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

The environmental impact and sustainability analysis of BEMs provide a comprehensive understanding of their implications throughout their lifecycle, spanning from production to disposal.[131] The comprehensive analysis of the environmental impact and sustainability of BEMs offer a fine understanding of their implications across their entire lifecycle, from the initial production stages to their eventual disposal.[138] This thorough examination is crucial in evaluating the ecological footprint of these materials and assessing their alignment with sustainable practices. By scrutinizing each phase of their lifecycle, researchers and industries can gain valuable insights into how these membranes contribute to or alleviate environmental challenges. The lifecycle perspective is particularly significant in identifying potential environmental hotspots and areas for improvement, guiding the ongoing efforts to enhance the sustainability of these membranes.[139] It is through such comprehensive analyses that a more informed and environmentally responsible approach to material design can be fostered, reflecting a commitment to sustainable practices in the field of advanced materials.

BEMs derive their eco-friendly credentials from the selection of raw materials. These membranes are often fabricated from renewable resources such as corn starch, sugar cane, or other plant-based polymers. This deliberate choice of sustainable feedstock not only reduces dependence on finite resources but also lessens the environmental footprint associated with the extraction and processing of nonrenewable materials. Furthermore, the electrospinning process itself, employed in the fabrication of these membranes, is recognized for its relatively lower energy consumption compared to conventional manufacturing methods.[140] This efficiency contributes to a reduction in the overall environmental impact during the production phase.

During the utilization phase, BEMs fulfill specific functions in applications like single-use medical devices and environmentally conscious packaging, addressing the need for functionality without contributing to persistent waste issues.[141] This stands in contrast to nonbiodegradable materials that can remain, leading to pollution and waste accumulation. In the disposal phase, the sustainable attributes of biodegradable materials shine as they naturally degrade into nontoxic components, reducing the strain on waste management systems and minimizing environmental burdens.

Beyond waste reduction, the use of BEM contributes to resource conservation.[142] This shift toward resource-conscious manufacturing underscores a commitment to environmental stewardship and aligns with the broader goals of sustainable development. In essence, the environmental impact and sustainability profile of BEM manifest a conscientious effort to address ecological concerns at every stage of their existence.[143] From the adoption of renewable resources in production to the mitigation of waste accumulation and resource conservation, these membranes embody a commitment to environmentally responsible material choices, reflecting a paradigm shift toward a more sustainable and circular approach to material design.

7. CHALLENGES OF BEMS

Addressing the current challenges and limitations of BEMs is pivotal for advancing their widespread application. Two key challenges, namely, durability and cost, stand out as critical considerations in the ongoing development of these materials. While BEMs offer significant advantages in terms of sustainability and end-of-life disposal, concerns about their durability persist.[132] In certain applications, particularly those requiring prolonged use or exposure to harsh conditions, the mechanical strength and resilience of these membranes may fall short when compared to their nonbiodegradable counterparts. The challenge lies in balancing the desirable biodegradability with the need for durability, especially in fields such as filtration systems, where extended longevity is often a prerequisite.[130] Researchers are actively exploring innovative approaches to enhance the durability of BEMs without compromising their eco-friendly characteristics. Strategies involve refining the selection of polymers, optimizing fabrication techniques and incorporating reinforcing elements to bolster the mechanical properties. Addressing this challenge will be instrumental in expanding the applicability of these membranes across a broader spectrum of industries.

In the field of air filtration, the use of nanofiber membranes manufactured by using electrospinning technology plays an important role. There are still several issues that require attention: for improving membrane efficiency, innovative forms of biobased matrices for air filtration and various composite electrospun polymer materials need to be investigated. To fulfill more sophisticated air filtration conditions, such as photocatalysis, hazardous gas adsorption, antibacterial, self-cleaning, and other functionalities, low pressure drop electrospun nanofiber membranes with numerous properties need to be developed.[103]

Many methods have been developed for the purification of water with a significant amount of salt in order to satisfy the growing need for pure drinking water. Electrospun membranes are thought to be the most appropriate method for cleaning saline water due to their flux and affordability. For desalination, these electrospun nanofiber scaffolds/membranes are employed as self-supporting membranes.[37] Some electrospun nanofiber scaffolds and membranes can hold their stability for as long as 4 weeks. Thus, these electrospun nanofiber scaffolds/membranes can be utilized in place of traditional distillation membranes in many applications.[37,139] The increased surface area of electrospun nanofibers eventually increases their sensitivity as a sensor, making them promising for application in the development of sensing devices.[141,144] A new avenue for the utilization of nanofibers produced by electrospun technology in the purification and desalination of water has been made possible by this latest class of scalable and sustainable floating membranes.

Electrospun nanofibers have certain drawbacks, despite their unique characteristics. A challenge is the inadequate cellular uptake into electrospun nanofiber scaffolds, but initiatives are underway to generate electrospun nanofiber scaffolds that are capable of functioning as three-dimensional scaffolds owing to improved cell infiltration capabilities. Likewise, after regeneration, adsorption and removal capabilities of electrospun nanofibers are significantly diminished which is associated with the fact that the water molecule occupies the adsorption

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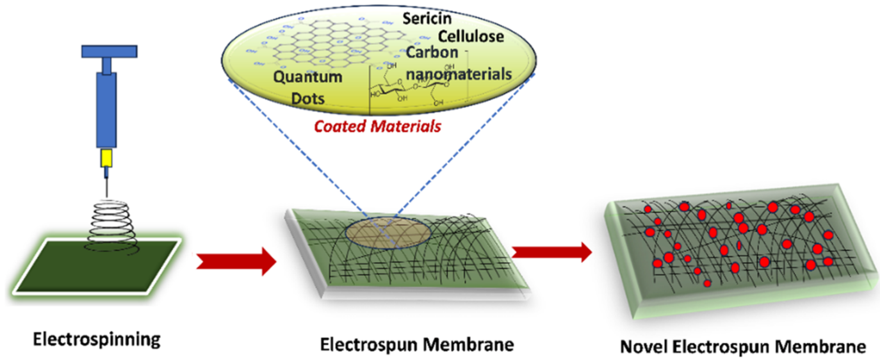

Figure 11. Pictorial representation of the coating electrospun membrane.

sites.[37] Therefore, surface functionalization strategies should be developed in a way that avoids pore alterations as well as a reduction in adsorption capabilities after desorption. Furthermore, in the context of both research and commercialization of electrospun nanofibers, safety and scale-up production remain unresolved. Some electric-sensitive materials, particularly biomolecules, cannot be effectively used with the electrospinning method due to its high voltage requirement, which may harm the workers. Simultaneously, efforts are being made to find substitute techniques that can generate nanofibers without the use of an electric field and electrostatic interactions. Large-scale manufacturing, precision in controlling the electrospinning products, environmental concerns, enhanced usefulness, and diversity of nanofibers are the primary obstacles and challenges in transferring electrospinning technology from laboratory to industrial production.[145] To achieve large-scale production, needleless electrospinning and multiple-needle electrospinning have significant potential for boosting production volume. Working on scaling-up spinning technology, environmental factors including pollution and safety concerns must be taken into complete consideration. Chemical waste, safety risks, and environmental impact will all arise from the solvent's evaporation into the environment. Particularly for items utilized in pharmaceutical and biomedical applications, residual solvents in the products may also affect their qualities and provide a safety risk. Even though electrospinning has been used to produce high-value and high-performance products from regenerated common plastics by removing the need to purify the recycled raw materials, the technology is still less environmentally friendly due to the use of organic solvents.[88]

The production of biodegradable materials from sustainable sources and the intricacies of the electrospinning process contribute to elevated manufacturing costs.[146] Overcoming this challenge necessitates advancements in production technologies, economies of scale, and the development of cost-effective sourcing strategies for raw materials. Research efforts are underway to explore innovative solutions, such as the use of alternative sustainable feedstocks and process optimization, to make BEMs more economically viable. As technology advances and market demand grows, it is anticipated that these cost challenges will gradually diminish, making biodegradable membranes more competitive and accessible in the marketplace.

8. FUTURE DIRECTIONS OF BEMS

The future directions for BEMs involve a multidimensional approach. Research and development efforts should focus on the integration of advanced polymers that balance biodegradability with enhanced durability, expanding the potential applications of these membranes. Concurrently, innovations in production processes should aim at reducing costs without compromising the material quality. The pursuit of these future directions holds the promise of overcoming current challenges, positioning BEM as a sustainable material with broader applications across diverse industries. As technology continues to evolve and awareness of environmental issues grows, these challenges can be seen not only as obstacles but also as catalysts for driving innovation and positive change in the realm of biodegradable materials. The future of BEM lies in transformative solutions that address these challenges head-on, positioning these materials as frontrunners in sustainable, eco-conscious alternatives across diverse industries. As technology evolves and environmental consciousness deepens, these challenges are poised to usher in a new era of innovation, pushing the boundaries of what is possible in the realm of biodegradable materials.

Electrospun membrane coating with diverse materials such as sericin, cellulose nanocrystal, and various carbon-based nanomaterials is a straightforward and highly advantageous method with broad industrial applications (Figure 11). The choice of coating material for electrospun membranes depends on their desired properties and specific application. An adaptable method for creating tunable BEMs involves post-treating nanofibers produced by electrospun technology to achieve adjustable pore size, porosity, and morphology. Zhao et al. developed a high-flux ultrafiltration membrane by coating electrospun fibrous scaffolding with an ultrathin top barrier layer, achieving excellent water−protein liquid filtering.[147] Deng et al. utilized green electrospinning and thermal treatment to create an efficient, environmentally friendly, and biosafe T-PVA/SA/HAP nanofiber with enhanced PM capture capability (removal >99% for PM0.3−2.5).[148] Our research group has been working on this innovative approach focusing on wastewater treatment, biomolecule separation, and pharmaceutical processes and many more. The versatility of this coating technique allows us to develop tailor-made membranes for specific industrial requirements, contributing to efficient solutions in environmental remediation and pharmaceutical requirements. Our ongoing efforts underscore the potential to address critical challenges in various industrial sectors.

9. CONCLUSION

In conclusion, this review illuminates the transformative role of BEMs in advancing sustainable industrial practices. From the

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foundational understanding of the electrospinning technique to the exploration of diverse applications spanning water treatment, food packaging, biomedical fields, agriculture, horticulture, and air filtration, these membranes emerge as versatile solutions with tangible benefits. The thorough examination of properties and performance reveals the mechanical, chemical, and biological ability of BEMs, demonstrating their capacity to outperform traditional non-biodegradable materials in specific applications. The environmental impact and sustainability analysis underscore their positive footprint, contributing to reduced waste and resource conservation throughout their lifecycle. Challenges, notably, durability, and cost are acknowledged as focal points for future research, presenting avenues for innovation and improvement. Real-world case studies emphasize the successful integration of these membranes into industrial practices, while regulatory considerations provide a framework for responsible adoption.

As industries strive for eco-conscious solutions, BEMs emerge as pioneers, not only offering functional advantages but also aligning with global sustainability goals. This review serves as a compass, guiding researchers and industries toward a future where sustainable materials play a central role in shaping the industrial landscape. The journey from electrospinning to real-world applications, regulatory insights, and challenges paves the way for a more sustainable and resilient industrial future.

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Notes

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