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New Advances in Extracted Polymer Electrospinning: Preparation, Recent Aspects, Overview and Biomedical Applications

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Abstract

The electrospinning technique is widely recognized as a practical and effective method for creating functional nanofibrous biomaterials. Electrospun fibers have been made from a lot of different materials, including hybrid mixtures and natural and manmade polymers. The use of ecologically acceptable biomaterials found in natural polymers is becoming increasingly important due to ongoing environmental concerns. Natural polysaccharides are the preferred choice due to their excellent cell affinity, low immunogenicity, practicality, moldability, flexibility, lightweight nature, durability, chemical and physicochemical stability, biodegradability, bioadhesion, natural availability, and cost-effectiveness. In this review, we explore recent contributions in the electrospinning of natural polymers, with a particular focus on polysaccharides. We discuss the challenges and limitations associated with the electrospinning process, evaluate the electrospinnability of these materials, and highlight their promising biomedical applications. Additionally, we examine the potential of electrospun natural polymer-based materials in various therapeutic and regenerative fields, emphasizing their unique properties and performance in medical applications.

Keywords: Electrospinning; polymer; polysaccharides; biomaterial; biomedical applications.

1. Introduction

Electrospinning: is an electrohydrodynamic phenomenon in which a polymer jet is drawn out under a strong electric field to form fibers. At the beginning, a fluid polymer (a polymer solution or a melted or emulsion polymer) is required. Solution, melt, and emulsion electrospinning are the three methods available. Electrospinning is considered the most popular approach to the production of nanofibers because of its ease of use and industrial scalability [1]. Nanofibers are solid structures made of polymer that are elongated in one direction and have a nanometer diameter. Melting, blowing, drawing, and self-assembly are all ways to make nanofibers, but electrospinning is the most popular method. Electrospun nanofibers are being investigated for a lot of applications, including electronics, acoustics, composites, filters, skincare and cosmetics, functional textiles, functional apparel, electronics, and biomedical applications [2]. Nanofibers have several benefits in the field of biomedicine, including the ability to be loaded and released under control, a large surface area, a tiny diameter, and controllable pore architectures. Electrospinning can be used to modify the nanofiber mat's three-dimensional structure, giving it a similar structure to the extracellular matrix. This property makes the structure suitable for applied in tissue engineering and chronic wound healing [1] (**Figure. 1**).

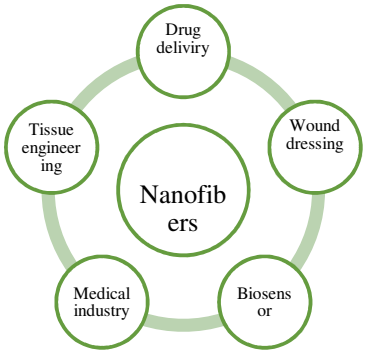

Figure 1: Electrospinning biomedical applications

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Electrospun nanofibers can be fabricated from a wide range of polymers, including melts, solutions, and sol-gel suspensions. To date, more than 200 different materials, encompassing natural polymers, synthetic polymers, and hybrid composites, have been utilized for the production of electrospun fibers. Owing to increasing environmental concerns, there is growing interest in the development of eco-friendly biomedical materials, particularly those from natural polymers. Natural polysaccharides are preferred due to their properties of high cell affinity, low immunogenicity, durability, flexibility, moldability, lightweight, practicality, chemical and physicochemical stability, biodegradability, bio-adhesion, natural abundance, low cost, and the fact that they are inexpensive [2–4]. Natural polysaccharides unfortunately have a weak mechanical strength. Polymer composites with better physical and biological capabilities can be created by combining natural polysaccharides with synthetic or natural polymers [5,6].

Chitin, chitosan, hyaluronic acids, collagen, gelatin, casein, fibrinogen, and silk protein are among the most widely used natural polymers [7-11]. (**Figure. 2**) shows various chemical structures of different natural polymers.

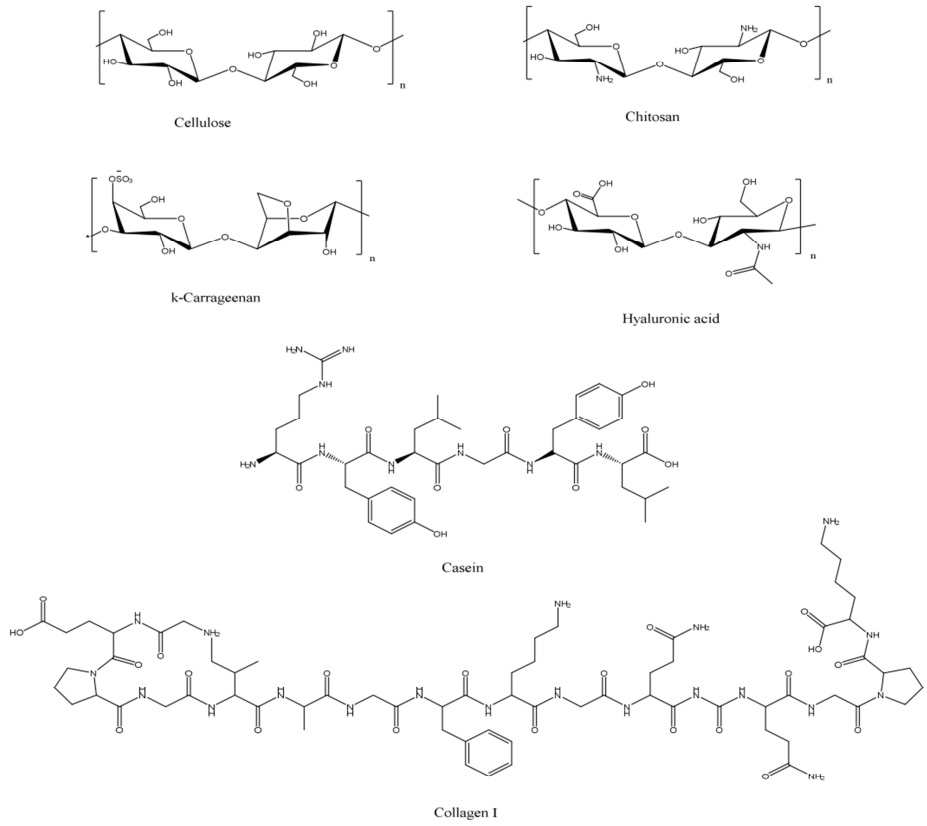

Figure 2: Chemical structures of different natural polymers

1.1. Principle

Nanofibers can be made easily and effectively through electrospinning. The electrospinning apparatus primarily includes a high-voltage power source, a spinneret, and a collector. Electrospinning is based on the idea that when polymer droplets outdo surface tension to form a jet, the solvent evaporates or solidifies to produce ultrafine fiber. Electrospinning works by pumping a polymer melt or solution through a needle while applying a high voltage. Using a high voltage, the user can create polarity and an electrical charge in the polymer solution. The Taylor cone (which is a polymer flow in the shape of a conical) forms at the dispensing needle's tip as charge accumulation occurs. The polymer solution-charged jet is then emitted from the Taylor cone's tip. Consequently, the solution jet is greatly extended, and the nano- or micro-sized fibers deposit themselves on the collector. The prepared fibers are presented in felt mat non-woven form and could be deposited on a substrate or support. Additionally, the process of electrospinning makes it possible to add (micro or nanoparticles) to the polymer solution and create composite fiber materials that have several uses. Electrospinning makes it simple to make nanofibers with significant biological properties in situ. These nanofibers' surface morphology could be effectively regulated throw a variety of parameters, including ambient, solution, and processing characteristics [1, 12] (**Figure 3**).

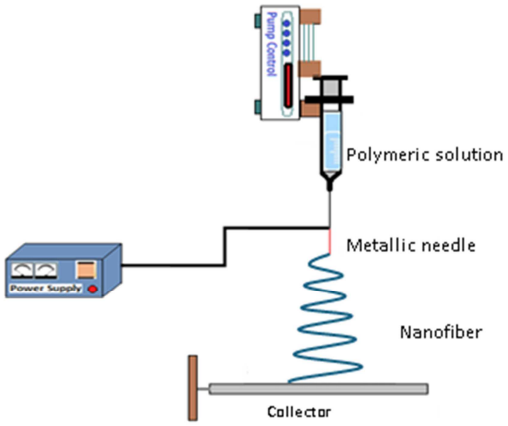

Figure 3: Electrospinning principle diagram

1.2. Parameters

1.2.1. Solution Parameters

The three main variables influencing the physiochemical characteristics of electrospun micro- and nanofibers are the polymer solution, electrospinning processing variables, and electrospinning environmental parameters. Among these, the polymer solution's characteristics—which are directly tied to the structure and molecular weight of the polymer—are crucial for producing electrospun fibers with exceptional qualities. They are directly impacting the size and form of the electrospun fibers. Thus, the electrospinning process variables influence the diameter, distribution, morphology, and other characteristics of the resulting fiber to a certain extent, consequently impacting the morphological and mechanical qualities of the electrospun fibers [13, 14]. **Table 1** summarizes the effects of parameters on nanofibers.

To get a high spin ability—that is, a high molecular weight of the electrospun polymer—a proper concentration is needed. Generally speaking, low-concentration electrospun solutions require high-molecular-weight polymers. The electrospun micro/nanofiber is somewhat influenced by the polymer solution's concentration [13]. On the other hand, molecules will find it more difficult to separate and form independent fibers in a solution with a higher concentration because of the increased intermolecular interaction forces. Additionally, the shape of the electrospun fibers is impacted by the conductivity of the electrospun polymer solution. Significant electrostatic force is applied to the polymer jet as a result of greater charge building up on the jet's surface area as the solution's dielectric constant rises. As a result, the produced fiber's diameter would decrease [15]. On the other hand, the electrospinning process would be somewhat impacted by the surface tension of the polymer jet, which is typically dictated by the polymer solution properties and environmental factors like humidity and temperature [16].

1.2.2. Process parameters

Electrospun nanofiber diameter and production are significantly affected by process parameters. The spinning voltage is among the most fundamental electrospinning operating parameter. A "Taylor cone" is formed once the voltage hits a critical threshold. After that, more voltage is applied to make a jet that eventually becomes a nanofiber. High voltages generally aid in fiber stretching by decreasing the diameter of the fiber and increasing the jet's surface charge density. However, an overvoltage will cause the "frying" phenomenon and reduce the effectiveness of fiber collection [17].

Another important electrospinning process characteristic that may be adjusted by varying the syringe pump's speed is the rate of spinning solution injection. The electrospinning process will take longer to complete if the rate is slow. Excessively high speeds will cause larger fiber widths or even massive drops that land directly on the receiving board. As a result of insufficient time for drying before reaching the collector, excessive feeding rates, on the other hand, lead to beaded fibers. Zuo et al. showed that increasing the rate of feeding from 2 mL/h to 3.5, 5.6, up to 9 mL/h, while keeping constant all other parameters, resulted in beads with an average size of 8 µm, 14 µm, and 23 µm, respectively [17, 18].

Additionally, the distance between the capillary and collector will also have an effect on the extension and solidification of the jet. Too short a distance prevents solvent volatilization, which raises the fiber diameter, increases fiber adhesion and decreases fiber performance. When the spin ing distance increases and the diameter visibly decreases, the spinning jet will have more opportunities to divide. Nevertheless, because the electric field strength is inversely proportional to the square of the distance, it drastically drops as the distance grows. Since the voltage and other factors affect each electrospinning operation, the ideal distance varies and often falls between 10 and 25 cm. Accordingly, to produce the best nanofibers, all processing parameters must be altered [1, 17].

1.2.3. Environmental parameters

Environmental factors such as temperature and moisture play a significant key in determining the outcome of the electrospinning method as well as the properties of the generated nanofibers. In addition to precise operational parameters and inherent material properties [19]. The ambient moisture content plays a critical role in the electrospinning process. Extremely low humidity conditions can lead to rapid solvent evaporation, increasing the risk of needle clogging and disrupting fiber formation. Conversely, excessive moisture levels may interfere with the stability of the polymer jet, potentially resulting in

electrospraying rather than continuous fiber production. In addition, the degree of ambient moisture can change the structure of the fiber, which is related to the polymer's ability to attract or repel water. Adjusting the moisture content of water-attracting and water-soluble polymers can help change the thickness of the fiber. The solvent dries more slowly when the temperature lowers and the air becomes more humid. This causes the jet's travel to be longer, which leads to finer fiber widths. Conversely, a reduction in humidity speeds up the drying process and results in coarser fibers. In addition, high relative humidity can prevent the water-based solvent from drying, which may cause beads to develop. The rate of solvent evaporation increases under hotter conditions. Additionally, the polymer melt or conductivity of solution, viscosity, and surface tension may be affected by the surrounding temperature. [20].

Temperature is an important factor in nanofiber formation, as it affects both the viscosity of the polymer solution and the rate of solvent evaporation, leading to the production of thinner fibers at very high or very low temperatures compared to moderate conditions. The fiber jet expanded more as a result of the slower evaporation rate of solvent at lower temperatures. Conversely, hotter temperatures decreased the viscosity, allowing for the formation of thinner nanofibers. It's important to remember that these effects vary from one substance to the next, so different polymers may react differently. The indirect effects of temperature on the structure and diameter of fibers were the subject of several studies. This suggests that temperature and viscosity interactions could be used to tailor nanofibers. On the other hand, increased humidity could lead to the developing of porous nanofibers from hydrophobic polymers. This is brought about by the intricate interactions that take place between the polymer, the solvent that draws moisture into the polymer, and the water [21].

1.3. Other methods of electrospinning

1.3.1. Multiple-needle electrospinning

Multi-jet or multi-needle electrospinning and needleless electrospinning was created in response to the weak output of single-needle electrospinning [26, 27]. Multi-needle electrospinning, as the name suggests, uses many spinneret configurations to boost the rate at which fiber is produced. By loading the spinnerets with different spinning dopes or even incompatible polymers, multi-needle electrospinning may also be used to make customized composite mats. Coaxial electrospinning and multi-needle electrospinning are able to used together to further customize the qualities of the fiber further or speed up coaxial electrospinning's production rate [28].

During multi-needle electrospinning, uniformity of the electric field must be improved by taking into account three essential aspects: needle configuration, number, and spacing [27]. In this process, linear and two-dimensional needle configurations are the two most common types. Within a linear array, the jets situated at the edge of the array behave very differently from the remaining jets, particularly concerning their envelope cone and bending direction. These discrepancies only get worse when the array is tried to be scaled up [29].

Table 1: Effect of electrospinning parameters on nanofibers

		Low	High	Too high	Ref
Process parameters	Applied Voltage	Beads form	Decreasing the fiber's diameter.	Excessive voltage increases the fiber's diameter.	[22, 23]
	Flow rate	Cause beaded morphology.	Increasing the fiber's diameter.	Excessive feeding rates cause beaded fibers.	[18, 23]
	Distance between the collector and capillary	Increases fiber diameter	Decreasing the fiber's diameter.	Electric field decreases	[1, 22, 23]
Solution parameters	Concentration	Sticky, non-dried fibers or beaded fibers.	Increasing the fiber's diameter.	The polymer may occlude the spinneret due to increased surface tension	[13, 20, 24]
	Viscosity	Decreasing the fiber's diameter and beads form	Increasing the fiber's diameter.	Occlude the spinneret	[24, 25]
	Conductivity	Electrospinning cannot be performed	Decreasing the fiber's diameter.	Create many jets	[1, 15]
Environmental Parameters	Temperature	A slower rate of solvent evaporation. Thinner fibers	Reduced the viscosity. Thinner fibers.	Increases rate of solvent evaporation	[20, 21]
	Humidity	The solvent evaporates quickly (needle clogging)	Decreasing the fiber's diameter.	Electrospraying takes place	[19-21]

1.3.2. Needleless electrospinning

The shortcomings of traditional needle-based electrospinning have been addressed by advancements in needleless electrospinning systems. One of the important benefits of needleless electrospinning is that it can use a variety of structural approaches to produce high quantities of polymeric droplets without the use of any needle. An open reservoir is typically used in needleless electrospinning in place of syringes filled with solution [30, 31]. In needleless electrospinning, a high voltage is used while the spinning dope is vigorously stirred. Together, the agitated solution and the electric field that goes with it create "Taylor cones" on the dope spinning's free surface. The creation of nanofibers occurs in the collector after polymer jets are created at the tips of the Taylor cone. Needleless electrospinning for a variety of solution agitation techniques, including slot,

ball, spiral coil, disk, bubble, and rotary cone, has been accomplished with this technology. Despite its success in increasing the rate of fiber production, needleless electrospinning has drawbacks. More solvent evaporation occurs during needleless electrospinning because of the dope's increased exposure to air. Greater solvent evaporation occurs during needleless electrospinning resulting in spinning dope's greater exposure to air. The spinning concentration of the dope's polymer rises steadily as a result of this evaporation, producing coarser fibers [32-34].

1.3.3. Coaxial electrospinning

The principle of coaxial electrospinning is essentially the same as for traditional electrospinning, with the use of a co-axial needle (which is made up of two hollow needles that are aligned in a concentric circle). In contrast to the traditional method, coaxial electrospinning uses a coaxial needle made up of two hollow needles that are concentrically aligned. through the outer and inner needles two syringe pumps were injecting two polymeric solutions in distinct batches. The main disadvantages of coaxial electrospinning in comparison to other techniques are its complexity, difficulty scaling, and parameter adjustment [35] (**Figure. 4**).

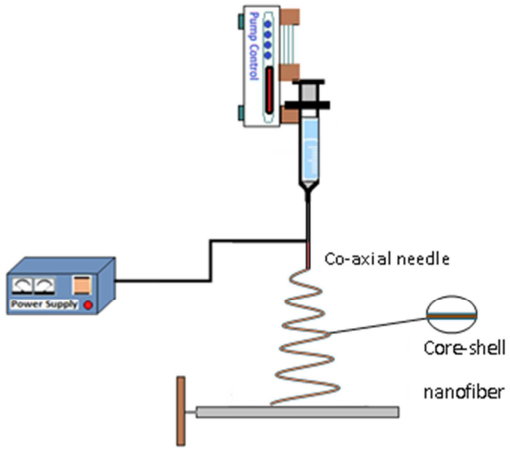

Figure 4: Coaxial electrospinning

Compared to nanofibers made by blend electrospinning, coaxial electrospinning-created core-shell nanofibers had a higher drug loading efficiency additionally a lower first burst release. This method can also be used to maintain the bioavailability and functionality of the drug. Coaxial electrospinning is more successful at keeping the release of medications when an external barrier layer is present [36, 37]. Nanofibers may also contain sensitive substances like cells, enzymes, and growth factors in their core as the shell transports the electrical charge [38, 39]. Additionally, the miscibility of the solvents and the polymers used in the core and shell solutions is essential for ensuring continuous release from the core-shell fibers during coaxial electrospinning. This is made possible by the core-shell nanofiber, which allows for the simultaneous addition of numerous medicinal compounds with varying solubility characteristics in a single step [40, 41].

2. Electrospinning of polysaccharides

2.1. Alginate

Alginate, an unbranched anionic natural polysaccharide derived from brown seaweeds, is utilized extensively in the biomedical, pharmaceutical, textile industries, and food because of its biocompatibility, non-immunogenicity, non-toxicity, and biodegradability, in addition to its ability to retain water and stabilize emulsions [42, 43]. Alginate has numerous favorable properties that render it appropriate for an extensive array of applications. When thinking about upgraded manufacturing and industrial uses, alginate is advantageous because it is widely accessible, economically viable, and sustainable. Furthermore, in terms of biomedical applications, alginate exhibits good biocompatibility, absorptivity, nontoxicity, biodegradability, and a low human immunogenetic response. Additionally, depending on the intended use, alginate's water solubility and hydrophilicity may be advantageous or disadvantageous [29]. Electrospinning of alginate fibers has been studied for various applications, including biomedical uses (such as drug delivery, tissue engineering, cancer therapy, and wound dressings), waste management (like bioremediation and filtration), sensing and energy technologies, as well as the encapsulation of hydrophilic food bio-actives [44-48].

Challenges and Electrospinning-ability

Alginate has many good qualities, but it has poor electrospinnability, and it hasn't been possible to electrospin pure alginate in water with a single solvent yet. Polyelectrolyte properties, high electrical conductivity, high surface tension, and alginate's tendency to gel at low concentrations are just a few of the characteristics that have been shown to contribute to its low electrospinnability. The electrospinnability of alginate is adversely affected primarily by its rigid and extended structure [45, 47-50]. Di-axial couplings in (G blocks) which are supported by hydrogen bonds, cause rigid intermolecular and intramolecular links. Alginate's spinnability is severely impacted by this structure, which severely limits chain entanglements

during electrospinning. Co-spinning polymers, surfactants, cosolvents, and chemical changes are frequently used to improve alginate's electrospinnability. These methods can also be used for various polymers [29].

It has been determined that the best method for producing fibers without beads is to blend them with hydrophilic polymers like polyethylene oxide (PEO) and polyvinyl alcohol (PVA). The hydrogen bonding between hydrophilic polymers and alginate polymers reduced the intramolecular and intermolecular network between the chains and enhanced their flexibility. This enhances the solution's electrospinnability by lowering its viscosity, conductivity, and surface tension [51-53]. Barakat et. al. have successfully developed environmentally friendly and economic verapamil-loaded HCl composite nanofibrous mats from two biopolymers polysaccharide sodium alginate (SA) of marine origin (brown algae) and protein zein from plant origin (maize or corn). It was blended with hydrophilic polymers PVA to successfully fabricate bead-free fibers. Complete healing without the formation of scars has been achieved for both verapamil hydrochloride (HCl) -loaded composite nanofibrous mats. Even while PVA-SA nanofibers loaded with verapamil (HCl) had a quicker rate of healing, PVA-Z nanofibers showed more sustained drug release and were better at improving the histological features of the newly created tissues [54].

Casula et al. also successfully created a unique biocompatible nano-delivery system that is a promising and successful dressing for chronic wound therapy created by combining nanofibers and liposomes. The dressing healing wounds incorporated simvastatin and an antioxidant into alginate/poly(ethyleneoxide) nanofibers. By green electrospinning without organic solvents because they had been encapsulated into liposomes beforehand. After integrating simvastatin (SIM) into liposomes, PEO and alginate were mixed in an aqueous liposome dispersion at a mass ratio of 80:20, and the mixture was electrospun. Various doses of an antioxidant (butylated hydroxyanisole, BHA) were added to the liposomal formulations to avoid degradation and improve SIM stability [55].

The process of implementing a cosolvent involves adding another solvent (one or two) to the spinning dope at a concentration that is usually less than twenty percent of the weight of the first solvent [47]. The cosolvent usually forms new hydrogen bonds, charge repulsions between the polymer chains, and increases chain flexibility, which reduces the electrical conductivity and surface tension of the solution. During the electrospinning of alginate, cosolvents such as glycerol, ethanol, propanol, dimethyl sulfoxide (DMSO), and dimethylformamide (DMF) are frequently utilized. By using glycerol as a cosolvent Nie et al. successfully electrospinning the first pure alginate fibers. The main way that glycerol made alginate more electrospinnable was by making new hydrogen bonds between the polymer chains and breaking many of the initial intramolecular and intermolecular hydrogen bonds. Glycerol also improved alginate spinnability by raising the solution's viscosity and elasticity while lowering its conductivity and surface tension [29].

Surfactants are materials with a non-polar and a polar group that are amphiphilic. They are frequently employed to improve electrospinnability and fiber characteristics in conjunction with a co-spinning polymer or cosolvent. For instance, according Bonino et al. incorporating Triton X-100, a surfactant, into an alginate and PEO blend enhanced fiber shape and permitted a greater concentration of functional alginate. Surfactants reduce the surface tension of the dope of spinning, increasing its functional concentration. Furthermore, surfactants typically reduce solution conductivity and alginate stiffness, which promotes a bead-free morphology [47].

Esterification, oxidation, and sulfation are often employed as chemical changes to improve electrospinnability. These alterations change the solubility of alginate in different organic and aqueous media and reduce the stiffness of alginate by decreasing the hydrogen bonds density in both intra- and intermolecular connections. Furthermore, chemical modifications can affect the functionality of electrospinning fibers for certain applications. Sulfation, for instance improves alginate's blood compatibility, anticoagulation characteristics, and cell adhesion, all of which are useful in a lot of biomedical applications [47, 48].

2.2. Chitosan

Chitosan is a natural modified polysaccharide made by partially N-deacetylating chitin, a naturally occurring biopolymer obtained from the shells of crustaceans, including crabs, shrimp, and lobsters. Certain fungi, yeasts, and microorganisms can also contain chitosan. The main unit in the chitin polymer is 2-deoxy-2-(acetylamino) glucose. These units combine to create a long-chain linear polymer through (1,4)-glycosidic linkages. Chitin is insoluble in most solvents but chitosan is soluble in most organic acidic solutions with a pH less than (6.5), such as formic, citric acid, acetic, and tartaric. But phosphoric and sulfuric acids do not dissolve it. Chitosan has a large variety of degrees of deacetylation and molecular weights, which are the primary factors influencing particle size, aggregation, and particle formation [56, 57].

Electrospun chitosan fibers have been studied for their possible use in food packaging, water purification, wound dressings, medication administration, tissue engineering (such as bone regeneration), and biosensing because of their many benefits. In particular, because of chitosan's inherent hemostatic and antimicrobial, antibacterial, and antifungal qualities, it has attracted particular attention in the biomedical industry. Its capacity to bind cells and imitate the extracellular matrix also makes it useful for tissue engineering applications. Beneficially, electrospun chitosan has also shown promise in effectively encasing growth factors and compounds with antibacterial, antioxidant, and anti-inflammatory properties. This increases the range of possible uses for chitosan in the biomedical industry [58-60].

Challenges and Electrospinning-ability

Due to its inflexible (D-glucosamine) repeat units and propensity to generate intermolecular or intramolecular hydrogen bonds, chitosan is limited in its solubility in common organic solvents and pure water. Because protonated of primary amines, it has been demonstrated that chitosan is more soluble in water at lower pH [61]. The creation of inter-chain hydrogen bonds with water molecules (which are blocked by the electrostatic repulsive interactions between positive ammonium groups) increases the solubility of chitosan in aqueous acidic solutions. Acetic acid has been used the most frequently as a pH correction agent. By utilizing a water-based solvent high in acetic acid pure chitosan has been electrospun successfully [62]. Surface tension is reduced by acidic pH reduction, but viscosity is also increased, which has the opposite effect on the spinnability of chitosan. Electrospinning can be used to make chitosan nanofibers, but there are a lot of challenges to

overcome, like a lack of suitable solvents and a lot of variables that affect how the nanofibers are made and how good they are. Because of the special characteristics of this polymer in solution (such as its high molecular weight, polycationic nature, and wide range of molecular weights), the process of electrospinning chitosan is complex. Numerous factors impact the electrospinning procedure and final product quality, such as electric field voltage, solvents, molecular weight, feed rate, inner tip, and collector gap. Chitosan dissolution has been studied with a lot of organic and inorganic acids [63, 64]. Furthermore, the biological activity of chitosan formulations is also influenced by the type of solvent utilized. In light of this, it was discovered that trifluoroacetic acid (TFA) and dichloromethane (DCM) were the most effective solvents for the production of electrospinning chitosan fiber [65]. Using TFA and DCM, Korniienko et al. made chitosan nanofibrous membranes and examined their physiochemical and antimicrobial properties. Electrospun Chitosan-TFA/DCM nanofibrous membranes showed a bacteriostatic impact on the planktonic bacteria and associated biofilms. Because fluorine atoms were added to the chitosan polymeric chain backbone in nanofibers made with the TFA and DCM (9:1) co-solvent system, the rate of bacterial reduction was higher. The results provided that the electrospun fibers' morphological properties can control the nanofibrous membranes' biofilm formation. In addition to producing nanofibrous insoluble membranes of chitosan that are suitable for tissue engineering and biomedical applications, through the structural and physicochemical properties of the membranes, these studies also stimulate additional research into the use of electrospun biofibrous materials as antibacterial agents that regulate bacterial adhesion and proliferation [66].

Adding a second polymer -typically synthetic and readily electrospinnable- is one way to include chitosan in nanofiber biomaterials. The following chitosan blends produced high-quality electrospun chitosan-based nanofibers: chitosan and poly (ethylene oxide) (PEO) [67], chitosan and poly (lactic acid) (PLA) [68], and chitosan and polyvinyl alcohol) (PVA) [69]. This is because adding highly electrospinnable polymers to the blends facilitates the electrospinning of chitosan. However, the chitosan content of these blends is often low, crosslinking is required to stabilize the nanofibers, and pure chitosan nanofiber production is not accomplished. It should be remembered that some commonly utilized crosslinkers, including glutaraldehyde (GA), can cause calcification and ultimately lead to transplant failure. For this reason, using GA to improve the processability of biomaterials is not recommended [70]. Chitosan exhibits favorable biological properties (e.g. biodegradability, nontoxicity, biocompatibility, and antibacterial qualities). Nevertheless, it lacks the same mechanical qualities as PVA and is more difficult to electrospun. Conversely, PVA provides great mechanical stability for the mesh and is easily electrospun; nonetheless, its biological properties need be improved. Stoica et al. created an electrospinning nanofibrous mesh using PVA, chitosan (CS), and usnic acid (UA), which might represent a favorable material for wound healing. The 5%PVA_2%CS_UA showed increased anti-biofilm efficacy against the S. aureus strain [71].

Using co-solvent Vu et al. developed nanofibers incorporating biologically active molecules involving PVA and chitosan (CS) nanofibers with a targeted mode of action, which are typically produced through the electrospun of aqueous solutions of these polymers with (acetic acid). Using ethanol as the co-solvent in the electrospinning solution of PVA-CS to improve drug integration. This leads to several significant findings, including the interplay of the different component forces, the rheological and optical characteristics of the PVA/CS solution, and discernible changes in the system of solvent solubility parameters. It also demonstrated positive results for enhancing the morphology and production yield of PVA/CS nanofibers. Due to defect reduction, PVA-CS nanofibers' morphology, diameter, and production productivity increased by two to three times. Their diameter decreased from 326 ± 62 nm to 285 ± 65 nm (0.2 mL/h) or 300 ± 79 nm (0.3 mL/h). Moreover, the mechanical properties of nanofibers vary depending on the structure of their crystal lattice. When the vertical tensile strength rises by 33%, the vertical and horizontal Young's moduli rise by 59% and 15%, respectively, and the elongation at break falls by 1%, the PVA/CS nanofibers seem to get stronger. These findings show that the suitable aqueous solution for boosting the productivity of nanofiber production contains 3 percent (CS), 4 percent (PVA), 15 percent (ethanol), and 45 percent (acetic acid). This solution also improves the diameter and shape of PVA/CS nanofibers without altering the chemical bonds [72].

2.3 Cellulose

Cellulose is a polymer composed of hundreds to thousands of unbranched D-glucose units joined by β(1→4) links. To maintain the polymeric chain's linear structure, each glucose residue contains three hydroxyl groups that form intra-chain hydrogen bonds with the neighboring ring's oxygen [73]. Due to strong intramolecular hydrogen bonds and Van der Waals forces the aggregation of cellulose chains with lateral diameters of up to several (nm) [74]. Numerous functional substituents and hydroxyl groups can react simply to produce a broad range of cellulose derivatives. Certain functional groups enhanced the characteristics of cellulose derivatives, improving the caliber of electrospinning solutions [75]. Because of its superior capacity to absorb exudates through the action of its numerous hydroxyl groups, cellulose has been utilized in basic wound dressings (such as cotton) since the middle of the 1970s. Furthermore, electrospun cellulose fibers' capacity to contain medications, vitamins, enzymes, antibacterial agents, and bioactive chemicals is advantageous for the development of biological dressings (including dressings that promote both physiological and mechanical wound healing). In addition, cellulose fibers have shown a sustained release of the molecules they encapsulate, which is beneficial for tissue engineering applications, long-term medication delivery (such as for cancer and other chronic diseases), and wound dressings. [76-79].

Challenges and Electrospinning-ability

Due to their low solubility and the requirement of unusual solvents, which frequently contain highly acidic or dielectric ingredients (such as trifluoroacetic and acids acetic), semi-crystalline polysaccharides such as cellulose, chitin, and chitosan are thought to be less suitable polymers for direct electrospinning, limiting further experimental work with biological applications. As a result of these challenges, research interest has diverted to cellulose derivatives as the starting polymer for solving electrospun. Many studies indicate that pure cellulose-based non-woven materials can be produced from cellulose derivatives through post-treatment after spinning. Hydrolyzing the fibers in an aqueous or alcohol alkali solution is the most common post-treatment method. Since the derivatives serve as the building blocks for the creation of fibers and are

subsequently converted to cellulose—also referred to as "regenerated cellulose"—a lot of study on electrospun cellulose is concentrated on these derivatives [80, 81].

Changed-structure cellulose derivatives dissolve considerably better in common solvent systems. It is possible to dissolve cellulose acetate, the most often used material to create electrospinning nanofibers, in acetone/DMAc, acetic acid, or acetone/DMF/water solvents [82–84].

Li et al. developed an anisotropic flexible strain sensor utilizing conductive and precisely aligned cellulose composite nanofibers to detect complex multidimensional strains through straightforward electrospinning of cellulose acetate, deacetylation, and in situ pyrrole polymerization. Because of the unique good-ordered structure of conductive hybrid nanofibers, the resulting strain sensor exhibits exceptional anisotropic sensing capability, with sensitivity values of 0.73 and 0.01 for the tensile exerted perpendicular to and parallel to the nanofiber alignment, respectively. Because of the strong hydrogen connection between polypyrrole and cellulose nanofibers (2000 cycles), the sensor also exhibits remarkable endurance. Flexible strain sensors also have a lot of potential for the detection of motion, as exhibited by the identification of different joint motions in the human body [85]. Concerning wound dressing applications, Goher et al. developed and produced electrospun nanofibers loaded with Tamarindus made of crosslinked cellulose acetate (CA), poly(ethylene oxide), and (PEO) poly(methyl methacrylate) (PMMA). Nanofibers with potent phytochemicals could be used as wound-healing composites and more effective, biocompatible, and environmentally friendly antimicrobial biomaterials. T-indica leaf extract at varying percentages was combined with a precisely adjusted matrix composition consisting of CA (2%), PEO (1.5%), and PMMA (10%), and subsequently electrospinning to produce a smooth, dense material. Indica-loaded nanofibers showed low cytotoxicity and high compatibility when applied to normal human skin fibroblasts (HBF4). When compared to the extracted free plant, T. indica-loaded nanofibers dramatically boosted the healing activity of scratched HBF4 cells, and the healing activity increased as the concentration of the extracted plant rose. Additionally, T. indica-loaded nanofibers displayed substantial antibacterial efficacy. Nanofibers showed a higher wound healing efficiency in vivo than the untreated control animals [86].

2.4. Carrageenan

Carrageenan polymers are sulfated polysaccharides anionic found in the red seaweed cell walls. They consist of D-galactose and 3,6-anhydroD-galactose units that alternate and are connected by α-(1,3) and β-(1,4) glycosidic linkages. They are divided into three major types: kappa (κ)-carrageenan, iota (ι)-carrageenan, and lambda (λ)-carrageenan, depending on the sulfation degree and the amount of (3,6-anhydroD-galactose) [87, 88]. They have been extensively used in the pharmaceutical industries, cosmetics, and food due to their antiviral, anticoagulant, immunomodulatory, anticancer, and antioxidant properties [89, 90]. Carrageenans have garnered considerable interest in tissue engineering applications because of their great biological properties, biodegradability, biocompatibility, low cost, and chemical similarity to glycosaminoglycans of the native extracellular matrix. κ- and ι-carrageenans in particular have great osteogenic promise [91-93]. Because they have demonstrated significant promise for tissue engineering (bone regeneration) by encouraging the adhesion and proliferation of osteoblasts, they are perfect candidates for periodontal tissue regeneration when formulated in electrospun nanofibers [94, 95].

Challenges and Electrospinning-ability

The most commonly used carrageenans variation in electrospinning applications is native κ-carrageenan (κC). The inability of commercially available food-grade lambda- and kappa-carrageenans to electrospun nanofibers has likely been caused by their shearing thin behavior at high shear rates and very hydrophilic nature [96, 97]. κ-carrageenan has been mixed with different biopolymers in varying ratios to increase the ability to generate electrospun fibers [98-102]. However, commercially available food-grade lambda- and kappa-carrageenans' thin-shearing behavior at high shear rates and highly hydrophilic nature are likely to blame for their inability to electrospun nanofibers [96, 97]. PVA is one example of a synthetic biopolymer that is used to facilitate the electrospinning process and improve the finished structure's mechanical strength [103]. Salmasi et al., prepared an electrospun membrane of PVA-CMC-κC (PCκC40) and it has great potential to be used as a hemostasis patch in clinical and medical settings. For the first time, κC was electrospun and its membrane exhibited a superior coagulation action compared to carboxymethyl chitosan (CMC). An electrospun membrane of PVA-CMC-κC loaded with tranexamic acid (TXA) manufactured under optimal conditions improves blood coagulation. According to ISO 10993 (<5%), all structures could be submitted as non-hemolytic materials (<2% hemo-compatibility). PC-C-TXA nanofibers promote coagulation, assist in platelet adhesion and activation, and shorten the clotting time compared to the control [104].

Kikionis et al. developed bi- and tri-layer nanofibrous guided tissue regeneration (GTR) membranes based on carrageenans and other biocompatible polymers. The membranes were designed, fabricated, and characterized. In a saliva substitute solution at 37°C after 28 days of incubation, all GTR membranes were sufficiently stable and continued to release Ca^{+2} continuously for at least three weeks. These results suggest that GTR membranes can function as an ongoing source of calcium ions to encourage osteoblast growth and bone regeneration. The created GTR membranes' initial strength was sufficient and on par with resorbable membranes that are currently sold commercially and utilized in clinical settings [87]. Since oral dispersible films (ODF) dissolve easily in the tongue, they are an excellent substitute for tablets in medicine. ODFs can be made in a variety of ways, but electrospinning is currently the most effective technique because it boosts the surface-to-volume ratio, which facilitates easy dissolution. Electrospinning successfully produced an ODF based on -carrageenan and containing vitamin C, according to Sapiee et al. The Fourier transform infrared spectroscopy (FTIR) spectra electrospinning solutions showed that the polymers and vitamin C did not interact or form bonds. In the meanwhile, the 8% vitamin C sample had the best morphology and the most consistently generated nanofibers, according to the findings made from the scanning electrode microscope (SEM) pictures. In terms of diameters, disintegration time, and water contact angle the same sample (8 percent vitamin C) was also preferred. It had the smaller water contact angle and the quicker disintegration time (196.4 9 ±

57.47 nm, 38.5 ± 0.20^, and 3.68 s) respectively. To make drug delivery easier, analogous techniques might be created and applied to load different active pharmaceutical ingredients (APIs) onto the electrospun κ-CAR/PVA thin film [105].

2.5. Other natural polymers

2.5.1. Collagen

The most prevalent protein in both animals and humans, collagen is the major component that gives the extracellular matrix (ECM) its structural stability, which makes it biocompatible and low-allergenic. Collagen is often used as a component in wound dressings and skin substitute materials because of its superior hemostatic and proliferative qualities in keratinocytes and fibroblasts [106–109]. Only collagen I, one of the 29 types of collagens, is used to make biomaterials based on collagen. Due to its biodegradability, low antigenicity, ability to form three-dimensional scaffolds versatile mechanical properties, and capacity to interact with a range of cell types, collagen is a material of attention for therapeutic and tissue engineering applications [110].

The main challenges with collagen electrospun are low denaturation temperature, no swelling in water (it dissolves immediately), and loss of physiochemical structure as a result of high voltage. These limitations have been overcome through structural modifications and blending with various biopolymers. It has been successfully electrospun from a variety of solvents based on fluoroalcohol, such as water-based ethanol solutions, 2,2,2-trifluoroethanol (TFE), and 1,1,1,3,3,3-hexafluoro-2-propanol (HFP). Collagen has been electrospun with other natural and synthetic polymers, also collagen nanofibers have been crosslinked to enhance relatively weak mechanical qualities and high breakdown rates after implantation [111-114]. Abdelazim et al., have created electrospun nanofiber loaded with plant extracts as a potent scaffold for topical wound healing. electrospun nanofibers were created from extracted Syzygium cumini leaf (SCLE), poly(lactic-co-glycolic acid) (PLGA), poly(methyl methacrylate) (PMMA), collagen, and glycine. The results demonstrated more antibacterial activity against the tested Gram-positive (Bacillus cereus, Candida albicans, Staph aureus, and Candida glabrata) and Gram-negative (Escherichia coli and Salmonella paratyphi) pathogens when nanofibers containing Syzygium cumini extract were compared to the same concentrations of the extracted plain. In addition, in vivo wound healing was tested in Wistar rats for 14 days. Demonstrated that nanofiber mats containing collagen and SCLE greatly accelerated wound healing in less than 2 weeks when compared to the untreated control group. As a result, these SCLE-loaded nanofibers could be used to treat acute wounds and traumas as a biocompatible antimicrobial and wound-healing composite [115].

2.5.2. Gelatin

Gelatin is a popular and commonly utilized animal protein with a stronger electrospinnability than other proteins. Collagen is the source of gelatin, a fibrous protein with a triple-helical structure that readily aligns and stretches into fibers when electrostatic forces are applied. Many of the polar amino acids in gelatin, like serine, tyrosine, and aspartic acid, have the potential to create hydrogen bonds with the molecules of solvent. Therefore, it can dissolve in a wide range of solvents, including water, ethanol, formic acid, and acetic acid. Additionally, the cyclic amino acids proline and hydroxyproline, which are abundant in gelatin, can stabilize the helical structure and promote the production of fiber [116-118]. Gelatin is biocompatible, biodegradable, and less antigenic than collagen because it is the result of denaturing collagen. Crosslinking gelatin has been studied to alter the rate at which encapsulated cargo degrades and releases [119-120]. Gelatin has been widely used as a drug delivery system for growth factors. Among gelatin's main features are lack of denaturation phenomena, non-immunogenicity, biocompatibility, flexibility, biodegradability, and low cost. Gelatin is therefore employed in the food and biomedical industries in different ways, particularly in tissue engineering. The main benefit is that it has no denaturation phenomena after electrospinning, making it a preferred material over collagen [121].

The primary disadvantage of gelatin nanofibers is that they dissolve in water. To address problems with dissolution, gelatin is typically crosslinked using a variety of crosslinkers, most of which are aldehydes. These include succinimide, carbodiimides, glutaraldehyde (GA), and genipin (GEN). GA and GEN are the best crosslinking agents due to their low toxicity and resilience to degradation at 37 °C cell growth conditions [121]. Song et al. developed a carrier for cultured corneal endothelial cells (CECs). In this study, they used electrospinning and glutaraldehyde (GA) crosslinking to successfully create a nanofiber membrane of gelatin (gelNF membrane). The manufactured gelNF membrane kept a thickness of 20 µm and was approximately 80% clear when compared to glass. An analog of Descemet's membrane showed poor permeability and degradability compared to the gelNF membrane. Notably, high densities of CECs cultivated on the gelNF membrane did not result in any cytotoxic effects. According to the results, this gelNF membrane has the potential for use as a suitable carrier for transplanting cultured CEC since it has the necessary mechanical characteristics, transparency, and permeability [122].

2.5.3. Keratin

Keratin is one of the most common natural proteins, and it is preferred to be used in tissue engineering studies because of its biofunctionality, biodegradability, and biocompatibility [123, 124]. It can be present in mammals' hooves, hair, nails, feathers, horns, and wool. It has been demonstrated that the application of keratin to tissue-engineered scaffolds increases the material's tissue biocompatibility both in vitro and in vivo by proliferation and encouraging cell adhesion [125-127]. Keratin is a good option for air and water purification because of its exceptional capacity to absorb metal ions, pigments, and volatile chemical pollutants. In addition, its intrinsic bioactivity makes it suitable for a variety of potential applications in biomedical [126].

Some of the challenges faced in electrospinning keratinous material are its low viscosity and relatively high molar mass [128]. To be electrospun into nanofibers, keratin was combined with other polymers, including PEO, PVA, Polyacrylonitrile (PAN), gelatin, chitosan and others to get around the unfavorable mechanical characteristics and brittleness of pure keratin nano-fibrous mats. Keratin with polymer blends can only be dissolved in specific solvents, including acetic acid, trifluoroethanol, trichloromethane/N,N-dimethylformamide, formic acid, and hexafluoroisopropanol (HFIP) to enable electrospinning [129, 130]. Aadil et al. fabricated nanofibers based on keratin using the electrospinning technique and investigated their application as scaffolds for tissue engineering. Keratin was blended with PVA. In a three-dimensional co-culture study, the growth and infiltration pattern of adjacent HaCaT and NHDF cells resembled those of dermal and epidermal skin cells. Additionally, the

in vitro cell culture investigation indicates that PK-NF scaffolds are non-cytotoxic by promoting the growth of human keratinocytes (HaCaT), dermal fibroblast (NHDF) cell lines, and mouse embryonic stem cells (ESCs). Furthermore, the immunocytochemical evaluation showed that ESCs, HaCaT, and NHDF cells seeded on PK-NF scaffolds successfully underwent infiltration, adhesion, and proliferation. Regardless of the random and aligned internal fibril of the PK-NF scaffold configuration, no appreciable variations in cell growth and viability were noted. This demonstrates PK-NFs' potential as a scaffold for applications involving skin tissue engineering [131] (**Table 2** summarizes the features, applications, and limitations of the discussed polymers).

Table 2: Features, applications, and limitations of the discussed polymers

Name of polymer	Features	Applications	Limitations
Alginate	Biocompatibility Absorptivity Nontoxicity Biodegradability A low human immunogenetic response	Biomedical Waste management Sensing and energy technologies Encapsulation of hydrophilic food bio-actives	High electrical conductivity High surface tension Alginate's tendency to gel at low concentrations
Chitosan	Biodegradability Nontoxicity Biocompatibility Antibacterial qualities	Biomedical Food packaging Water purification Biosensing	Limited in its solubility in common organic solvents and pure water High molecular weight Polycationic nature Wide range of molecular weights
Cellulose	Excellent mechanical properties Superior capacity to absorb exudates	Biomedical (tissue engineering applications, medication delivery, and wound dressing)	Low solubility Requirement of unusual solvents
Carrageenan	Biocompatible Nontoxicity	Biomedical Pharmaceutical industries Cosmetics Food	Thin-shear behavior at high shear rates Highly hydrophilic nature
Collagen	Biodegradability Low antigenicity Ability to form three-dimensional scaffolds Mechanical properties	Biomedical (therapeutic, wound healing, and tissue engineering applications)	Low denaturation temperature No swelling in water (it dissolves immediately) Loss of physicochemical structure as a result of high voltage
Gelatin	Biocompatible Biodegradable Non-immunogenicity Flexibility Low cost Low antigenicity (less antigenic than collagen)	Biomedical (drug delivery and tissue engineering) Food	Dissolve in water
keratin	Biofunctionality Biodegradability Biocompatibility	Biomedical Air and water purification	Low viscosity Relatively high molar mass

2.6. Blend natural polymers

Natural polymers have important biological properties, including antibacterial, antiviral, antifungal, and anticancer. Additionally, they are biodegradable and non-toxic. Blending natural polymers is a useful and efficient way to enhance the properties of biopolymers. Blending has been employed to combine the benefits of single materials to create high-performance materials. In biomedical applications Saber et al successfully created a new Silk fibroin/gelatin electrospinning nano-fibrous dressing loaded with roxadustat, accelerating wound healing [132]. To enhance wound healing, Zhang et al. developed composite membranes made from chitosan and collagen. The electrospun membrane is an attractive option for full-thickness skin wound healing due to its many wound-healing-friendly properties, including excellent blood coagulation, sufficient antibacterial performance, and the stimulation of cell proliferation [133]. Khalilimofrad et al. created gelation/Chitosan electrospun collagen type I mats that improved skin tissue regeneration with success. The electrospun mats were prepared using a 90:10 volume ratio of a gelatin and chitosan blend. Then, to enhance its biological properties, collagen type I was crosslinked with chitosan. Besides providing a potential solution for skin tissue engineering applications, the proposed modified mats display convenient structural and functional characteristics [134].

In other applications, Du et al. revealed the possibility of electrospun membranes cellulose acetate and chitosan as a potential remedy for aquatic heavy metal contamination [135]. In line with this, Lopez et al. created electrospun fibers of a mixture of chitosan and cellulose acetate polymer in the aim to link Cu^{2+}, Pb^{2+}, and Mo^{6+} ions. The findings show that there is potential for evaluating these fibers in copper mining tailings effluent [136].

3. Biomedical applications

3.1. Drug delivery

Electrospun micro or nanofibrous scaffolds have received much promise in drug delivery applications, thesis is owing to their substantially increased surface area-to-volume ratio, medication loading capability, and compact size. They also demonstrate a high capacity for loading functional agents, possess flexible morphology, enable sustained drug release, and closely resemble

the natural extracellular matrix (ECM). These properties make them particularly attractive for biomedical applications aimed at achieving long-term, targeted drug delivery for chronic disease treatment. Additionally, advanced nanofibers, designed to release drugs in response to specific stimuli, allow for more controlled medication release with reduced side effects. In diseases such as cancer, where therapies like chemotherapy can significantly affect the overall health of a patient, it is crucial to tailor medication release to the specific conditions of the illness and the characteristics of the area where the drug will be administered. Electrospinning techniques, including coaxial, melt, emulsion, and blend electrospinning, have been investigated for the preparation of electrospun nanofibers for biomedical and various other applications. The drug delivery mechanism relies on the interactions between drugs and polymers and the type of polymer swelling, erosion, or degradation. Numerous drugs, including growth hormones, RNA, DNA, antibiotics, living cells, and anticancer agents, have been incorporated into electrospun nanofibers [137, 138].

Nanotechnology improves mechanical durability, flexibility, heat resistance, controlled drug release, water absorption capacity, and enhanced skin adhesive properties. Furthermore, nanoparticles, including silver, gold, or magnetic ones, can be added to naturally occurring plant fibers, showing a great deal of potential for the production of nanocomposites with antibacterial, antimicrobial, or magnetized properties. These combination materials exhibit increased wound healing abilities, antibacterial impacts, and diagnostic characteristics [139, 140]. Cellulosic or lignin reinforcements are ideal for several biological applications, such as drug delivery, owing to their lower immunogenicity by comparison to glass or artificial alternatives. [141, 142]. Cellulose nano-fibrils (CNF) derived from raw filaments of jute are a fantastic alternative for topical medication delivery systems because a rise in CNF levels in the nanocomposite layer reduces the overall drug release proportion. They are safe, guarantee water absorption, have a lot of surface area, and have appealing rheological properties. It is feasible to use fiber of sisal to be applied in medication administration, cosmetics, and tissue engineering [139, 143].

3.2. Wound dressing

There has recently been a lot of interest in making electrospun wound dressings with extracts from plants and animals. Numerous studies have demonstrated that, as natural active ingredients, plant and animal extracts aid in wound healing and treatment by providing antioxidant, antibacterial, immune-modulating, and anti-inflammatory properties. Electrospinning technology has advanced into a flexible technique for producing ultrafine fibers having a diameter of 50–500 nm on average. The structure of electrospun nanofiber membranes resembles that of the extracellular matrix found in natural tissues, as both are porous. This distinctive feature allows for the deposition of extracellular matrix components and supports essential cellular processes, such as cell adhesion, proliferation, differentiation, and migration at the wound site. In addition, the electrospinning nanofiber membranes' high specific surface area makes it possible to effectively absorb wound exudate and blood. Sufficient gas exchange between the wound and the environment is further enhanced by the macroporous nature of these membranes. Furthermore, different nanofiber shapes can be created to fit certain applications thanks to the electrospinning process's programmable nature [144, 145].

Due to the structural morphology of electrospun nanofibers closely resembling that of native tissue, there has been growing interest in their use for medical dressing applications. Natural polymers such as chitin and chitosan are particularly well-suited for these applications, offering excellent material properties for medical dressings [146]. These polymer materials, which are abundant in nature and a renewable resource, are both biocompatible and biodegradable. The large surface area of these materials, which gives them additional capabilities, particularly in the biomedical domains, has made their embedding into nanofibers even more advantageous. But this is not an easy task: the enormous molecular weights of chitin and chitosan, along with their rigid backbones that make the polymer solution too viscous for the electric field to stretch through, make them difficult to electrospun. Researchers discovered that using concentrated acetic acid (90%) as a solvent reduced surface tension, alongside the combination of solvents like 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP), DCM, and TFA, which are employed in the electrospinning of chitosan-based nanofibers. When submerged in an aqueous medium, crosslinked nanofibers that were electrospun using glutaraldehyde vapors preserve their fibrous integrity. Using blends of chitosan or chitin with other polymers, such as PEO or PVA, was the second method for creating good, silky nanofibers [65, 147].

In the biomedical field, electrospun alginate has currently proved to have the greatest promise for tissue engineering and wound dressing applications. Wound dressings based on alginate can absorb a large amount of exudate, which can then be removed without worsening the patient's suffering or creating further damage. Alginate-based wound dressings are also quite comparable to human skin in terms of their mechanical and malleable qualities. They can help move moisture and oxygen to and from the site while preventing microbial fermentation. These wound dressings with an alginate foundation are already available on the market today. Furthermore, because electrospun alginate mimics important characteristics of the ECM, it has generated a lot of attention within the tissue engineering of bone, cartilage, and skin [29].

3.3. Tissue engineering

Tissue engineering is a regenerative approach that involves reconstructing tissues in vitro and transplanting the structures to the areas where in vivo tissue regeneration is required. Creating artificial cellular scaffolds that imitate the ECM is highly desirable for this technique. The electrospinning technology may create nanoscale fiber mats with mechanical strength similar to native tissue ECM, low density, and great porosity. Additionally, electrospinning makes it possible to incorporate biologically active molecules into the fiber in an efficient manner, whether they are entrapped or covalently bound, which greatly improves the ability of nanofibrous textiles to heal tissue [3]. In the engineering of living tissues, biodegradable scaffolds are frequently utilized. A scaffold acts as a temporary framework for cell seeding, proliferation, and differentiation, facilitating the regeneration of physiologically active tissue or the natural extracellular matrix [148]. The most prevalent method for fabricating these scaffolds is electrospinning. Polymeric nanofibers have become attractive materials for creating scaffolds for biomedical applications. Natural tissue engineering and medical uses have generated considerable interest in spinning technologies. Compared to polymer microfibers, nanofibers with nanometer-scale diameters possess significantly larger surface areas, enhancing surface functionality. Electrospun nanofibers of natural and synthetic polymers were employed

to manufacture scaffolds. Polymer nanofibers have been suggested as scaffolds for the formation of various structures, such as bones, heart tissue, cartilage, neurons, and arterial blood vessels [149-151].

Many electrospun polysaccharidic textiles have structures that resemble the natural components of the ECM. Due to their biocompatibility, non-toxicity, and biodegradability, they are increasingly utilized in tissue engineering applications. The mechanical characteristics of their electrospun fabrics, as well as the solubility and viscoelasticity of the spinning solutions, may be enhanced by chemically modifying polysaccharides with physiologically active groups and other functional groups [152].

Applications for electrospun fibrous membranes in tissue engineering are numerous. A scaffold that sustains cells, renews ECM elements and acts as a vector for the delivery of biochemical components is necessary for tissue engineering. Cell anchoring is provided by the supporting meshwork around the cells and the border between tissues created by the native ECM's nanoscale structure, which is composed of proteins and glycosaminoglycans (GAGs) [153].

3.4. Cancer Therapy

Electrospun fibers, produced using biodegradable and biocompatible polymers, present numerous benefits for biomedical applications. Electrospinning has been utilized as a processing method to create cancer theranostic devices, allowing for the straightforward incorporation of various biofunctional chemicals into a nanostructure [154].

Anticancer medications administered orally or intravenously have several drawbacks, including low stability and solubility, limited effectiveness, adverse effects on healthy tissues, the need for numerous injections, and a high rate of reticuloendothelial system clearance [155]. Researchers have been employing various strategies, such as limited and continuous postsurgical medication delivery, to reduce the undesirable side effects on healthy tissues, enhance effectiveness, and extend the duration of action. Electrospun nanofiber scaffolds in anticancer drug formulations can mitigate these drawbacks and be easily incorporated into solid tumor sites [156]. The application of electrospun membranes in cancer treatment is bolstered by their role as carriers, facilitating local and targeted delivery of medications, proteins, nucleic acids, and cells. These membranes offer significant advantages, including the ability to deliver a high and customized dose to tumor sites, minimal adverse effects on adjacent tissues, and effective regulation of drug release, making them primarily suitable for implantation [157]. By administering small amounts of the medication, this approach not only provides a high local dose but also decreases the frequency of doses, making patients more comfortable and fostering a successful recovery [22].

3.5. Biosensors

Electrospun nanofibers can be employed as functional components of sensors or as substrate materials in biosensors. The sensitivity and detection limit of the sensors can be enhanced by using electrospun nanofibers as the fundamental material due to their large surface area, which improves biomolecule adsorption. Additionally, the pore structure of the electrospun nanofibers facilitates the transport and transfer of biomolecules, thereby enhancing the stability and reaction time of the sensors. Furthermore, electrospun nanofibers can serve as functional elements such as fixed biomolecule transporters and fixed biometric molecule substrates. Immobilizing biomolecules or biometric molecules can achieve a highly sensitive and selective detection of various biomolecules onto electrospun nanofibers [158].

4. Conclusion

This review summarizes the principle of the electrospinning technique as an efficient method to produce fine nanofiber materials. Many parameters impact the physiochemical properties of electrospun micro or nanofibers, including polymer solutions, electrospinning processing variables, and electrospinning environmental parameters. Thus, all the parameters must be adjusted to obtain ideal nanofibers. Electrospun nanofibers can be produced from natural/synthetic polymers or by blending these polymers to improve the required properties for specific applications or to facilitate an electrospinning process. Nanofibers could be applied in many fields, including biomedical applications, electronics, acoustics, composites, filters, skincare and cosmetics, functional textiles, functional apparel, and electronics. Finally, for sustainability and due to ongoing environmental issues, there is more attention on the use of eco-friendly biomaterials derived from natural polymers.

5. Conflicts of interest

There are no conflicts to declare.

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