

Review

Challenges Associated with the Production of Nanofibers

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Abstract: Nanofibers, with their high surface area-to-volume ratio and unique physical properties, hold significant promise for a wide range of applications, including medical devices, filtration systems, packaging, electronics, and advanced textiles. However, their development and commercialization are hindered by several key challenges and hazards. The main issues are production cost and yield, high voltage, clogging, and toxic materials driven by complex production techniques, which limit their adoption. Additionally, there are environmental and health concerns associated with nanofiber production and disposal, necessitating the development of safer and more sustainable processes and materials. Addressing these challenges requires continued innovation in materials science and industrial practices, as well as a concerted effort to balance production, material, and surrounding condition parameters. This study emphasizes the challenges and hazards associated with nanofiber materials and their production techniques, including electrospinning, centrifugal spinning, solution blow spinning, electro-blown spinning, wet spinning, and melt spinning. It also emphasizes biopolymers and recycling as sustainable and eco-friendly practices to avoid harming the environment and human beings.

Keywords: polymer; electrospinning; technique; nanofibers



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1. Introduction

Nanofibers have gained significant attention due to their large surface area-to-volume ratio, small diameter, and flexibility, making them suitable for various applications in fields such as healthcare, filtration, packaging, electronics, and textiles. Nanofibers are fibers with diameters in the nanometer range, and typically, fiber diameters < 100 nm are most commonly used in various applications [1–3]. It is estimated that by 2031, the global nanofiber industry will grow from USD 9873.9 million to USD 53,543.79 million, which is an increase of about 542%. It is estimated that the market will be dominated by polymers and composites [4].

Nanofiber production has some challenges, including achieving uniformity and consistency in nanofiber properties, scaling up production, and managing the high costs associated with production processes and materials. Furthermore, because of their small size, they pose potential risks to human and animal health, hence the need to adopt environmentally friendly biopolymer materials. Toxic volatile organic solvents are used to dissolve polymer materials. Conventional polymers are not biodegradable and biocompatible, and as such, limit their usage in health applications. Nanofiber biopolymers are derived from renewable sources, such as microorganisms, plants, and animals, and offer a sustainable and environmentally friendly alternative to traditional synthetic fibers [1,2].

The production of nanofibers is largely influenced by polymer types and production methods [4]. Various techniques are employed to produce nanofibers, including electrospinning, centrifugal spinning, solution blow spinning, electro-blown spinning, wet spinning, and melt spinning, each presenting its own set of challenges and hazards related to production costs, processes, and material characteristics. Electrospinning specifically uses electrostatic forces to elongate polymer jets from a conductive polymer solution,

thereby forming nanofibers, whereas the non-electrospinning techniques rely on different mechanisms that do not involve electrical force [1,3,5]. Despite progress in alternative nanofiber production techniques, electrospinning remains widely used. This is attributed to challenges in production, such as the cost and complexity of the process, as well as the quality of the resulting nanofibers.

Nanofiber production and the quality of fibers are mainly affected by the polymer concentration, polymer weight, viscosity, solvent, feeding rate, distance between the nozzle and collector, and surrounding conditions. In addition, depending on the production technique used, the solvent, voltage, and air pressure influence the production and quality of nanofibers [6]. The parameters are managed together to enhance both the production and quality of the nanofibers. For example, increasing the voltage can generate heat, which will increase the evaporation of the solvents, resulting in the solvent solidifying quickly at the nozzle tip and clogging it. Decreasing the distance between the collector and nozzle to increase production would result in coarse fibers, as the distance would be too small for the jets to be stretched to reduce their diameter [6–8].

One of the key challenges in the field of nanofibers lies in the materials used. Conventional polymers and solvents are not biodegradable, leading to the rise of biopolymers and eco-friendly solvents as alternative sources of sustainable, environmentally friendly, and biodegradable materials. However, these alternatives come with their own set of challenges, as the extraction and processing of biopolymers are complex. Additionally, biopolymers are prone to heat damage at elevated temperatures [1–3,6,9,10]. Polycaprolactone has a relatively low melting point of around 58 °C [11,12], while polylactic acid melts at 175 °C [13], and polyglycolic acid has a higher melting point of 228 °C [14]. Recycling nanofibers offers a potential solution to sustainability and environmental challenges [15]. The manufacturing and application of nanofibers pose human health and environmental hazards, largely due to the use of high-voltage and toxic solvents [16]. Using high voltage to spin polymer solutions presents a safety hazard due to the potential for electrocution [5,17]. Additionally, toxic solvents and nanofibers have been linked to health issues in animals [1,16].

2. Nanofiber Production

2.1. Electrospinning

The electrospinning technique is widely used because of its simplicity, versatility, cost-effectiveness, and ability to use a variety of materials and produce a variety of nanofiber structures. A basic electrospinning setup typically includes a high-voltage source to charge the extruded polymer solution, a collecting plate to gather the nanofibers, a syringe with a pump to pump the polymer solution, and a polymer solution, as illustrated in Figure 1. It employs electrostatic force from high voltage to charge the polymer jets. The charges repel each other and are attracted to the collector. This causes the polymer jet to elongate in a cone Taylor form. Simultaneously the volatile solvent evaporates, causing the elongated fine jets to solidify to form fine nanofibers [1,7,18–21].

Electrospinning encounters various difficulties, including the need for high voltage, issues with needle tip clogging, and restricted control over the alignment, orientation, and structure of the fibers. Additionally, only charged polymer solutions are suitable for this technique [20]. Using polymer solutions with low electrical conductivity can lead to charge accumulation on their surface, causing jet instability and breakage, which, in turn, impacts the quality of the resulting nanofibers [17]. The production of nanofibers through electrospinning remains impractical for large-scale industrial applications due to its low yield [15]. To improve production yields, multiple needles were employed; however, this brought about new challenges. The use of multiple needles can lead to interactions between polymer jets caused by uneven electric field distributions, which may compromise the quality of nanofibers. Additionally, more space is required to house the larger equipment. To overcome the issue of needle clogging, needleless electrospinning has been investigated [3–5,20,22]. Fibers produced using this technique have better alignment, resulting in improved mechanical properties, comparable to those of conventional

fibers [4]. Unconventional needleless electrospinning techniques have production rates of 0.5 to 600 g/h, which are significantly higher compared to the 0.01 to 0.1 g/h typical of conventional single-needle electrospinning [20,22]. For example, the double-ring slit needleless spinneret replaces the needle with a 35 mm diameter slit. The larger area in which the solution is ejected has production rates of 0.1 to 2.25 g/h. Another approach, coil-based electrospinning, uses submerged wire coils to better distribute the electrical field, achieving production rates of 2.94 to 8.1 g/h. However, the curvature in the coils can cause uneven electric field distribution, affecting fiber quality [20].

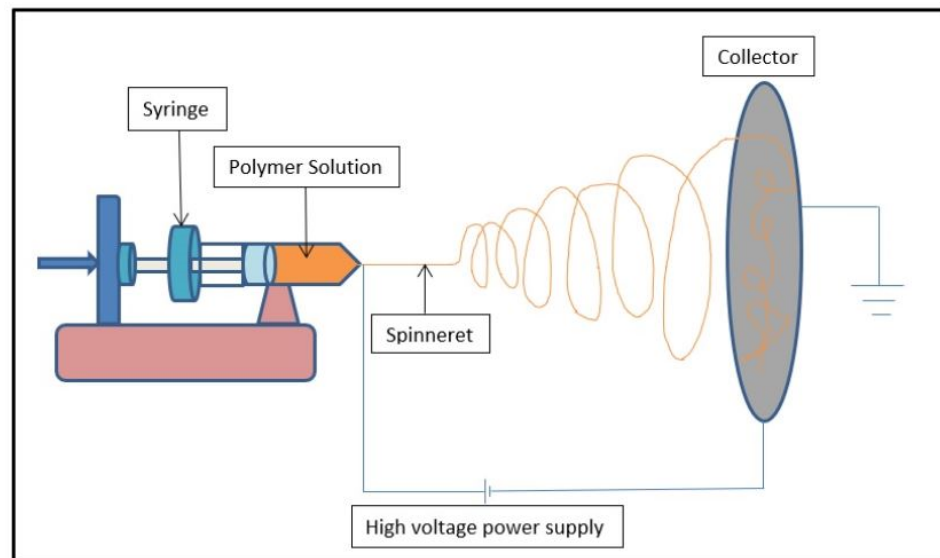


Figure 1. Basic electrospinning setup [3].

Rotary electrospinning is needleless electrospinning; the rotating cylinder with a spinneret is partially immersed in a polymer solution. The polymer jets on the large surface of the cylinder are charged and stretched to form the nanofibers. Because of the large surface area of the cylinder, the production yield is higher with good-quality nanofibers [22]. In a rotary cone electrospinning, a rotating cone with holes is fed with the polymer solution. The charged polymer jets from the rotating accumulate enough charges and are stretched to form the fibers. Despite having production rates in the range of 30.95 g/h to 600 g/h, the cone's shape causes uneven charge distribution, leading to mixed fiber quality [20,23,24]. Foam-based electrospinning uses compressed gas to create bubbles in the polymer solution, enhancing polymer jet formation under an electric field, with a production rate of 9 g/h [20].

Collectorless electrospinning is being investigated to produce nanofiber yarns. In this procedure, there is no collector; rather, fibers from two needles with opposite charges combine to create nanofiber threads when the take-up roller rotates [4].

2.2. Centrifugal Spinning

To compensate for the limitations such as high electric voltage and conductive solution, less expensive centrifugal spinning is suggested. Centrifugal spinning uses centrifugal force to rotate the polymer solution at high speeds, as shown in Figure 2. The high-speed rotations cause the polymer solution to be expelled at high speeds and elongated. At the same time, the solvent evaporates, causing the elongated polymer jet to solidify, and the fibers are gathered by the collector. The fibers created with this technique are coarser than those made using electrospinning. To increase production, multiple nozzles can be employed, while airflow can be utilized to decrease fiber diameter [6,25,26].

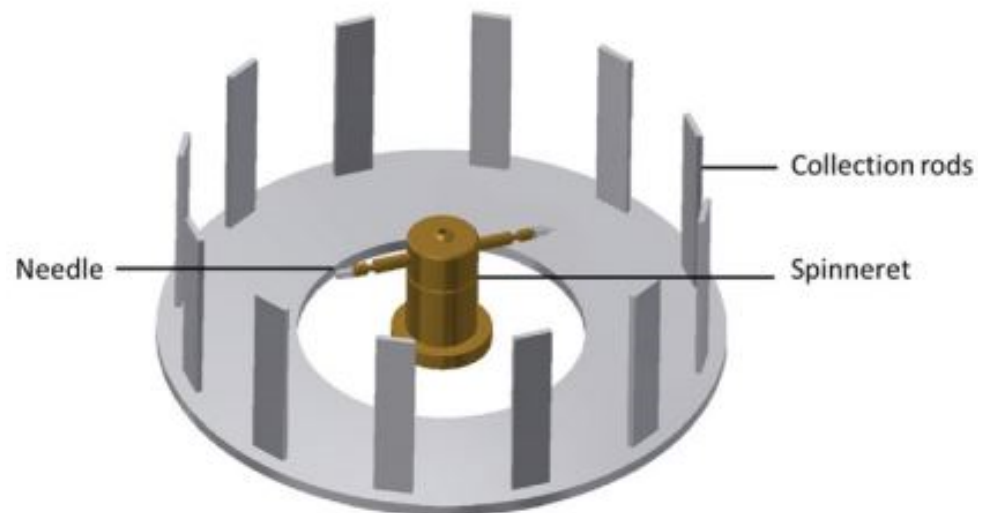


Figure 2. Basic setup of centrifugal spinning [6].

Centrifugal spinning, like other nanofiber spinning production techniques, is affected by the viscosity, solvent, and distance between the nozzle tip and collector, which can cause nonuniformity in the nanofiber structure [6]. The main challenge of the centrifugal is the instability of the jet solution, which causes the jet to break, especially at higher speeds, resulting in the quality of the nanofibers being affected [25,27]. Initially, the technique was associated with coarse fiber in the range of 1 to 1000 nm; however, with further advances, the diameter was reduced to 45 nm [28]. Pen and Lin produced soda lignin nanocarbon fibers using the centrifugal spinning technique, indicating that their diameter of 472 nm was comparable to that of electrospun fibers [29]. The production of the centrifugal spinning technique is reported to be significantly higher than conventional electrospinning [27]. A production rate of 50–60 g/h was reported in a published study on the centrifugal spinning technique [30].

To address the challenges of electrospinning and centrifugal techniques, electrocentrifugal spinning is being investigated. It incorporates the principles of both the electrospinning and centrifugal techniques. The main factor initiating the formation of the spinning jet is centrifugal force, with the electrostatic field playing a crucial role in improving the uniformity of the fibers. An ethyl cellulose fibrous membrane incorporated with antimicrobials was produced using this technique [27,31].

2.3. Solution Blow Spinning

This technique produces nanofibers by blowing pressurized air jets into the polymer solution. It is considered inexpensive and simpler to use, with better production capacity than the electrospinning technique, as it does not require the use of high voltage. Using this technique, Penconek et al. produced nanofibers from soy protein isolate–polyethylene oxide using water as a natural source solvent that does not pose health and environmental hazards [32]. A basic setup consists of a syringe with a solution, gas compressor, and collector. The pressurized gas is released at a high speed to eject the dissolved polymer solution. The solution jet is stretched and becomes thinner. When the solvent evaporates, the jet solidifies to form a nanofiber collected on the collector, as seen in Figure 3. The diameter of the fibers decreases with the increasing air pressure. Production in the range of 3.6–50 g/h has been reported [33–35].

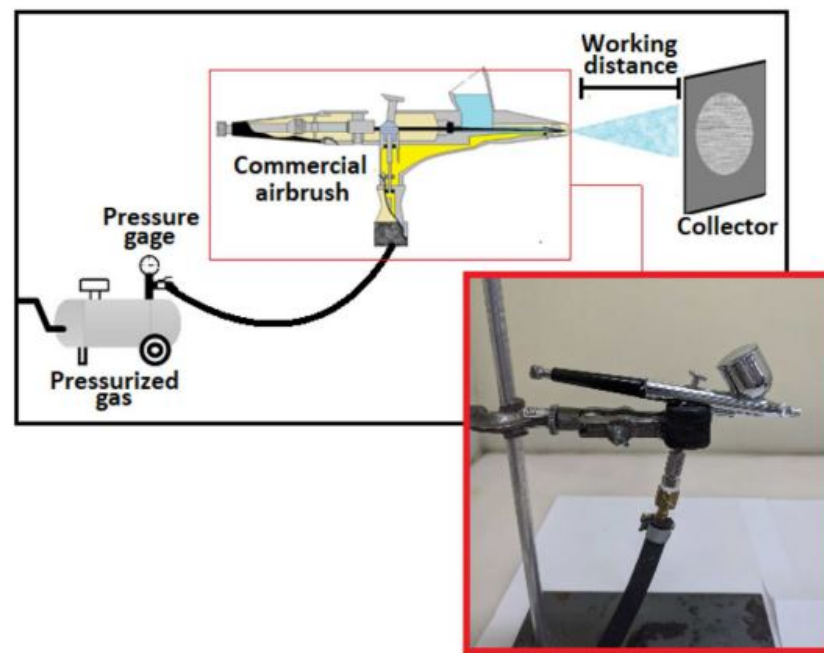


Figure 3. Basic setup of a solution blow spinning [33].

2.4. Electro-Blown Spinning

This technique is a derivative of needle electrospinning and is also being investigated in relation to the efficiency of conventional electrospinning, as seen in Figure 4. It uses both the electrical field and pressurized air to enhance the elongation of polymer jets. The combination produces finer nanofibers. Unlike conventional electrospun techniques, its feed rate can be increased to achieve higher production yields [1,36].

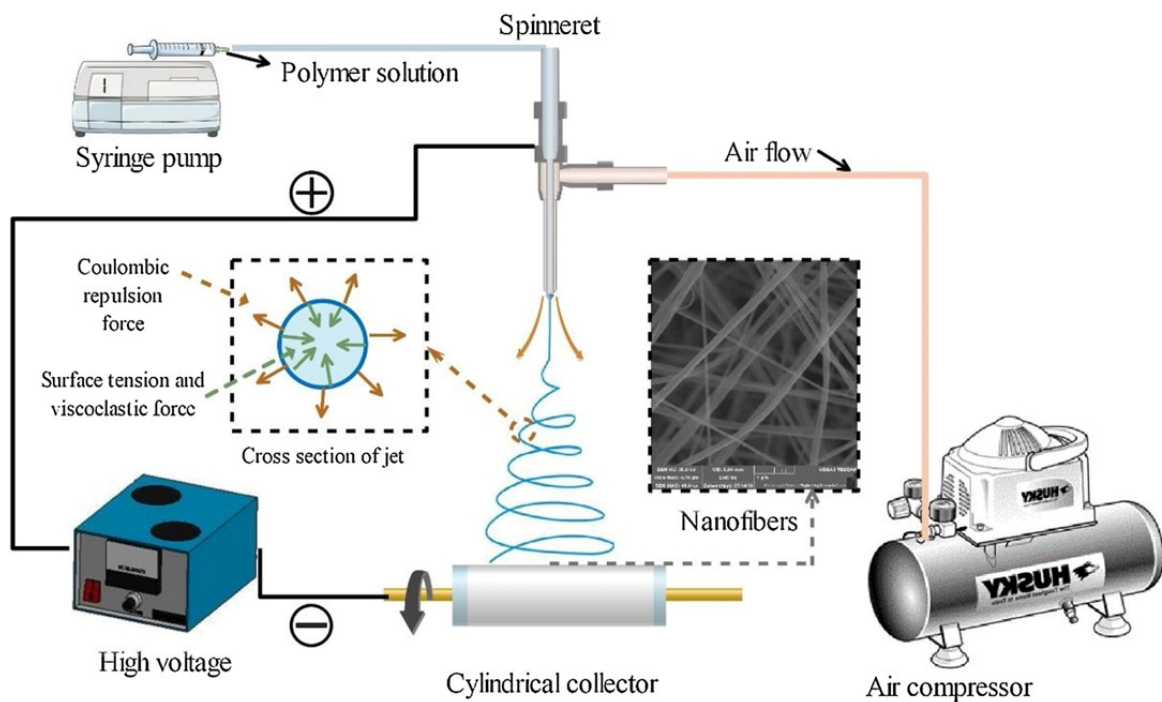


Figure 4. Electro-blown spinning setup [36].

2.5. Wet Spinning

The wet spinning technique for producing nanofibers operates on the same principle as conventional wet fiber spinning, which is used to create synthetic fibers in a coagulation bath containing a nonsolvent liquid. In this process, a polymer solution is introduced into the coagulation bath, where it is stretched and solidified into coarse nanofibers, as seen in Figure 5 [21,37,38]. Fibers are washed in the second bath to remove the remaining solvents [39]. Wet electrospinning, which is an adaptation of wet spinning and electrospinning, involves applying electrical force to polymer jets from a needle tip, which is then stretched and deposited into the coagulation bath. Wet spinning has a low production yield, and the fibers are cleaned to remove the nonsolvent from the coagulation [21,40]. Wet spinning produces nanofibers with a larger surface area and better porosity than those produced through conventional electrospinning. Using wet spinning, Abe and Utsumi [41] successfully produced cellulosic nanofibers from wood with diameters of 12–20 nm, and Huang et al. prepared an electrically conductive poly(3,4-ethylenedioxythiophene)-polystyrene sulfonate-2,2,6,6-tetramethylpiperidine-1-oxyl-oxidized cellulose nanofiber composite [42].

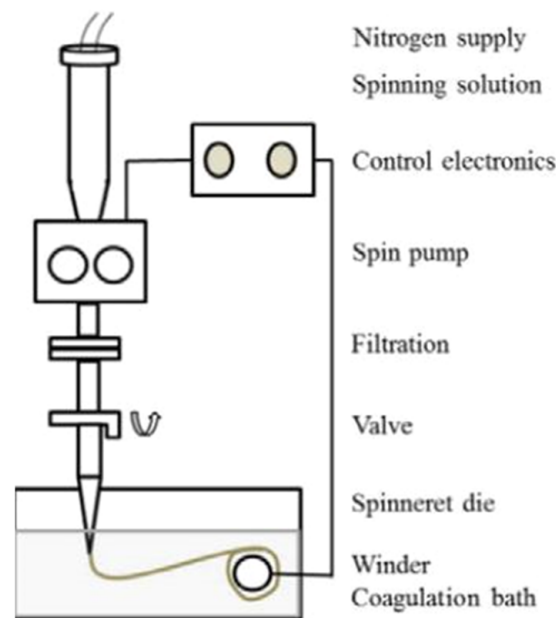


Figure 5. Wet spinning basic setup [43].

2.6. Melt Spinning

Melt spinning is divided into melt electrospinning and melt centrifugal spinning [28]. Melt electrospinning uses a combination of heat and an electrical field to stretch the melted polymer, which solidifies and is collected by the collector, as seen in Figure 6. The fact that it does not require the use of solvents makes it a good alternative, considering that some of the solvents, like chloroform and methylene chloride, are hazardous to human beings and the environment. The removal of these toxic solvents increases the cost, which can limit the adoption of some of the nanofiber production techniques for mass production. Melt electrospinning advantages include high productivity, no solvents, and the use of thermoplastic polymers. The disadvantages include high temperature, difficulty removing electrostatic charge, low electrical conductivity, high viscosity, whipping instability, and fast curing [5,28]. To avoid the use of high voltage and solvents that pose health and safety risks, Zhang et al. used magnetic fields to stretch to produce coarse nanofibers with a diameter of 900 nm [17]. Melt centrifugal spinning is also being investigated. It combines melt and centrifugal spinning and avoids the use of high voltage and solvents. The melted polymer is ejected under the centrifugal force and stretched to form the nanofibers [28].

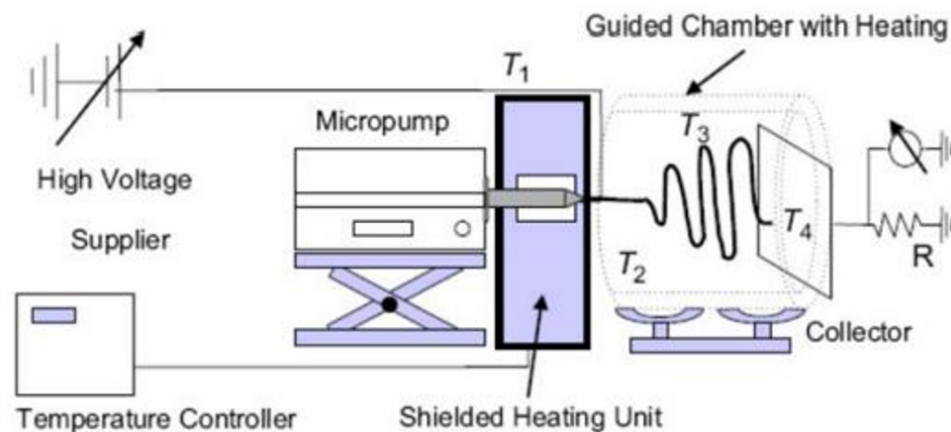


Figure 6. Melt electrospinning basic setup [26].

3. Parameter Challenges

In order to produce nanofibers of high quality, the solution, equipment, and ambient parameters indicated in Tables 1 and 2 are managed together to optimize the production yields and quality of the nanofibers. Changing one parameter affects the entire system and thus the optimal production yields and quality of the nanofibers [1,8,21]. In electrospinning, using a low voltage will result in the polymer jet not having enough electrical charge to be stretched, thus affecting the diameter of the nanofibers [3,17]. Extracting high concentrations of nanofiber materials from renewable natural resources is complex and often requires that temperature, time, and pH be controlled [9]. Excessively high voltage can damage equipment and affect nanofiber quality, but electrospinning is preferred for producing finer fibers without beads, as beads alter nanofiber morphology and diameter. However, this is dependent on the voltage applied to the polymer jet [20]. Cellulosic and protein polymers, such as chitosan and collagen, are degraded at high temperatures and cannot be spun into nanofibers using other nanofiber production techniques but can be spun using wet spinning [21,44]. Polyamide 4, which has a melting temperature of 265 °C, rapidly degrades when exposed to temperatures above its melting point, which limits its ability to be spun into nanofibers. Its melting temperature can be lowered by modifying its chemical structure. Alternatively, electrospinning can be used as reported by Reinsteinova et al. to produce environmentally friendly polyamide 4 nanofibers with diameters in the range of 270 nm to 350 nm [45].

Using polymers with low electrical conductivity can result in charge rejection on their surfaces, resulting in jet breakage and affecting the quality of the nanofibers [17]. Increasing the flow rate and distance between the collector and needle tip to increase the production yields causes problems. A high flow rate and a shorter distance result in the solvent not having enough time to evaporate. Another challenge when working with different polymer materials and solvents is that the new blended solution will have a different viscosity. Adding a new solvent to reduce the viscosity of the blended polymer solution can cause the original solvents to separate. When tetrahydrofuran was added to the polydimethylsiloxane–polymethyl methacrylate polymer solution, the solvents separated. Electrospinning the polydimethylsiloxane polymer is challenging because of its short polymer chain, and to compensate for this, it is spun with polymers with longer chains. The polydimethylsiloxane polymer has an extremely low viscosity, making it difficult to generate polymer jets that do not break [3].

Lu et al. reported that as the concentration of polyacrylonitrile (PAN) polymer solution increased, both its viscosity and surface tension also increased. However, the rise in surface tension was relatively minor compared to the significant increase in viscosity. This suggests that controlling viscosity is more crucial, as it plays a larger role in the nanofiber formation [30]. Quan et al. reported that increasing the PAN solution concentration increased the fiber diameter from 404.5 nm to 1154.8 nm. Similarly increasing the solution

concentration, the PAN nanofiber membrane strength increased from 13 cN to 21 cN, and the thickness increased from 18 μm to 26 μm [23]. By adjusting the concentrations of polymers, it is possible to produce nanofibers of consistent fineness regardless of their molecular weight. A low concentration of a high-molecular-weight polymer solution and a high concentration of a low-molecular-weight polymer solution can both yield fibers with the same fineness [8].

The inadequate orientation and crystallinity of polymer molecules result in the poor mechanical strength of nanofibers (mat), which impacts the overall mechanical properties, including strength and durability. Nanofiber mechanical strength can be enhanced by applying heat and elongation. When subjected to heat and elongation, polymer chain orientation and crystallinity improve. Conventional electrospinning nanofiber production does not subject the fibers to heat treatment, hence the poor mechanical properties of the mat. Heat treatment has the additional benefit of evaporating the remaining volatile solvent residue, thereby improving the nanofibers' quality [4,8]. When phosphorus-containing polylactic acid (PPLA) nanofibers were subjected to post-heat treatment, their strength improved, which was better than that of non-post-heat treated PLLA microfibers. Similar observations were reported when PAN was further subjected to post-heat treatment compared to PAN not subjected to heat [4]. Zhang et al. enhanced the crystallinity of nanocarbon fibers by treating them with nanoscale flake graphite and boron nitride, resulting in improved mechanical properties [46]. Elastic materials are produced using polymers such as polyurethane, styrene-butadiene-styrene (SBS), styrene-isoprene-styrene (SIS), and styrene-ethylene-butylene-styrene (SEBS). In applications like sports, these materials must elongate and return to their original shape without sacrificing the wearer's comfort [4].

Table 1. Factors that influence nanofiber spinning [6–8,21,30,47].

Parameters	Fiber Formation
Polymer concentration	Low concentrations promote the formation of beads, whereas excessively high concentrations lead to the formation of coarse fibers or discontinuous fibers.
Polymer weight	Viscosity, conductivity, and surface tension are affected. A polymer with a high molecular weight has a high viscosity, leading to the production of fibers with larger diameters than those with low molecular weights.
Solution viscosity	Viscosity is affected by the solvent used and the polymer concentration. A jet easily breaks up a solution with low viscosity, leading to the formation of beads. Excessive low viscosity leads to no nanofiber formation due to a lack of polymer chain entanglement. When the viscosity is excessively high, coarse fibers are formed.
Surface tension	High surface tension causes the jet to break, which can lead to the formation of beads when the liquid jets form spherical droplets when the surface tension is not sufficiently overcome. It is adjusted by the solvent. Centrifugal speed is also used to overcome surface tension.
Solution conductivity	A polymer with high conductivity promotes the formation of finer nanofibers, whereas a lower conductivity will promote bead formation.
Solvent	Solvents influence the surface tension, viscosity, and solution conductivity. Volatile solvents that do not dry quickly or take longer to evaporate affect the quality of nanofibers.
Voltage	The voltage is easier to manage to control the intensity of the electrostatic field between the collector and needle. Increasing the voltage to the critical level decreases the nanofiber diameter. Excessive voltage can cause the formation of beads. It does not affect wet spinning, centrifugal spinning, or solution blow spinning.
Feed rate	Increasing the feeding rate increases the fiber diameter.
Air pressure	Increasing the feeding rate decreases the fiber diameter.
Collector	For the electrospinning, the collector must have good conductivity to remove the charges from the plate. Accumulated charges repel the incoming fibers.
Distance between nozzle and collector	Short distances produce coarse fibers as the distance is too small for the solvent to evaporate and for the jet to be stretched to reduce its diameter.
Surrounding conditions	A moderately high temperature at low humidity decreases the viscosity and increases solvent evaporation, leading to the formation of finer fibers. High humidity leads to the formation of coarse fibers.
Rotational speed	High rotational speeds cause vibrations, which cause the jets to break. Rotational speed can be used to overcome surface tension.

Table 2. Advantages and disadvantages of the nanofiber production techniques [1,17,22,28,48].

Technique	Advantages	Disadvantages
Electrospinning	<ul style="list-style-type: none"> • Fine nanofiber formation • Cost-effective and simple to operate • Small to large production yield of 0.01–600 g/h 	<ul style="list-style-type: none"> • Risk of electrocution due to high voltage • Limited to conductive polymers • The solvent must be recovered • Nozzle clogging
Electro-blown spinning	<ul style="list-style-type: none"> • Fine and uniform nanofibers formation • Create a stable solution jet • Suitable for highly viscous polymers • Good production yield of 5–9 g/h 	<ul style="list-style-type: none"> • Risk of electrocution due to high voltage • Limited to conductive polymers • The solvent must be recovered • Nozzle clogging • Controlling air pressure and voltage parameters simultaneously • Increasing the air pressure too high, increases the nanofiber diameter
Solution blow spinning	<ul style="list-style-type: none"> • No risk of high voltage • Wide range of polymer materials used • Good production yield of 3.6–50 g/h 	<ul style="list-style-type: none"> • The solvent must be recovered • Uneven distribution of nanofibers • Easy folding and bending of nanofibers • Polymer jet instability • Formation of bundles at high airflow speed • Nozzle clogging • Medium-fine to coarse nanofibers
Centrifugal spinning	<ul style="list-style-type: none"> • No risk of high voltage • Good production yield of 3.6–124.3 g/h • Cost-effective 	<ul style="list-style-type: none"> • The solvent must be recovered • Fiber instability • Coarse fibers
Wet spinning	<ul style="list-style-type: none"> • No risk of high voltage • Low production yield 	<ul style="list-style-type: none"> • The solvent must be recovered • Coarse nanofibers
Melt electrospinning	<ul style="list-style-type: none"> • No solvents required • Large production yield of 0.9–5.1 kg/h • Cost-effective 	<ul style="list-style-type: none"> • Risk of electrocution due to high voltage • Limited to conductive and thermoplastic polymers • High temperatures used • Fiber instability • Coarse nanofibers

3.1. Clogging

Clogging of the nozzle affects the quality of the nanofiber and disrupts continuous fiber production, necessitating cleaning whenever the blockages occur [31]. This problem is associated with the use of high-volatility solvents, the application of electrical fields, and the electrospinning distance. The application of electrical fields generates Joule heating, and when voltage is increased, more heat will be generated, which increases evaporation and changes the solution's viscosity, causing it to solidify and clog the tip. Similarly, increasing the spinning distance decreases the electrical field strength, which, in turn, decreases the electrical density of the polymer solution, causing it to solidify and clog the spinneret tip. The volatility of the solvent also affects clogging. Highly volatile solvents evaporate rapidly, causing the droplet jet to solidify and clog the spinneret [49,50]. Kanjanapongkul et al. reported introducing additional solvent to the polymer solution at the spinneret tip cap to prevent clogging [49]. In a comparable approach, Li et al. used a sponge soaked in ethanol to cover the spinneret tip, which prevented ethanol evaporation at the tip and thereby avoided blockage [50].

3.2. Nanofiber Materials

The use of toxic solvents and non-biodegradable materials from non-renewable sources is a risk to the environment, animals, and human beings [33]. Conventional polymers used for producing nanofibers are derived from non-renewable fossil fuels because they are cost-effective and thermally and mechanically stable, which allows for their large-scale industrial production. However, these benefits are accompanied by environmental pollution and sustainability issues [9,34,51]. Producing nanofibers from renewable natural resources is complex and often requires that temperature, time, and pH be controlled. Time influences the amount of nanofiber that can be produced from raw materials [9].

The use of biodegradable polymers and solvents is increasingly being investigated to address environmental and health hazards posed by conventional materials [2,33,52]. Nanomaterials are extracted from plants and animals using solvents and lengthy produc-

tion processes [34,44]. Recovered nanofiber materials are cleaned to remove the remaining volatile solvents that pose a health hazard to humans [34]. Measures are also put in place to recover the evaporated solvents that also pose a hazard to humans and the environment [34].

Natural nanofiber materials are good alternatives to conventional nanofibers because they are biocompatible and biodegradable; however, they are affected by extreme pH and temperatures [53,54]. They are mixed with other compounds or conventional polymers to improve their stability [34]. It must be noted that synthetic biobased nanofibers, such as polylactic acid, polyglycolic acid, and polycaprolactone, are also increasingly being used in biomedical applications due to their biocompatibility and biodegradability. Their degradation occurs via hydrolytic or enzymatic processes. Due to its hydrophobic nature, polycaprolactone degrades more slowly through hydrolysis compared to polylactic acid and polyglycolic acid. Additionally, polycaprolactone has a low melting point temperature and reduced tensile strength. To enhance both its degradation rate and tensile strength, it is often blended with nanofibers like polylactic acid [11,12,55,56].

Polysaccharides (starch, chitosan, cellulose, pectin) are the most abundant source of fiber materials that can be investigated to produce biodegradable and biocompatible nanofibers. They can tolerate higher temperatures than proteins. The solubility of polysaccharides is still a challenge, as they do not dissolve easily, which necessitates the use of chemicals that are not environmentally friendly [34]. The crystalline structure of the polysaccharides makes it difficult to spin; therefore, higher temperatures and other substances such as polyethylene glycol, and dimethyl sulfoxide (DMSO) are added to improve spinnability [34,57]. The lignocellulose treatment temperature for nanofiber production is around 200 °C, and if a thermoplastic material is to be blended with it to produce a composite material, the thermoplastic material must have a melting point below 200 °C [58]. Electrospinning starch is challenging because of its high molecular weight and crystalline structure. To overcome these difficulties, researchers investigated using solvents like DMSO–water solutions, which led to enhanced fiber stability [57,59]. The cellulose acetate membrane exhibits hydrophilicity, limiting its use in food applications. However, when mixed with hydrophobic chitosan, the hydrophobicity of the cellulose acetate is enhanced. The challenge of jet breakup when using a starch solution is addressed by lowering the starch concentration. Alginate has high viscosity at low concentrations and is mixed with polyethylene oxide to prevent needle clogging. Polylactic acid is mixed with polydioxanone to lower its bending resistance. In dry conditions, 3D structures printed from nanocellulose fibers are inflexible, making them unsuitable for applications that require rigidity. Calcium chloride (CaCl₂) is used to make these structures more flexible and elastic [34]. Bora et al. utilized a modified cellulose nanofiber–zinc oxide hydrogel membrane to remove copper and iron. The maximum removal of copper and iron was influenced by time, temperature, pH, and adsorbent concentration [60]. Polyester is incorporated with acetylated cellulose nanofibers to increase the tensile strength of the polyester membrane [61]. When pre-polylactic acid was reacted with ethyl phosphoryldichloride, it was imparted with flame retardancy [62].

Protein nanofibers have also received interest as a source of bio-nanofibers. Whey protein isolate, soy protein isolate, gelatin, and collagen are some of the proteins that can be spun into nanofibers [63,64]. Processing them is a challenge, as they are more sensitive to temperature and pH conditions. Soybean protein nanofiber mixed with sodium alginate and CaCl₂ produce nanofiber membranes that can function at different pH values [54]. Ali et al. mixed the polysaccharide pullulan with whey protein isolate to produce a composite material with improved hydrophobicity [63]. A nisin/cellulose nanofiber/protein biocomposite antibacterial coating was able to prevent microbial growth in tomatoes [65].

4. Hazards

The use of high voltage, toxic solvents, and toxic nanofibers is hazardous to humans and the environment [51]. Using nanofiber production techniques that require the

use of high voltages poses a safety hazard as the operator can be electrocuted [5]. Non-electrospinning techniques like solution blow spinning and wet spinning are alternatives that avoid the use of high voltage [5,21]. The use of toxic solvents like chloroform, tetrahydrofuran, dichloromethane, and hexane in dissolving polymer materials also presents a health risk as these solvents are considered carcinogenic, necessitating their recovery and thorough cleaning of nanofibers that may come into contact with humans. The recovery of these solvents involves complex processes. Eco-friendly alternatives like dimethyl carbonate and ethanol are currently being investigated [1,28,51,66].

Furthermore, the use of non-biodegradable nanofiber materials poses significant environmental and health hazards [67]. Carbon nanotubes, for example, are toxic to lung cells and can contaminate water sources, potentially being ingested by aquatic animals [68]. Nanocellulose blended with citric acid and polyethylenimine has shown toxicity to sea urchin embryos [16], while polyaniline nanofibers negatively affected the growth of *Rhinella arenarum* embryos [69]. Although Chaika et al. reported that carbon nanofibers in the stomachs of aquatic insects caused no harm [70], other studies indicate that these nanofibers can impact the livers and brains of turtles [71] and cause body mass loss and cellular stress in earthworms [72] due to carbon nanofiber exposure. Polyester nanofibers induced apoptosis in zebrafish [67], whereas nanofiber silicon carbide was found to be toxic to bacteria [73].

5. Recycling

The recycling of nanofiber materials is being investigated to address the environmental pollution issues associated with conventional nanofibers, as they are not biodegradable. Using the solution blow spinning technique, Mogharbel et al. created a color-changing membrane by incorporating strontium aluminate (SrAl_2O_4) nanoparticles into recycled polycarbonate (PC) nanofibers. The transparent membrane, which was stable in chemicals and heat, changes its color to green when exposed to UV light [15]. Nicolau et al. also used recycled PC using the solution blow spinning technique, producing nanofibers with an average diameter of 28 nm. They reported that recycled PC at lower concentrations of 5 g/L and 10 g/L were not ideal for nanofiber production, whereas 15 g/L was ideal for nanofiber production [33]. In cementitious materials produced from recycled fine aggregates, incorporating polyvinylidene fluoride nanofibers improved compressive and flexural strength [74]. Ran et al. created a recyclable fluorescent carboxylated polyarylene ether nitrile nanofiber membrane that can detect and adsorb chromium. The membrane was treated with ethanol to regenerate it, and its fluorescence intensity did not significantly decrease [75]. Incorporating nanocellulose into recycled and pure PA increased the elastic modulus, whereas a decrease in tensile strength was observed [58]. The use of recycled materials shows that non-biodegradable nanomaterials can be used for other applications to reduce their environmental and health hazards.

6. Conclusions

The development of nanofibers marks a significant milestone in materials and production technologies. The production of nanofibers is complex and requires the careful management of the different production, solution, and surrounding parameters, which is essential to maximizing production and producing better-quality fibers. Several challenges and hazards remain before their unique properties can be fully leveraged in diverse applications. The primary obstacles include ensuring the quality of the nanofibers, achieving scalability, developing cost-effective production practices, the clogging of nozzles, and the use of toxic solvents, toxic nanofibers, and high voltage. Parameters are managed carefully to address these challenges and hazards. Using biodegradable materials and recycling materials is also part of mitigating the environmental and safety hazards associated with nanofiber production and utilization.

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