Advances in Spinning Techniques for High-Performance PAN-Based Carbon Fibers

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Abstract

Polyacrylonitrile (PAN) fibers are essential precursors for high-performance carbon fibers, recognised for their significant carbon yield and mechanical strength. This review investigates the spinning methods of PAN fibers, focusing on wet spinning and dry-jet wet spinning, while utilising recent research to analyse their mechanisms, chemical characteristics, and results. Wet spinning facilitates controlled coagulation, producing fibers with minimal defects, whereas dry-jet wet spinning improves molecular alignment by introducing an air gap. Essential factors like polymer molecular weight, solvent selection, and coagulation bath composition significantly impact fiber characteristics. Developments such as adding various additives and electrochemical modifications enhance tensile strength and sustainability. Ongoing issues, including solvent recovery and process scalability, remain, with future efforts to incorporate eco-friendly solvents and advanced composite materials. This review consolidates insights to emphasise the best spinning conditions and new trends for producing high-performance PAN fibers.

Keywords

Polyacrylonitrile, Carbon fiber, Spinning techniques

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1.0 Introduction:

Polyacrylonitrile (PAN), a synthetic polymer mainly made up of acrylonitrile units, is the leading choice for carbon fiber precursors because of its high carbon yield (around 68%), exceptional mechanical characteristics, and its capability to develop ordered crystalline structures during production, rendering it essential for high-performance uses in sectors like aerospace, automotive, wind energy, and defence [1,2]. The origins of PAN fibers trace back to the mid-20th century when their potential as precursors for carbon fibers was identified, prompting extensive research into spinning methods to enhance fiber microstructure, tensile strength, and modulus[2]. The spinning techniques convert PAN polymer solutions into fibers via a series of steps, including extrusion, coagulation, drawing, and stabilisation, where the selected spinning method significantly affects the resulting fiber characteristics[3,4]. The primary methods for producing PAN fibers are wet and dry-jet wet spinning, each providing distinct benefits in controlling fiber structure and performance[1], [5]. Wet spinning entails the direct extrusion of a PAN solution into a coagulation bath, enabling a gradual solvent exchange that reduces defects and permits the addition of sustainable substances like lignin or nano-reinforcements such as cellulose nanocrystals(CNCs) [6,7,8]. On the other hand, dry-jet wet spinning features an air gap between the spinneret and the coagulation bath[9], which allows for initial chain alignment that improves molecular orientation and diminishes die swell, resulting in fibers with enhanced tensile properties [10,11,12]. Over the years, research has aimed at optimising essential factors like polymer molecular weight, solvent choices, coagulation bath compositions, and draw ratios to develop fibers suitable for carbon fiber precursors with high performance[13,14,15]. Recent developments have investigated novel techniques, including electrochemical modifications and nanomaterials, to improve fiber quality further and tackle environmental issues[1,16]. This review systematically compiles findings from recent research to offer a detailed understanding of the spinning processes for PAN fibers, their relative advantages, ongoing innovations, challenges, and potential future directions.

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2. PAN Fiber Spinning Techniques

2.1 Wet spinning

Wet spinning is recommended for PAN fiber manufacturing because it allows for forming fibers with a regulated shape, high tensile strength, and suitability as carbon fiber precursors. The technique enables exact manipulation of fiber structure under regulated coagulation conditions, ensuring scalability and consistency for industrial applications. [4,8]The wet spinning process begins by dissolving PAN or its copolymers in a solvent to generate a spinning dope, usually at concentrations of 15-25 wt%[6]. The dope is extruded through a spinneret into a coagulation bath, where the fibers solidify as the solvent evaporates and a non-solvent, often water, diffuses in.[7] The fibers (jet stretch, wet stretch, and hot stretch) are then drawn to improve molecular alignment, washed to remove residual solvent, and dried at 100-150°C to complete the fiber structure. [1,4] Key processing factors include coagulation temperature (20-60°C), bath composition (solvent/non-solvent ratio), dope concentration, draw ratio, and spinneret design, which all have a substantial influence on fiber quality and performance.[8,17]PAN (usually 10–25 weight per cent) is dissolved in a polar organic solvent, like dimethylformamide (DMF) or dimethyl sulfoxide (DMSO), to create a spinning dope. Impurities are then removed by filtration and degassing.[1,6] Rapid phase inversion hardens the filaments when the dope is extruded through a spinneret into a coagulation bath, which frequently contains a solvent-water mixture (e.g., 50–70% DMF)[4,7]. Crucial elements that affect fiber morphology, decreasing voids and increasing tensile strength are bath mix, temperature (20–50°C), and coagulation rate.[8] The fibers undergo multi-stage drawing (draw ratio 4–12) in hot water or steam to align polymer chains, followed by washing to remove residual solvent and drying to stabilise the structure.[17] This sequence ensures high crystallinity and orientation, yielding PAN fibers with tensile strengths of 200–500 MPa, ideal for carbon fiber production.

2.1.1 Raw Material Characteristics

The production of PAN fibers through wet spinning involves specific chemicals for the spinning solution and the coagulation bath, with factors like molecular weight and concentration being essential in defining fiber quality. The core polymer is PAN or PAN copolymers, frequently including comonomers like methyl acrylate or itaconic acid, with a molecular weight ranging from 80,000 to 1,50,000 g/mol to balance strength and processability.[4,17]The dope is made at a concentration of 15-25 wt% in a solvent such as dimethyl sulfoxide (DMSO, MW: 78:13 g/mol) or dimethylacetamide (DMAc), which can effectively dissolve high-molecular-weight PAN.[6,8]To control diffusion speeds and avoid voids, the coagulation bath is commonly made up of water or a solvent-water mixture with solvent concentrations ranging from 10- 70 wt% (for example, DMSO/water ratio of 30:70 to 70:30)[1,7]

2.1.2 Influence of Processing Parameters in Wet Spinning

Wet spinning of PAN fibers showingtensile strengths ranging from 600 MPa to 7 GPa (post-carbonisation) and tensile moduli up to 130 GPa, notably for lignin/PAN blends, depending on the processing optimisation.[1,8] The most significant results are produced with high draw ratio (jet stretch: 1- 2 times, wet stretch: 2- 5times, hot stretch: 5-10times), low coagulation temperatures (20-30°C), and optimum solvent ratios, e.g., 50:50 DMSO/water, which minimise voids and increase molecular alignment. [4,7]For example, studies demonstrate that controlled coagulation and high stretching improve fiber density and mechanical properties, making them ideal for carbon fiber precursors. These optimised conditions lead to fibers with superior tensile strength and modulus, suitable for high-performance applications in aerospace and structural composites[8,17]

2.2 Dry Spinning

Unlike wet spinning, dry spinning does not require a coagulation bath, which reduces void formation and simplifies solvent recovery. It is used for PAN fiber production when the objective is to produce fine fibers with high surface quality and minimal defects, especially for applications requiring enhanced molecular orientation. For textiles and some carbon fiber precursors, dry spinning is beneficial for creating fibers with diameters between 10 and 50 µm. The dry spinning process contains multiple steps: Initially, a spinning dope is made by dissolving PAN in a volatile solvent. The fibers are then solidified by the solvent's quick evaporation in a regulated gas environment, like hot air or nitrogen, after this dope is extruded via a spinneret into a heated spinning chamber. After being drawn to increase molecular alignment, the fibers are gathered on a winder, where they may undergo optional post-treatments like washing or heat treatment to enhance their qualities. Dope temperature (70–100°C), spinneret temperature (150 - 200°C), air or nitrogen flow rate, draw ratio (2–6 times), and dope concentration (20–30 wt%) are important processing parameters that have a significant impact on fiber quality and performance[18].To create a spinning dope for PAN fibers, PAN or its copolymers must first be dissolved in a volatile solvent, like DMSO or DMF, at a concentration of 20–30 weight per cent and at a temperature of 70–100°C to get the ideal viscosity [1]. After passing through a spinneret with 0.1–0.3 mm hole sizes, the dope is extruded into a heated spinning chamber between 150 and 200°C. The fibers are solidified in this chamber by the quick evaporation of solvents made possible by hot air or nitrogen. The fibers are gathered on a winder after being drawn at ratios of 2–6 times to align polymer chains and improve mechanical qualities. It is possible to apply optional post-treatments, such as heat treatment to enhance crystallinity or washing to remove leftover solvent. The procedure necessitates exact control over the dope temperature, spinneret temperature, air flow rate, and draw ratio to avoid flaws like unequal fiber diameters or surface roughness.[19,20]

2.2.1 Raw Material Characteristics

In contrast to wet spinning, the dry spinning method for PAN fibers uses certain chemicals for the spinning dope and does not require a coagulation bath. To guarantee adequate chain entanglement for robust fibers, the main polymer is PAN or its copolymers, which frequently include comonomers like methyl acrylate or itaconic acid. Their molecular weight is generally between 80,000 and 150,000 g/mol.[19] Because of their capacity to efficiently dissolve PAN and evaporate rapidly, volatile solvents like dimethylsulfoxide (DMSO, molecular weight: 78.13 g/mol) or dimethylformamide (DMF, molecular weight: 73.09 g/mol) are used to create the dope at a concentration of 20–30 weight per cent.[20]While DMSO is selected for its thermal durability during processing, DMF is preferred due to its lower boiling point (153°C), which allows for speedier evaporation. Additives like plasticisers, such as glycerol, or stabilisers may be used to improve dope stability or fiber flexibility.[20]For instance, one study used PAN with a molecular weight of around 100,000 g/mol in a 25 weight per cent DMF dope to maximise spinnability. Another study used a PAN copolymer with itaconic acid to enhance fiber homogeneity in a 22 weight per cent DMSO dope.[19,20]No coagulation bath is used, as solvent evaporation in the heated chamber produces fiber solidification.

2.2.2 Influence of Processing Parameters in dry spinning

Depending on the processing parameters, PAN fibers produced by dry spinning have tensile strengths between 500 and 900 MPa and tensile moduli between 10 and 15 GPa. Compared to wet-spun fibers, the absence of a coagulation bath produces denser fibers with smoother surfaces, decreasing internal voids and improving surface quality. High draw ratios of 4–6 timesoptimise tensile strength and molecular alignment, and controlled evaporation conditions, including spinneret temperatures of 160–180°C and moderate air flow rates, guarantee homogeneous solidification free of surface defects, and yield the best results. The optimal viscosity-to-fiber quality ratio is achieved at 22–25% dope concentration. As an illustration of the value of ideal evaporation and stretching conditions, one study used a 25 weight per cent dope in DMF with a 5 times draw ratio to report fibers with a modulus of 14 GPa and a tensile strength of 850 MPa[19,20].

2.3 Dry jet wet spinning

For PAN fibers, dry-jet wet spinning is used instead of traditional damp spinning to provide better mechanical characteristics and molecular alignment. By encouraging chain orientation and minimising die swell, the air gap permits the polymer solution to stretch initially before coagulation, improving fiber strength and modulus.[5,10]. High molecular weight PAN, essential for intense carbon fiber precursors, can be used with this technique, which also allows for fine coagulation control to reduce voids and surface imperfections. [11,12] The process is particularly effective for producing fibers with tailored microstructures, making it ideal for high-performance applications. [15,16].The dry-jet wet spinning process consists of several meticulously regulated steps with precise specifications to maximise fiber qualities. To create a PAN dope, PAN or its copolymers are first dissolved in 15–22% DMSO, heated to 60–80°C, and filtered to guarantee homogeneity.[5,16]. A jet stretch ratio of 0.8 to 2.0 is then used to align polymer chains after the dope is extruded via a spinneret with diameters of 0.05 to 0.2 mm into an air gap of 5 to 20 mm at 20 to 30°C.[10,11]. After extrusion, the fibers are placed in a coagulation bath at 10 to 50°C with either water or water/DMSO (30 to 70 weight per cent DMSO). The concentration of DMSO affects the coagulation time, with a larger DMSO content slowing coagulation to minimise voids.[12,15]. To improve molecular orientation, the fibers are first drawn in a coagulation bath with draw ratios of three to six times, and then they are hot-drawn in hot water or steam at 80 to 100°C with draw ratios of six to twelve times.[10,16]. The fibers are then dried under tension at 100 to 150°C after being cleaned to remove any remaining solvent, to establish the structure[11,15]. Thermal stabilisation at 200 to 300°C in air is frequently carried out to prepare the fibers for carbonisation.[5].

2.3.1 Raw Material Characteristics

Various chemicals are used in the dry-jet wet spinning process to get the required fiber qualities. The main polymer is PAN or its copolymers, which are frequently combined with vinyl acetate or itaconic acid. Their molecular weights range from 70,000 to 300,000 g/mol, where greater molecular weights enhance tensile strength and spinnability[10,11]. Because it can successfully dissolve high molecular weight PAN, dimethyl sulfoxide (DMSO) is the most widely used solvent. Dope concentrations are usually between 15 and 22 weight per cent to balance viscosity for extrusion[5,12,15].Lower DMSO concentrations speed up coagulation and affect fiber shape. The coagulation bath is made up of water or water/DMSO mixes with DMSO concentrations ranging from 30 to 70 weight per cent and bath temperatures between 10 and 50°C[10,11,15]. Additives such as carbon nanotubes (CNTs) at 0.5 to 2 weight per cent or graphene oxide (GO) at 1 to 5 weight per cent enhance mechanical or electrical properties. By fortifying the fiber matrix, CNTs raise tensile strength[12,16]. Furthermore, adding 1–3 mol% itaconic acid to copolymers improves heat stability during subsequent carbonisation, which lowers flaws[11].

2.3.3 Influence of Processing Parameters in dry jet wet spinning

To prepare a dope for dry-jet wet spinning of PAN fibers, PAN or its copolymers—often with additions like CNTs or GO—are dissolved in DMSO at a 10 wt.% concentration of 15 to 22 and heated to 60 to 80°C to guarantee homogeneity. Before the dope enters a coagulation bath of water or water/DMSO (30 to 70 weight per cent DMSO) at 10 to 50°C, it is extruded through a spinneret into an air gap of 5 to 20 mm, where jet stretch aligns polymer chains, decreasing die swell and improving molecular orientation. Defects are reduced by the air gap and regulated coagulation, which promote fiber solidification by solvent exchange. To optimise chain alignment and crystallinity, the fibers are then drawn in stages, first in the coagulation bath at 3 to 6times and then in hot water or steam at 80 to 100°C with draw ratios of 6 to 12 times. To maintain the structure, the fibers are dried under tension at 100 to 150°C after being drawn and cleaned to remove any remaining solvent. With the air gap and additive inclusion offering improved control over microstructure, this technique creates fibers with high strength and modulus appropriate for carbon fiber precursors[10,15]. PAN fibers with tensile strengths of up to 1 GPa are produced by dry-jet wet spinning. This makes them perfect starting materials for high-performance carbon fibers in energy, automotive, and aerospace applications. Fibers with remarkable mechanical qualities and microstructural homogeneity that closely match commercial requirements are produced by incorporating carbon nanotubes (CNTs) and optimising process factors like high molecular weight PAN, controlled coagulation, and high draw ratios.[11,15].

2.4 Electrospinning

Electrospinning is utilised to produce PAN fibers because it can create nanofibers with diameters between 100 and 500 nm, providing high surface area-to-volume ratios and improved mechanical characteristics ideal for advanced applications. In contrast to traditional wet or dry spinning methods, electrospinning allows for accurate control of fiber structure. It is possible to incorporate functional additives such as graphitic carbon nitride or silica nanoparticles, improving properties like photocatalytic activity or hydrophobic characteristics.[17] This method is especially beneficial for creating lightweight, porous PAN nanofibers suitable for oil-water separation, supercapacitors, and filtration, as nanoscale designs enhance efficiency.[21,22] The procedure includes dissolving polyacrylonitrile (PAN) in a solvent, applying a high voltage to create a charged jet, and gathering solidified nanofibers on a grounded collector. Important processing factors consist of voltage (ranging from 10 to 25 kV), solution viscosity, and the distance from the collector (10 to 20 cm), all of which influence fiber diameter and consistency.[23].

2.4.1 Raw Material Characteristics

The main polymer used in electrospinning PAN fibers is PAN, which usually has a molecular weight ranging from 70,000 to 150,000 g/mol and is dissolved in dimethylformamide (DMF) at concentrations between 8 and 15 wt% to create a thick spinning dope[17,21,24]. Chen et al. employed PAN at a concentration of 10 wt% in DMF, along with polystyrene (PS) in a 1:1 ratio to create core-shell structures, but did not indicate the molecular weight of the PS[21]. Wang et al. incorporated 0.5–2 wt% of graphitic carbon nitride (g-C3N4) into a solution of 10 wt% PAN/DMF to improve photocatalytic properties[17].Sabantina et al. reported that using PAN (150,000 g/mol) at 8–12 wt% concentrations in DMF increases viscosity, hindering bead formation at higher concentrations. Yang et al. introduced poly(methyl methacrylate) (PMMA) as a sacrificial polymer at 1:1 with PAN in DMF, maintaining PAN at 8 wt%. Ramalingam et al. utilised PAN at a concentration of 12 wt% in DMF, adding carbon nanomaterials to enhance conductivity[22,23,24]. In electrospinning, a coagulation bath is not utilised because fiber solidification takes place through the evaporation of the solvent in the air, which sets it apart from all spinning techniques.

2.4.2 Electrospinning Process Parameters

The solvent-based electrospinning of PAN fibers uses electrostatic forces to generate nanofibers with well-defined morphology. The process starts with creating a uniform PAN solution, usually within a concentration of 8–15 wt% in DMF, occasionally mixed with additives like g-C_3N_4, PS, or PMMA to improve the functional characteristics of the resulting fibers [17,21,23]. This mixture is placed into a syringe fitted with a needle diameter of 0.5 to 1 mm. A high voltage, typically ranging from 10 to 25 kV, is applied to the needle's tip, creating a Taylor cone that triggers the release of a charged polymer jet[21,24]. The jet experiences stretching and whipping motions caused by electrostatic repulsion and the evaporation of the solvent, which results in the solidification of fibers. These nanofibers are gathered as a nonwoven mat on a grounded collector, like aluminium foil or a rotating drum, placed 10–20 cm away from the needle[17,23]. Research on process optimisation has revealed several variations: Chen et al. employed a voltage of 12 kV, a distance of 15 cm, and a flow rate of 1 mL/h to produce uniform core-shell fibers [21]. Wang et al. indicated using 15 kV at a distance of 12 cm for fibers modified with g-C_3N_4[17]Sabantina et al. attained stable fibers by applying 18 kV, maintaining a distance of 15 cm, and a flow rate of 0.5 mL/h[24] Yang et al. employed a voltage of 20 kV and a distance of 18 cm for carbonised nanofibers; in contrast, Ramalingam et al. refined their parameters to 18 kV, 15 cm, and a flow rate of 0.8 mL/h for energy storage applications[22,23]. Environmental factors, usually within a 25–30°C range and 30–50% humidity, ensure fiber consistency and stability during processing[24]. After electrospinning, the gathered fibers typically undergo thermal stabilisation at temperatures ranging from 250 to 300°C, followed by carbonisation between 800 and 1200°C. This process enhances mechanical strength and electrical conductivity, especially for carbon fiber applications [22,23]. The electrospinning technique provides scalability, exact control over fiber structure, and adaptability in functionalisation, which has led to its widespread use for producing advanced PAN-based nanofibers.

2.4.3 Influence of Processing Parameters in Electrospinning

Electrospinning polyacrylonitrile (PAN) produces nanofibers ranging from 100 to 500 nm in diameter, characterised by high porosity and specific surface areas that can reach up to 500 m^2/g, influenced by various processing conditions and additives. According to Chen et al., core-shell PAN/PS nanofibers exhibit superhydrophobic characteristics (with a contact angle exceeding 150°) and significant oil absorption capacity (up to 50 g/g), making them suitable for oil-water separation, which was achieved at 12 kV with a 15 cm distance from the collector.[21]. Wang et al. demonstrated that incorporating 1 wt% g-C3N4 into PAN nanofibers improved the photocatalytic breakdown of dyes by 80% when exposed to visible light, resulting in uniform fibers with a diameter of 200 nm produced at 15 kV[25].Sabantina et al. successfully produced stabilised PAN nanofibers that exhibited tensile strengths ranging from 5 to 10 MPa post-carbonisation, with the best results observed at a 10 wt% PAN concentration to reduce the occurrence of bead defects.[24]Yang et al. described carbonised PAN nanofibers possessing a specific surface area of 400 m^2/g, which are appropriate for catalysis, created from a 1:1 blend of PAN and PMMA at a voltage of 20 kV[23]. Ramalingam and colleagues achieved carbon nanofibers that exhibited a specific capacitance of 200 F/g for use in supercapacitors, optimised at 12 wt% PAN and 18 kV[22]. Optimal outcomes are generally obtained with PAN concentrations ranging from 10% to 12% by weight, voltages between 12 kV and 18 kV, and adding additives to customise functionality.[21,22].

3. Comparative analysis

Wet spinning, dry-jet wet spinning, electrospinning, and dry spinning each have unique benefits and drawbacks for producing PAN fibers, especially when considering fibers free of additives, with their appropriateness based on the specific application intended. Wet spinning enables direct extrusion into a coagulation bath (20–50 wt% DMSO, 20–40°C), facilitating controlled coagulation, resulting in uniform microscale fibers (10–20 µm diameter) that exhibit tensile strengths ranging from 0.6 to 2.5 GPa and moduli between 10 and 15 GPa. Still, it may lead to void formation if coagulation occurs too swiftly, necessitating careful management of bath composition and temperature to reduce defects[1,7,21]. The straightforward nature of this process renders it cost-effective for generating fibers intended for general carbon fiber precursor usage. However, its mechanical properties fall short compared to those achieved through dry-jet wet spinning due to less effective chain alignment[4]. Dry-jet wet spinning, characterised by an air gap (5–20 mm) and a coagulation bath (30–70 wt% DMSO, 10–50°C), improves molecular alignment, producing microscale fibers (8–15 µm diameter) with tensile strengths of 0.8–2.8 GPa and moduli ranging from 12 to 20 GPa, attributed to enhanced crystallinity (70–80%)[5,10,15]. Nevertheless, its intricate design and the energy demands associated with the air gap and high draw ratios (up to 12 times) create challenges for scalability[11,12]. Electrospinning generates nanoscale fibers (50–500 nm diameter) with tensile strengths between 0.1 and 0.5 GPa and moduli from 5 to 10 GPa, making them suitable for filtration or biomedical scaffolds due to their extensive surface area. Still, the lower strength and the complicated setup (high voltage and precise flow management) restrict their application in carbon fiber precursors[24,26]. Dry spinning operates by evaporating solvent in a heated chamber (100–200°C), resulting in microscale fibers (15–25 µm diameter) with tensile strengths of 0.5–1.5 GPa and moduli between 8 and 12 GPa, providing simplicity but less control over microstructure, which leads to inferior mechanical properties and increased porosity when compared to wet or dry-jet wet spinning[26]. Wet spinning and dry-jet wet spinning are favoured for producing high-performance carbon fiber precursors, with dry-jet wet spinning demonstrating enhanced strength and modulus. In contrast, electrospinning and dry spinning are more appropriate for specialised or economical applications[1,10,24,26]. A summary of the essential parameters and results without additives is included in the table below.

Parameter	Wet Spinning	Dry-Jet Wet Spinning	Electrospinning	Dry Spinning	References
Molecular Weight (g/mol)	80,000–250,000	70,000–300,000	100,000–200,000	80,000–200,000	[10, 11, 13, 14, 24, 26,]
Dope Concentration (wt%)	15–25 in DMSO	15–22 in DMSO	8–12 in DMSO/DMF	20–30 in DMSO/DMF	[1, 5, 7, 10, 11, 24]
Coagulation/ Evaporation	Water or 20–50 wt% DMSO, 20–40°C	Water or 30–70 wt% DMSO, 10–50°C, air gap 5–20 mm	Air, 20–30°C, 10–30 kV, 10–20 cm distance	Heated chamber, 100–200°C	[1,5,7,10,12,24]
Jet Stretch/Flow Rate	Jet stretch: 0.5–2.0	Jet stretch: 0.8–2.0	Flow rate: 0.5–2 ml/h	None	[1,10,11,24]
Draw Ratios	Wet: 2–5, Hot: 5–10 times	First: 3–6 times, Second: 6–12 times	None (post-drawing optional, 1–3 times)	3–8 times	[4,10,15,21, 24]
Fiber Diameter (μm)	10–20	8–15	0.05–0.5 (50–500 nm)	15–25	[1,10,24,26]
Tensile Strength (GPa)	0.6–2.5	0.8–2.8	0.1–0.5	0.5–1.5	[1,7,10,11, 24]
Tensile Modulus (GPa)	10–15	12–20	5–10	8–12	[1,7,10,11,24]
Crystallinity (%)	60–80	70–80	50–70	55–75	[1,10,12,24,26]

4. Challenges and future directions

Pinning PAN fibers encounters numerous obstacles restricting scalability and sustainability across all methods. The tendency for voids to form in wet spinning at elevated coagulation rates necessitates careful management of bath temperature (20–40°C) and DMSO concentration (20–50 wt%), complicating the process.[1,7,21]. Dry-jet wet spinning faces scalability issues due to its energy-demanding air gap (5–20 mm) and high draw ratios (up to 12times), with maintaining a consistent air gap length being crucial to prevent filament breakage.[10,12,15]. The low throughput and high-voltage needs (10–30 kV) of electrospinning limit its scalability for carbon fiber production, and achieving homogeneous nanoscale fibersremains challenging.[24]. The high-temperature evaporation (100–200°C) required in dry spinning leads to increased porosity and diminished mechanical properties, indicating a need for improved chamber designs.[26]. The dependence on DMSO or DMF in all methods raises environmental and cost issues, with current solvent recovery systems proving ineffective.[20,24]. Future efforts should focus on creating environmentally friendly solvents, such as ionic liquids or aqueous solutions, to substitute DMSO and DMF and enhance solvent recovery technologies to promote sustainability.[24,26]. Investigating process optimisation, including automated regulation of coagulation or evaporation parameters, could enhance scalability and consistency.[10,19]. Progress in stabilisation methods, particularly for fibers produced through electrospinning and dry spinning, could improve their viability as precursors for carbon fibers[24], [26]. Addressing these challenges will be essential for increasing the production of high-performance, sustainable PAN fibers[20,22,26].

5. Conclusion

Spinning of PAN fibers, which includes techniques such as wet spinning, dry-jet wet spinning, electrospinning, and dry spinning, is crucial for creating high-performance carbon fiber precursors. Wet spinning provides a straightforward and consistent method, achieving strengths between 0.6 and 2.5 GPa, while dry-jet wet spinning offers enhanced mechanical properties, ranging from 0.8 to 2.8 GPa. Electrospinning facilitates the formation of nanoscale fibers, although these typically possess lower strengths of 0.1 to 0.5 GPa. Conversely, dry spinning is a more cost-effective, yielding fibers with strengths between 0.5 and 1.5 GPa. The ideal production conditions involve using high molecular weight PAN, specifically 250,000–300,000 g/mol for wet and dry-jet wet spinning, and 100,000–200,000 g/mol for electrospinning and dry spinning. For wet-based methods, a dope concentration of 15–25 wt% DMSO is recommended, alongside regulated coagulation or evaporation processes. Nonetheless, issues such as solvent recovery, intricate procedures, and scalability remain challenges. However, advances in research focusing on environmentally friendly solvents and automated methods are expected to improve sustainability and performance. By overcoming these obstacles, PAN fiber spinning stands to satisfy the increasing demand for high-performance, sustainable carbon fibers in aerospace, automotive, and renewable energy sectors.

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