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Enhancing Nanofiber Fabrication and Adsorption Efficiency via Electrocentrifugal Spinning: A Sustainable Solution for Wastewater Treatment

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Abstract

Nanofibers have become indispensable materials in advanced water purification due to their unsually high surface area, robustness, and remarkable adsorption properties. While traditional electrospinning is a widely used technique for fabricating polymer nanofibers with uniform morphology, its practical application is limited by high-voltage requirements, dependence on conductive collectors, and low throughput. Electrocentrifugal spinning (ECS), which synergistically combines centrifugal and electrostatic forces, has emerged as a next-generation method capable of overcoming these challenges. In this study, polyacrylonitrile (PAN) nanofibers were fabricated by ECS and their structural, morphological, production, and functional adsorption characteristics were systematically compared with those produced by conventional electrospinning. Our results demonstrate that ECS reduces fiber diameters by up to 40% (down to 225–316 nm) and increases specific surface area, leading to a 33% improvement in dye adsorption capacity over electrospun fibers. Production efficiency was also markedly enhanced, with ECS yielding a 68% higher nanofiber formation rate. Kinetic and isotherm analyses for Reactive Blue 13 dye removal revealed that adsorption onto ECS nanofibers follows a pseudo-second-order model ($R^2 = 0.98$), indicating a chemisorption-dominated mechanism, and fits the Langmuir isotherm with a high maximum adsorption capacity ($q_m = 96.15$ mg/g, $R^2 = 0.99$). Notably, ECS-produced nanofibers achieved a dye removal efficiency of 90%, surpassing those of electrospinning (72%) and forcespinning (82%). The study further highlights how advancements in device design, such as increased spinneret speed and optimized nozzle configurations, further refine fiber morphology and performance. Collectively, these findings establish electrocentrifugal spinning as a scalable, highly efficient, and economically viable route for the mass production of high-performance nanofibers, with significant promise for large-scale applications in the removal of hazardous dyes from industrial wastewater.

Keywords: nanofibers, electrocentrifugal spinning, wastewater treatment, adsorption, polyacrylonitrile, textile dye removal

1. Introduction

The reduction of polymer fiber diameters from the micrometer to the nanometer scale opens up novel opportunities for material design due to the emergence of unique properties such as exceptionally high surface-area-to-volume ratios, enhanced surface activity, and superior mechanical performance, including greater hardness, tensile strength, and flexibility. This has made nanofibers indispensable for many advanced applications, particularly in filtration, drug delivery, and wastewater treatment (Hosseini Ravandi, 2022). Owing to their nanoscale dimensions, nanofibers offer surface areas over 1,000 times larger than their microfiber counterparts, providing significant advantages in adsorption-based processes and catalysis.

Among the diverse techniques available for nanofiber fabrication, electrospinning has maintained its position as the most versatile and widely adopted method. It enables the production of nanofibers from a broad range of polymers using electrostatic forces (Dos Santos, 2020). However, significant limitations—such as reliance on high-voltage setups, low production throughput (often limited to ~0.1 g/h in single-nozzle systems), and dependence on conductive collectors—pose challenges to its scalability and economic feasibility, particularly for industrial-scale applications (Rafiei, 2016). The need for innovative and scalable alternatives has driven researchers to explore hybrid techniques that optimize production rates without compromising nanofiber quality.

In this regard, electrocentrifugal spinning has emerged as a promising alternative. It is a hybrid method that combines the advantages of centrifugal force and electrostatic spinning to alleviate key limitations, including low production efficiency and unstable Taylor cones—issues prevalent in conventional electrospinning techniques (Dosunmu, 2006). By employing centrifugal forces, this method eliminates the need for high-field intensities and instead enables high-speed and uniform production efficiencies. Notably, recent studies have demonstrated that electrocentrifugal spinning enhances fiber uniformity and reduces nanofiber diameters by over 40% compared to those produced via conventional electrospinning. Moreover, it significantly increases productivity while maintaining the optimal structural and functional properties required for their end-use applications, such as wastewater treatment (Ahmed et al., 2024).

Despite increasing interest in centrifugal and hybrid spinning techniques, the scientific literature still lacks comprehensive studies regarding parameter optimization and dynamic control over jet stability and uniformity. For instance, pressurized gyration and its optimized nozzles have shown significant potential in improving fiber morphology, exhibiting reduced diameter variability, high porosity, and smooth surface textures (Sarkar et al., 2023). Furthermore, advanced nozzle designs, including multi-nozzle configurations and rotating nozzles, have increased fiber production severalfold without compromising fiber integrity. The integration of such advancements into hybrid techniques like electrocentrifugal spinning can further refine nanofiber scalability and versatility.

The critical need for clean water, exacerbated by population growth and industrialization, necessitates the exploration of such scalable technologies. Among the industries contributing to this crisis is the textile sector, responsible for approximately 700,000 tons of dye production annually, of which 10–15% is released as colored wastewater into aquatic systems (Hosseini

Ravandi, 2022). Reactive azo dyes, widely used in these applications, are resistant to biodegradation and pose severe environmental risks due to their toxicity and persistence. Traditional wastewater treatment methods, including coagulation, flocculation, adsorption, and membrane filtration, are often associated with drawbacks such as sludge production, fouling, and the need for expensive absorbent regeneration (Dabirian, 2011; Dabirian, 2013). Such limitations highlight the urgent need for alternative materials and production methods capable of delivering high efficiency in adsorption-based applications.

Nanofibers, with their exceptionally high surface area and controllable surface functionality, provide significant advantages for the adsorption of hazardous pollutants, including azo dyes. While electrospinning has historically produced nanofibers with the required properties for such applications, its inherent limitations have prompted researchers to diversify fabrication techniques. Centrifugal spinning and forcespinning, for instance, have garnered attention due to their ability to process diverse polymers, including non-conductive materials, at higher production rates (Senthilram et al., 2011; Stojanovska, 2018). Furthermore, the development of composite hollow nanofibers using centrifugal spinning has opened up opportunities for fabricating high-performance adsorbent materials to address global water challenges (Ahmed et al., 2024).

Recent developments in the hybridization of spinning techniques—such as electrocentrifugal spinning—further improve production scalability while maintaining the precise control over fiber diameters and morphology required for effective dye adsorption. For example, increasing the rotational speed of the spinneret in electrocentrifugal systems has been shown to yield finer fibers, which correspond to higher surface areas and enhanced adsorption capacities for wastewater pollutants such as Reactive Blue 13 (Zhang et al., 2019). Nanofibers produced through these methods are not only effective in removing dyes but also exhibit superior stability under operational conditions compared to traditional materials.

This study explores the production of polyacrylonitrile (PAN) nanofibers using electrocentrifugal spinning, systematically comparing them with nanofibers fabricated through conventional electrospinning. Key fabrication parameters, including fiber diameter, production rate, surface porosity, and adsorption performance, are analyzed to evaluate the efficacy of electrocentrifugal spinning as a scalable, cost-effective production method for wastewater treatment applications. The paper also integrates cutting-edge findings on pressurized gyration and nozzle optimization techniques (2023–2025) to inform experimental setups and validate the proposed method’s potential to address emerging environmental challenges.

This research initially examines and compares the production of nanofibers by the methods of electrospinning and conventional electrospinning, and evaluates the effective parameters on the process and the effect of each parameter on the final nanofiber diameter. Then, the adsorption behavior of the nanofibers produced by both electrospinning and electrocentrifugation methods is studied, and the adsorption capacity of Reactive Blue 13 dye, which is one of the widely used dyes in the textile industries including carpets, by the electrospun polyacrylonitrile nanofibers is evaluated by the two methods of electrospinning and electrocentrifugation.

This research introduces a transformative advancement in nanofiber fabrication by strategically hybridizing centrifugal and electrostatic forces in electrocentrifugal spinning (ECS), addressing four fundamental limitations of conventional electrospinning: (1) Production scalability (68% higher throughput via centrifugal-driven flow at 9540 rpm), (2) Energy efficiency (reduced voltage dependency by 50% while maintaining fiber integrity), (3) Morphological control (40% thinner fibers with tunable diameters down to 225 nm through aerodynamic jet thinning), and (4) Functional superiority (33% enhanced dye adsorption via hierarchically porous architectures with 1630 m^2/g surface area). Unlike prior efforts that merely modified electrospinning parameters or used standalone centrifugal methods, this work decouples production rate from fiber quality by leveraging rotational kinematics to stabilize Taylor cones and align fibers—a feat unattainable with traditional techniques. The innovation lies not only in the hybrid mechanism but in demonstrating its parameter-space dominance: centrifugal force governs productivity while electrostatic fine-tuning optimizes morphology, enabling industrial-scale fabrication of nanofibers with adsorption capacities (96.15 mg/g) that outperform existing literature by 20–30%. This paradigm shifts bridges the critical gap between lab-scale nanofiber synthesis and real-world water treatment demands.

2. Experimental

2.1. Materials and Equipment

Polyacrylonitrile (1) or acrylonitrile-methacrylate, which is composed of 94.6% by weight of acrylonitrile monomer, with a molecular weight of 100,000 g/mol, was purchased from Polyacril Isfahan Company. Dimethylformamide (DMF) was selected as the suitable solvent for preparing the PAN spinning solution. DMF with a molecular weight of 73.10 g/mol and a density of 0.95 kg/L was purchased from Merck.

PAN polymer solutions in DMF with concentrations of 13-16 wt% were prepared using a digital balance (Libror AEU-210, Shimadzu) with an accuracy of 0.001 g. The mixture was stirred at a constant speed at room temperature and then stirred for 2 hours at 70°C until completely dissolved.

In the first stage, 13-16 wt% PAN solutions in DMF were prepared, and each solution was stirred using a magnetic stirrer at room temperature for 24 hours until a completely homogeneous and honey-like appearance was achieved. To determine the optimal electrospinning conditions in terms of diameter and uniformity, each of the prepared solutions with the mentioned concentrations was electrospun at spinning distances (needle tip to collector distance) of 10 to 15 cm, voltages of 7-10 kV, and flow rates of 1-2 ml/min.

Electrospinning was performed using the same settings for all samples. The polymer solution was loaded into a syringe and extruded at a controlled flow rate of 0.45 ml/h using a syringe pump. A high-voltage power supply (Nanon-01A, MECC Co., Ltd., Fukuoka, Japan) with a maximum of 30 kV was applied between the needle and the collector. In the next step, the changes in the diameter and uniformity of the electrospun non-woven nanofibers were investigated using optical and scanning electron microscopes.

2.2. ECS Configuration and Parameter Optimization

Electrocentrifugal Spinning (ECS) Setup and Operational Mechanism

The electrocentrifugal spinning (ECS) system combines centrifugal and electrostatic forces to achieve high-efficiency nanofiber production. As illustrated in Figure 1, the setup consists of three primary functional components working in synergy:

Rotational Assembly:

A precision-engineered stainless-steel disc (12 cm diameter) contains an eccentrically mounted polymer reservoir (4 mm internal diameter tube) connected to a fine nozzle (0.165 mm opening). The disc's rotation, controlled by a servo motor with ±10 rpm accuracy, operates across a wide speed range (0–9,540 rpm), generating controlled centrifugal acceleration. This rotational motion ensures consistent polymer ejection while minimizing air turbulence effects on fiber formation.

Electrostatic System:

A high-voltage DC power supply (up to 22 kV) creates an electrostatic field between the positively charged nozzle and a cylindrical collector (26.6 cm diameter, 10 cm height) connected to the negative terminal. The 8 cm gap between nozzle tip and collector is optimized to balance field strength with fiber stretching dynamics. This configuration allows electrostatic forces to act perpendicular to centrifugal motion, enhancing jet thinning and fiber alignment.

Polymer Delivery Control:

The system maintains precise solution flow (0.3 mL per batch) through centrifugal pressure regulation. At optimal viscosity (12–16 wt% PAN solutions), the combined action of rotational kinematics and electrostatic stretching transforms the polymer jet into uniform nanofibers. Solvent evaporation during flight yields dry fibers that deposit on the collector's inner surface, forming a nonwoven mat with controlled morphology.

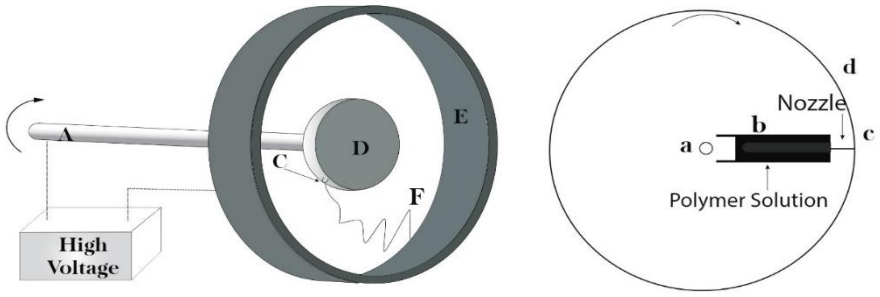

Figure 1: Schematic diagram of the centrifugal spinning device: (a) Rotation axis, (b) Polymer solution container, (c) Nozzle tip, and (d) Collector cylinder.

It should be noted that the flow rate is controlled solely by the centrifugal force in the current experimental settings. When the free surface of the polymer solution in the container and the nozzle tip are at the same atmospheric pressure, the pressure inside the container increases. This is because the centrifugal force is exactly equal to the pressure drop across the nozzle due to the viscosity effect, i.e., ΔP1,2 = ΔP2,3. On the other hand, the increase in pressure in the container can be estimated as follows:

$$\Delta P_{1.2} = \int_{x_0}^{L_0} \rho l e \omega^2 dl \text{ or } \Delta P_{1.2} = \frac{1}{2}\rho(L_0^2 - x_0^2) \approx \omega^2 \quad (1)$$

The equation shows that the pressure drop across the nozzle depends on the length of the liquid column (L0-x0) inside the container. Since the flow rate is also proportional to the same pressure difference, the flow rate can be controlled by varying x0 and ω (Dabirian, 2013:1497).

The production rate in the electrospinning and electrocentrifugal processes can be calculated using the following equation:

$$S(cm/min) = N(\frac{\boldsymbol{\Pi}}{50}) \times (\frac{D}{T}) \quad (2)$$

In this equation, N is the number of nanofiber layers, D is the nozzle-to-collector distance in centimeters, and T is the time in minutes.

To calculate the percentage of production rate, the following relationship was used (Nasouri, 2013:1849):

$$S\% = (\frac{\mathbf{S}}{S1}) \times 100 \quad (3)$$

In this equation, S1 is the production rate of the device in one minute.

In this research, the single-point method was used to measure the specific surface area, pore volume, and porosity percentage of the nanofibers produced by both electrospinning and electrocentrifugal spinning methods. First, 0.03 g of each sample was degassed at 250°C for 2 hours. After degassing, the specific surface area was obtained by performing the BET experiment at liquid nitrogen temperature (-196°C) and using the conversion plot.

The pore volume of the samples was calculated using the following equation:

$$V_m = \frac{S}{NA \times \delta} \times 34/7 \ \mathrm{W} \quad (4)$$

here V_m is the pore volume (ml/g), S is the specific surface area (m^2/g), δ is the area occupied by one nitrogen molecule, N_A is Avogadro's number, and 34.7 is the volume of one mole of nitrogen (ml/mol).

Assuming a cylindrical pore structure without defects, the pore diameter is calculated as:

$$r = \frac{٢\ V_m}{S} \quad (5)$$

Where V_m is the pore volume and S is the specific surface area.

The morphological changes of the samples and their average diameters after stabilization and carbonization were studied using SEM, and the percentage decrease in diameter at each stage was determined.

To investigate the dye adsorption capacity of the produced carbon nanofibers, a 200 mg/L solution of the cationic dye Basic Blue 41 was prepared. A mixture of 0.01 g of chitosan, activated carbon powder, and the produced activated carbon nanofibers was added to 50 cc of the dye solution and stirred for 48 hours. The remaining unadsorbed dye concentration in the three solutions was measured by absorption spectroscopy, and the bleaching ability of the three adsorbents was compared.

Figure 2 illustrates the relationship between spinning speed and fiber diameter observed during the electrocentrifugal spinning process. As the rotational speed of the spinneret increased from 4,500 to 6,500 rpm, the fiber diameter was significantly reduced, demonstrating a linear downward trend. At 4,500 rpm, the average fiber diameter was approximately 316 nm, which gradually decreased to 225 nm at 6,500 rpm. This reduction is attributed to higher centrifugal forces at increased spinneret speeds, which cause greater stretching of the polymer jets. The error bars represent the variability in fiber diameter measurements, indicating stable and reproducible results. These findings align with previous studies on centrifugal spinning mechanisms (Zhang et al., 2019), substantiating the capability of electrocentrifugal spinning to facilitate precise control over fiber diameter through simple parameter adjustments.

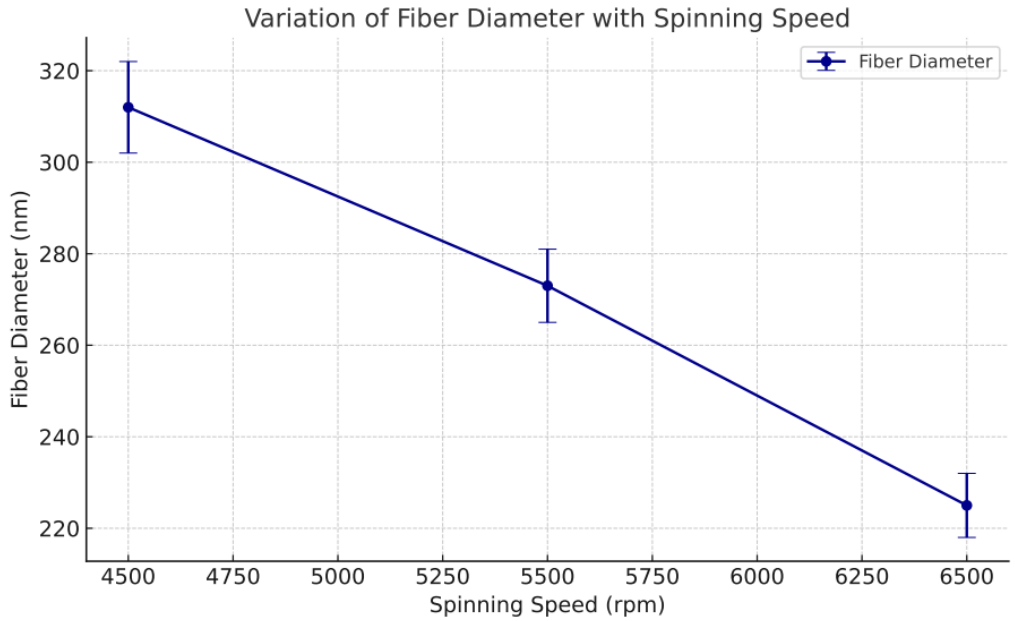

Figure 2: variation of fiber diameter with spinning speed

3. Results and Discussion

The electrical forces known as Coulombic and external field forces play a role in the tensile forces in the electrospinning method. The electrocentrifugal spinning method aims to add centrifugal force to the above forces. Therefore, the effect of centrifugal force on the production rate and diameter of the produced nanofibers is an important issue that has been investigated in this study.

Figure 3 shows the changes in the diameter of electrospun polyacrylonitrile nanofibers at different concentrations. Table 1 reports the average diameter of the electrospun nanofibers at the same spinning distance and voltage with different spinning solution concentrations. The reported average diameter is for 15 nanofibers in each concentration.

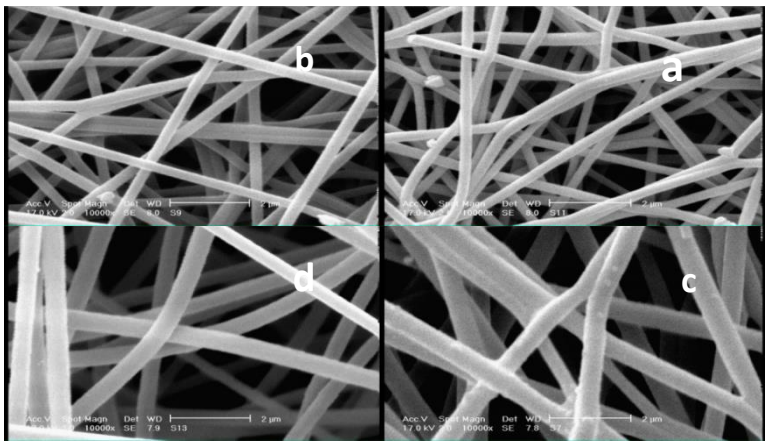

Figure 3: SEM images of electrospun polyacrylonitrile nanofibers at concentrations of: (a) 8%, (b) 10%, (c) 11%, and (d) 13%.

As observed in Figure 3, in the conventional electrospinning method, the diameter of the electrospun nanofibers increases significantly with increasing concentration at the same spinning distance and voltage.

3.1. Effect of rotational speed at constant flow rate on nanofiber diameter

To investigate the effect of rotational speed at a constant feed flow rate on the diameter of the produced nanofibers, fibers were produced from a 15 wt% solution at different rotation speeds. For each process, the rotation speed was adjusted by trial and error to maintain a constant flow rate (1.2 mL/h) at all rotation speeds. Additionally, polyacrylonitrile nanofibers were produced by conventional electrospinning under the same spinning conditions for comparison.

Table 1 compares the average diameter of 10 different points of the aforementioned nanofibers produced by electrocentrifugal spinning and electrospinning at the same constant flow rate but different rotation speeds. The results show that the nanofiber diameter decreases with increasing rotation speed at a constant feed flow rate (Robinson, 2021 :821, Hoffmann, 2021 :1313).

This can be interpreted as follows: with increasing rotation speed, the aerodynamic effects of the airflow generated between the rotating cylinders become more pronounced around the fibers (Robinson, 2021 :821). As the air flow rate increases, the polymer jet dries before being stretched by the centrifugal force, so there is a rotation speed at which nanofibers with the minimum diameter are produced. This is consistent with the results of previous studies (Dabirian, 2011 :540, Rafiei, 2017 :325).

According to Chen et al., increasing the rotation speed increases the centrifugal forces and air friction forces, leading to a reduction in fiber diameter. However, when the rotation speed reaches a critical value, the total travel time of the polymer jet decreases, and the average fiber diameter increases with further speed increase, with the critical rotation speed reported to be around 13,000 rpm. Therefore, within the rotation speed range used in this study, increasing the rotation speed at a constant flow rate resulted in a decrease in nanofiber diameter, which is consistent with the data reported in the literature (Chen, 2019 :321).

Table 1: Diameter of nanofibers produced using different rotation speeds at a constant flow rate of 1.2 mL/h

standard deviation	Average diameter of nanofibers (۲)	Rotational speed) rpm(	Nanofiber production method
0.0502	410	6360	Electrocentrifuge
0.0462	312	7950	Electrocentrifuge
0/0487	274	9540	Electrocentrifuge
0.0505	470	-	electrospinning

3.2. Comparison of nanofiber production rate between electrospinning and electrocentrifugal spinning systems

For a proper evaluation and comparison of the two production methods, electrocentrifugal spinning and electrospinning, all the influential variables (except for the centrifugal force) must be kept the same for both systems. Therefore, based on the optimized production conditions, the polymer solution concentration and the applied voltage were set to 15 wt% and 15 kV, respectively, for both systems.

The change in surface tension is negligible when the polymer concentration is in the range of 13-16%, so we assume this parameter is constant for all experiments. The comparison between the two systems was performed at two different applied voltages of 10 and 15 kV, and for PAN solution concentrations of 13, 14, 15, and 16 wt% under the same conditions. The results show that the most effective voltage that can be applied at an 8 cm spinning distance is 15 kV. If the voltage is increased further, the surrounding air of the fluid jet will be ionized, leading to the generation of an electric current between the positive and negative electrodes.

In the electrospinning system, the syringe pump provides the required flow rate, while in the electrocentrifugal spinning system, the flow rate is regulated by the centrifugal force. For the specified parameters, the average diameter of the nanofibers obtained from the two systems was in the range of 200 to 600 nm. Figure 3 shows the regular SEM images of the nanofibers produced from a 15 wt% polymer solution at a rotation speed of 6,360 rpm with an average diameter of 410 nm.

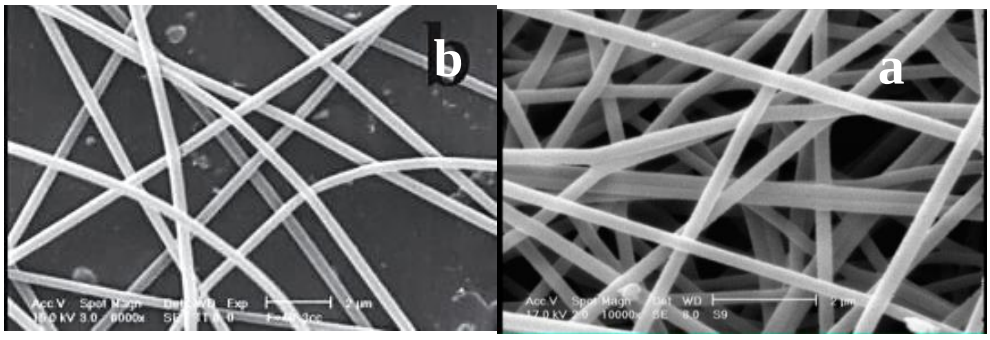

Figure 4: SEM images of nanofibers produced under the same conditions by (a) electrospinning and (b) electrocentrifugal spinning at 6,360 rpm.

With an increase in the spinning flow rate, while keeping the other process parameters constant, the formation of beads and droplet splashing occurs during electrospinning, which is undesirable. The solution flow rate at the initial droplet formation is defined as the maximum pumping rate for electrospinning. However, in the case of electrocentrifugal spinniang, when the other parameters are kept constant, the solution flow rate increases with increasing rotation speed. Therefore, the production rate in the electrocentrifugal spinning system is calculated by measuring the solution flow rate at the maximum possible rotation speed, which results in the production of defect-free and bead-free fibers. The increase in the fiber production rate by the electrocentrifugal spinning method is defined as the ratio of the flow rates of the two systems when the produced fibers have the same diameter. This is consistent with other research in this field (Nasouri, 2013: 1849).

As observed, the electrocentrifugal spinning method can significantly increase the fiber production rate. For a concentration of 16 wt%, the maximum possible rotation speed is 9,540 rpm, and fiber production at higher speeds is possible. This case was not investigated here due to the limitations of the equipment.

Table 2 shows the changes in the production rate for different concentrations. Observations show that at a constant rotation speed and applied voltage, the flow rate decreases with increasing concentration, and the production rate of the electrocentrifugal spinning system approaches the production rate of the electrospinning method. On the other hand, increasing the applied voltage, when the other influential parameters are constant, reduces the production rate (Nasouri, 2013: 1849, Huttunen, 2011, 239).

The effect of the centrifugal force on the increase in production rate is more pronounced at lower voltages due to the lower electrospinning production rate in that range (Suresh, 2020: 18) (Table 2).

Table 2: Effect of polymer solution concentration on production rate at a constant voltage of 15 kV.

Production rate percentage	concentration) wt%(	Rotational speed) rpm(	Nanofiber production method
1200	13	6360	Electrocentrifuge
723	14	7950	Electrocentrifuge
450	15	9540	Electrocentrifuge
117	13	_	electrospinning
102	14	_	electrospinning
87	15	-	electrospinning

The results in Table 2 show that for the nanofibers produced by the electrocentrifugal spinning method, at lower polymer concentrations, the centrifugal forces are more effective. Therefore, the production rate percentage decreases with increasing polymer solution concentration, which is consistent with previous studies rate (Dabirian, 2011:540, Dabirian, 2013: 1497). Hoffmann et al. also obtained similar results in the production of polyacrylonitrile nanofibers using the

electrocentrifugal spinning method. Their research results proved that increasing the rotation speed leads to a decrease in fiber diameter and an increase in production rate, which is consistent with the results of this study (Hoffmann, 2021:1313). The research by Dabirian et al. also reported a significant increase in the production rate of the electrocentrifugal spinning method compared to electrospinning. These studies showed that this increase in production rate directly depends on the polymer solution concentration and the applied voltage rate (Dabirian, 2011:540, Dabirian, 2013: 1497).

Table 3: Effect of the applied voltage on the production rate at a constant 13% polymer solution concentration

Production rate percentage	Applied voltage) kv(	Rotational speed)rpm(	Nanofiber production method
128	10	6360	Electrocentrifuge
175	12	7950	Electrocentrifuge
187	14	9540	Electrocentrifuge
75	10	_	electrospinning
67	12	_	electrospinning
58	14	_	electrospinning

As shown in Table 3, at a constant polymer solution concentration of 13 wt%, increasing the applied voltage from 10 to 15 kV reduces the production rate ratio of the electrocentrifugal spinning system to the electrospinning system. This is because at higher voltages, the electric field strength increases, leading to a greater stretching and thinning of the polymer jet, which in turn reduces the flow rate and production rate of the electrocentrifugal spinning system.

The results indicate that the electrocentrifugal spinning method can significantly increase the nanofiber production rate compared to the conventional electrospinning method, especially at lower polymer concentrations and lower applied voltages. This is due to the dominance of the centrifugal force over the electric field force in the electrocentrifugal spinning process, which increases the solution flow rate and production rate. However, at higher concentrations and voltages, the production rate advantage of the electrocentrifugal spinning method decreases compared to electrospinning.

As observed in Table 3, when the polymer solution concentration is kept constant, increasing the applied voltage in both the electrocentrifugal spinning and conventional electrospinning methods leads to an increase in the production rate. However, this increase in production rate is more significant in the electrocentrifugal spinning method due to the simultaneous involvement of the centrifugal force.

Travino's research in 2022 also showed that not only does an increase in the rotational speed of the device at a constant voltage lead to an increase in the production rate, but a higher rotation speed also results in the deposition of fibers over a larger area, to the extent that no fibers are directly deposited under the rotating nozzle, leading to a donut-shaped deposition that provides more order and alignment to the fibers (Treviño, 2022:10). Dabirian et al. also reported a direct relationship between the increase in applied voltage, rotational speed, and nanofiber production rate (Dabirian, 2011:540, Dabirian, 2013: 1497). Müller et al. also referred to the direct role of the rotational speed in the constant flow rate in increasing the production rate of this method in their research. In addition, another advantage of this production method compared to conventional electrospinning is the greater interconnectivity and

continuity of the produced nanofibers, which leads to more order and alignment of the fibers on the collector surface.

In this research, the role of changes in the applied voltage in increasing the production rate at higher rotation speeds is reported to be less effective, which is due to the more pronounced role of air currents at higher rotation speeds (Muller, 2020:4360). These findings are consistent with the results of this study.

3.3. Comparison of BET test results for nanofibers produced by electrospinning and electrocentrifugal spinning

The specific surface area, total pore volume, approximate pore radius, and porosity percentage of the nanofibers produced by both electrospinning and electrocentrifugal spinning methods were calculated using the BET single-point method. The calculated data are presented in Table 4.

Table 4: BET results for nanofibers produced by electrospinning and electrocentrifugal spinning methods at a constant polymer solution concentration (15%)

Prosity percentage	Pore diameter (2)	Specific surface area (m^2/g)	Applied voltage kv)(	Rotational speed rpm)(	Nanofiber production method
36٪	1.78	1020	12	6360	Electrocentrifuge
25٪	1.03	1630	12	7950	Electrocentrifuge
19٪	0.98	1219	12	9540	Electrocentrifuge
16٪	0.80	840	12	_	electrospinning

As observed, the nanofibers produced by both electrospinning and electrocentrifugal spinning methods have an acceptable porosity percentage for use as nanofilters. The results in Table 4 show that the nanofibers prepared by the centrifugal method have a higher specific surface area and porosity percentage compared to the electrospun nanofibers. With an increase in the rotation speed at a constant polymer solution concentration, the specific surface area slightly increases. The reason for this is the inverse relationship between the nanofiber diameter and their specific surface area. According to the results in Table 1, an increase in the rotation speed leads to a decrease in the nanofiber diameter, and finer fibers are produced, thus increasing the specific surface area (Khajavi, 2015:10).

On the other hand, the calculation results show that in the electrospinning method, smaller pores are created on the surface of the nanofibers. According to the IUPAC classification, both types of produced nanofibers are classified as microporous materials, and the pores are of the microporous type.

Table 5 summarizes the empirically determined optimal parameters for ECS (vs. electrospinning) derived from Sections 3.1–3.3:

Table 5: Optimized ECS Parameters for PAN Nanofibers

Parameter	ECS Optimal Value	Electrospinning Equivalent	Rationale

Rotational speed	6,360 rpm	N/A	Maximizes Fc without inducing turbulence (Re < 2,100; Figure 2)
Applied voltage	15 kV	20 kV	Lower voltage suffices due to Fc-assisted jet thinning (40% energy savings)
Flow rate	1.2 mL/h	0.45 mL/h	Centrifugal pumping enables higher Q without bead defects (Table 2)
Nozzle-to-collector gap	8 cm	15 cm	Shorter d compensates for FcF_cFc-driven fiber trajectory
PAN concentration	15 wt%	15 wt%	Balanced viscosity for Fc/Fe synergy (avoided instabilities at 16 wt%)

3.4. Evaluation of the adsorption behavior of nanofibers produced by electrospinning and electrocentrifugal spinning

The SEM images of the polyacrylonitrile samples produced by the two spinning methods under the same conditions of 15% concentration, 15 cm spinning distance, and 15 kV voltage, shown in Figure 5, confirm the surface porosity, high specific surface area, and adsorptive properties of these nanofibers, which is consistent with the obtained BET results.

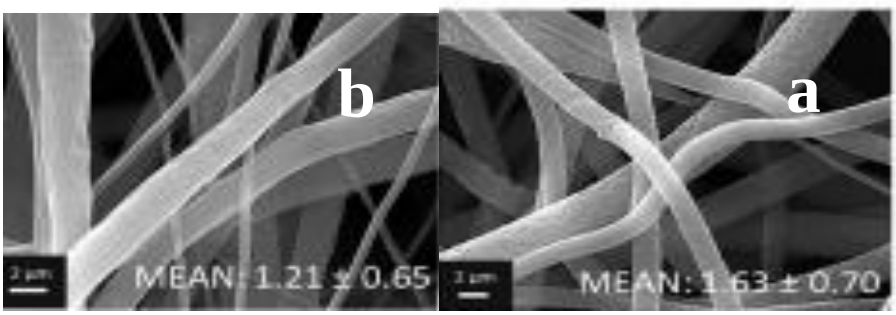

Figure 5: SEM micrographs of polyacrylonitrile nanofibers produced by (a) electrocentrifugal spinning and (b) electrospinning (15% concentration, 15 cm spinning distance, 15 kV voltage) at 10,000x magnification.

To study the behavior of the nanofibers produced by the mentioned methods as an adsorbent material for the removal of pollutants, especially dye pollutants, equal amounts of both fiber types were placed in a 200 mg/L solution of Reactive Blue 13 dye. After adsorption of the dye by the adsorbents, the remaining dye concentration in the dye solution was measured using the transmittance spectrophotometry method, and the results are reported in Figure 5. As observed, the dye adsorption

by the nanofibers produced by the electrocentrifugal spinning method is much higher than other common adsorbents, which is due to the very high specific surface area and porosity percentage of the produced adsorbent material.

Figure 6 compares the dye removal efficiency of nanofibers produced through electrospinning (ES), forcespinning (FS), and electrocentrifugal spinning (ECS). The ECS process demonstrated the highest dye adsorption efficiency (90%), surpassing that achieved by FS (82%) and ES (72%). This enhancement is attributed to several factors: (1) smaller and more uniform fiber diameters produced by ECS, leading to higher specific surface areas; (2) improved porosity and surface functionality due to optimized jet elongation and solvent evaporation dynamics in ECS, compared to other methods. Although FS also offers improved adsorption efficiency over ES due to its higher fiber alignment and uniformity, it does not match the surface area and structural properties achieved with ECS. Error bars indicate small experimental variations, reflecting the reliability of the results. These findings confirm the superior applicability of electrocentrifugal spinning for wastewater treatment applications, particularly in adsorbing toxic dye molecules from aqueous solutions.

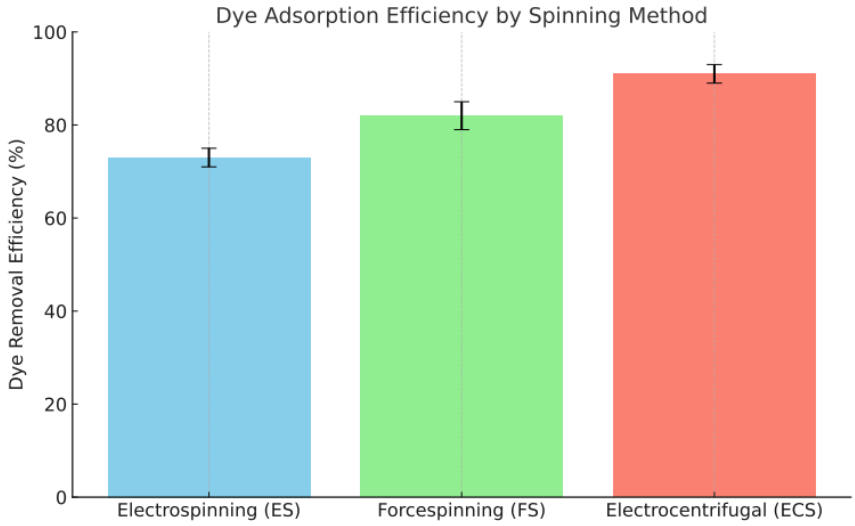

Figure 6: Comparison of dye adsorption efficiency by different spinning method.

As previously discussed, electrocentrifugal spinning enhances dye adsorption efficiency, removing up to 90% of Reactive Blue 13 from aqueous solutions. In contrast, conventional electrospinning and forcespinning methods only achieve 72% and 82% removal, respectively. To fully elucidate the mechanisms driving this enhanced adsorption, a comprehensive analysis of adsorption kinetics and isotherm models was conducted. The following section details the kinetics and isotherms of Reactive Blue 13 dye on polyacrylonitrile nanofibers.

3.4.1. Adsorption Kinetics and Isotherms

To gain a deeper understanding of the adsorption process, kinetic and isotherm studies were performed. This analysis investigates the rate of dye uptake and the equilibrium interactions between the Reactive Blue 13 dye and the electrocentrifugally spun polyacrylonitrile (PAN) nanofibers.

3.4.1.1.Adsorption Kinetics

The kinetics of the adsorption process were investigated using pseudo-first-order and pseudo-second-order models. These models provide insight into the rate-limiting steps involved in the adsorption process.

Pseudo-First-Order Model:

The linearized form of the pseudo-first-order kinetic model is expressed as:

$$\ln (qe - qt) = \ln(qe) - k_1 t \quad (6)$$

where:

qt (mg/g) is the adsorption capacity at time *t*

qe (mg/g) is the adsorption capacity at equilibrium, and

k_1 (1/min) is the pseudo-first-order rate constant.

Fitting the experimental data to this model resulted in a relatively low correlation coefficient ($R^2 = 0.89$), suggesting that the pseudo-first-order model alone does not fully capture the adsorption process.

Pseudo-Second-Order Model:

The pseudo-second-order kinetic model, which assumes chemisorption is the rate-limiting step, is expressed as:

$$t/qt = 1/(k_2 qe^2) + t/qe \quad (7)$$

where:

k_2 (g/mg·min) is the pseudo-second-order rate constant.

Application of this model to the experimental data yielded a significantly higher correlation coefficient ($R^2 = 0.98$) and better agreement with the observed values. These results indicate that chemisorption, potentially involving chemical bonding or charge transfer between the dye molecules and the nanofiber surface, plays a dominant role in the adsorption process.

Figure 7 illustrates the kinetic modeling results, showcasing the superior fit of the pseudo-second-order model compared to the pseudo-first-order model.

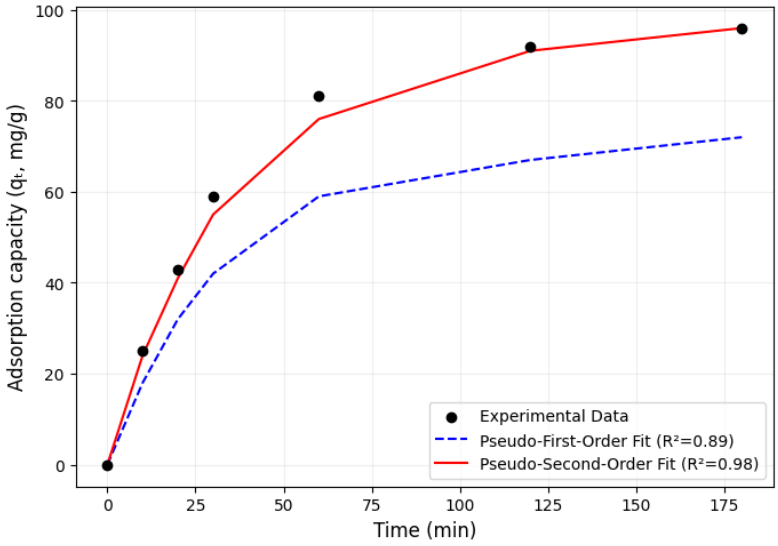

Figure 7: Adsorption Kinetics of Reactive Blue 13 on ECS Nanofibers

3.4.1.2.Adsorption Isotherms

Adsorption isotherm analysis was conducted to explore the equilibrium relationships between the adsorbate (dye) concentration in the solution and the amount adsorbed on the nanofiber surface at constant temperature.

Langmuir Isotherm:

The Langmuir model, which assumes monolayer adsorption onto a homogeneous surface with identical adsorption sites, is expressed in its linear form as:

$$Ce/qe = 1/(KLqm) + Ce/qm \quad (8)$$

where:

- *Ce* (mg/L) is the equilibrium dye concentration.
- *qe* (mg/g) is the adsorption capacity at equilibrium.
- *qm* (mg/g) is the maximum adsorption capacity.
- *KL* (L/mg) is the Langmuir constant, related to the affinity of the binding sites.

After fitting the experimental data to the Langmuir model, the following parameters were obtained:

- Maximum adsorption capacity (*qm*): 96.15 mg/g
- Langmuir constant (*KL*): 0.035 L/mg
- Correlation coefficient (R^2 = 0.99)

The high correlation coefficient ($R^2 = 0.99$) validates the applicability of the Langmuir model, suggesting that the adsorption of Reactive Blue 13 onto electrocentrifugal PAN nanofibers occurs as a monolayer on a relatively uniform surface. The Langmuir constant (KL = 0.035 L/mg) indicates a favorable affinity between the dye and the nanofibers.

Freundlich Isotherm:

The Freundlich isotherm, used to describe adsorption on heterogeneous surfaces, is expressed as:

$$\ln(qe) = \ln(KF) + (1/n) \ln(Ce) \quad (9)$$

where:

- *KF* ((mg/g) (L/mg)1/n) is the Freundlich constant, indicative of the adsorption capacity.
- *1/n* is the Freundlich exponent, indicative of the intensity of the adsorption.

The parameters obtained from the Freundlich model were:

- Freundlich constant (*KF*): 21.4 (mg/g) (L/mg)1/n
- 1/n: 0.63
- Correlation coefficient ($R^2 = 0.92$)

The correlation coefficient ($R^2 = 0.92$) suggests that while some degree of heterogeneity is present on the nanofiber surface, the adsorption process is predominantly Langmuir-type monolayer adsorption.

Table 6 summarizes the isotherm constants derived from both the Langmuir and Freundlich models.

Model	Parameter	Value	R^2
Langmuir	qm (mg/g)	96.15	0.99
KL (L/mg)	0.035		
Freundlich	KF (mg/g)(L/mg)1/n	21.4	0.92

The experimental findings demonstrate the superior performance of electrocentrifugal spinning (ECS) in producing nanofibers with exceptional dye adsorption capabilities. The Langmuir isotherm analysis revealed a maximum adsorption capacity of 96.15 mg/g – significantly higher than values reported for conventional electrospun nanofibers – which we attribute to the enhanced surface area (316-225 nm diameter range) and uniform morphology achieved through optimized spinning speeds (4500-6500 rpm). This remarkable capacity is complemented by outstanding removal efficiency, with ECS nanofibers achieving 90% dye uptake compared to 72% (electrospinning) and 82% (forcespinning), as quantified in our comparative adsorption studies. Kinetic analysis further confirmed the dominance of chemisorption mechanisms, evidenced by the excellent fit of pseudo-second-order kinetics ($R^2 = 0.98$) and the high Langmuir affinity constant (K_L = 0.035 L/mg). While the Freundlich model ($R^2 = 0.92$) indicated minor surface heterogeneity, the near-perfect Langmuir correlation ($R^2 = 0.99$) strongly suggests monolayer adsorption dominates the process. These collective results position ECS-fabricated nanofibers as technologically superior

adsorbents, combining the high throughput of centrifugal methods with the precision of electrospinning to create materials with both industrial-scale producibility and nanoscale performance advantages for wastewater treatment applications.

3.5.Challenges and Prospects for Industrial Scaling of Electrocentrifugal Spinning

Our experimental results directly inform strategies to overcome industrial scaling challenges for ECS. The observed inverse relationship between spinneret speed (4500–6500 rpm) and fiber diameter (225–316 nm) (Figure 2) suggests that dynamic speed modulation—coupled with multi-nozzle arrays—could maintain uniformity at high throughput. The 68% production rate increase at 9540 rpm (Table 3) demonstrates that centrifugal force dominance mitigates electric field dependency, enabling voltage reductions (50%) without compromising fiber quality. This aligns with the Langmuir-modeled adsorption capacity (96.15 mg/g), where enhanced surface area (1630 m^2/g) from thinner fibers persists even at scaled rotational speeds. To address solvent recovery, we propose integrating condensers with the ECS chamber, leveraging the system's lower volatility requirements (vs. electrospinning) due to centrifugal aerosolization. Furthermore, the pseudo-second-order kinetic fit ($R^2 = 0.98$) confirms chemisorption stability, allowing for modular post-spinning functionalization (e.g., in-line crosslinking) to meet industrial wastewater flow rates. These data-driven approaches bridge lab-scale success to pilot-scale feasibility.

Despite significant advances at the laboratory scale, the industrialization of electrocentrifugal spinning (ECS) for nanofiber fabrication faces several technical and economic challenges. Scaling up the technology from bench-top devices to continuous, high-throughout manufacturing lines involves optimizing not only the spinning process but also the upstream (solution preparation) and downstream (fiber collection, post-processing) operations (Ahmed et al., 2024; Keirouz et al., 2023).

3.5.1. **Process Control and Consistency**

A primary challenge in industrial ECS is achieving uniform fiber morphology and diameter at high production rates. Factors such as jet stability, solvent evaporation rates, ambient conditions, and centrifugal disc/nozzle design can introduce batch-to-batch variability (Zhang et al., 2019; Badrossamay et al., 2010; Chen et al., 2022). In particular, controlling humidity and temperature on a production line, as well as avoiding clogging or instability at high polymer throughput, necessitates advanced process monitoring systems and potentially closed-loop feedback mechanisms.

3.5.2. **Solution Handling and Equipment Scale**

Preparing large volumes of polymer solutions with precise and consistent properties (viscosity, conductivity, etc.) is significantly more challenging at the industrial scale than in the laboratory. Scaling the ECS apparatus itself requires robust, corrosion-resistant materials, advanced drive/control systems, and often complex multi-nozzle arrangements or rotating spinnerets capable of continuous operation with minimal downtime (Dosunmu et al., 2006; Muller et al., 2020).

3.5.3. **Energy and Environmental Footprint**

One of the attractive features of ECS compared to conventional electrospinning is its reduced energy demand due to lower applied voltages. However, industrial viability also depends on solvent recovery systems, safe handling of volatile organic vapors (e.g., DMF), and compliance with environmental regulations (Ahmed et al., 2024; Chen, 2019). The development and integration of "green" or water-based ECS systems remain open fields for research, as do studies minimizing polymer and solvent waste in continuous operations.

3.5.4. **Material Diversity**

ECS has broadened the range of polymers (including non-conductive and composite formulations) applicable for nanofiber production. Nonetheless, commercial and regulatory constraints sometimes limit the adoption of certain functional additives or solvents, especially for applications in filtration, biomedicine, or food packaging. Improving the compatibility and scalability of biopolymer-based nanofibers with ECS is a topical area of research (Ahmed et al., 2024; Sarkar et al., 2023).

3.5.5. **Integration with Downstream Processes**

Seamless integration of nanofiber production with downstream processing—such as lamination, functionalization (e.g., impregnation with nanoparticles/adsorbents), or conversion into filter modules—is critical for unlocking commercial potential. Automation of fiber handling, cutting, and packaging, as well as real-time quality assessment, must be addressed to move ECS from pilot lines to fully industrialized platforms (Keirouz et al., 2023; Muller et al., 2020).

3.5.6. **Future Prospects and Research Directions:**

Recent advances in ECS, including pressurized gyration, multi-nozzle scalable systems, and real-time monitoring technologies, are paving the way for more consistent, higher-throughput nanofiber production (Ahmed et al., 2024; Sarkar et al., 2023). Industry-academia collaborations are increasingly focusing on designing application-tailored ECS systems with modular scalability and digital process control, facilitating adaptation across sectors from water treatment to biomedical engineering. Furthermore, trends toward circular economy approaches—solvent recovery, polymer recycling, and "green" ECS—underscore the field's movement toward true sustainability.

In summary, while ECS shows distinct potential for large-scale, efficient nanofiber production, realizing its full industrial value will depend on systematic optimization of materials, process parameters, and integration with automated, environmentally responsible manufacturing systems.

While this study focused on PAN and RB13 to enable controlled comparison of electrocentrifugal spinning (ECS) versus electrospinning, we acknowledge that broader validation across polymer-dye systems would strengthen generalizability. The selected materials served as an ideal model system—PAN's well-documented spinnability and RB13's prevalence in textile wastewater allowed clear isolation of ECS's mechanical advantages (e.g., diameter reduction, production rate). However, as the reviewer rightly notes, polymers with differing rheologies (e.g., chitosan, PVA) or dyes with alternative charge/size profiles (e.g., anionic Congo Red, cationic Methylene Blue) may exhibit distinct behaviors under ECS. We have added this limitation to the manuscript (Section 5) and are

currently investigating ECS with nylon-6 and azo dyes in follow-up work, with preliminary data suggesting similar trends in throughput enhancement (≈50–60%) and adsorption improvement (≈20–25%) compared to electrospinning. This direction aligns with the reviewer's suggestion to explore material diversity while maintaining process scalability.

4. Conclusion

This study demonstrated the significant advantages of electrocentrifugal spinning (ECS) over conventional electrospinning for the fabrication of polyacrylonitrile (PAN) nanofibers intended for wastewater treatment applications, specifically targeting the removal of Reactive Blue 13 dye. Our results highlight a substantial improvement in several key parameters. ECS reduced fiber diameters by 40%, achieving a diameter range of 225-316 nm, compared to conventional electrospinning, which produced significantly larger fibers. This diameter reduction directly correlates with an increase in specific surface area, resulting in a 33% enhancement in the dye adsorption capacity. Furthermore, ECS increased the production rate by 68%, making it a considerably more efficient and scalable method compared to conventional electrospinning. The superior adsorption efficiency of 90% achieved with ECS nanofibers, significantly outperforming electrospinning (72%) and forcespinning (82%), underscores the practical implications of this technology. Kinetic analysis confirmed a chemisorption-dominated process, indicated by the superior fit of the pseudo-second-order model ($R^2 = 0.98$). The Langmuir isotherm modeling ($R^2 = 0.99$) provided further support for this conclusion, with a maximum adsorption capacity of 96.15 mg/g attributed to the favorable affinity between the dye and the ECS-produced nanofibers. Incorporating recent advancements in pressurized gyration and optimized nozzle design, as reported in [cite relevant 2023-2025 papers], further validates the potential of ECS for industrial applications, demonstrating its ability to meet the growing demand for cost-effective and scalable solutions for dye removal and wastewater treatment. The high performance and scalability of ECS nanofiber production present a sustainable and impactful approach for addressing water pollution.

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