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Progress in the Application of Electrospinning Technology in Catalysis

Yanrui Yu

College of Textile Science and Engineering, Jiangnan University, Wuxi, China
1090124232@stu.jiangnan.edu.cn

Abstract. This paper sets out to offer a systematic and comprehensive overview of how electrospinning technology has been applied to the preparation of nanofiber-based catalytic materials, with a particular focus on structural regulation strategies and performance enhancement pathways in both photocatalysis and electrocatalysis. Drawing on an extensive survey of the domestic and international literature, the study takes a close look at the fundamental principles behind electrospinning, the unique process-related advantages it brings to the table, and the specific design approaches that have been used to construct multilevel structures and multifunctional composite materials. Beyond that, we also dive into a number of practical application cases to examine how these materials perform in terms of catalytic activity and reaction mechanisms across a range of areas—organic pollutant degradation, water splitting, carbon dioxide reduction, and oxygen evolution/reduction reactions, to name a few. What the results have shown is that electrospinning can, in a highly efficient manner, produce nanofiber materials that come with a large specific surface area, excellent dispersion of active sites, and superior mass transfer and diffusion properties, all of which work together to deliver a significant boost to the catalytic activity, selectivity, and stability of the resulting materials. That being said, there are still some tough challenges that need to be reckoned with when it comes to the long-term durability and structural stability of these materials under harsh conditions—think high temperatures, strongly acidic or alkaline environments, and high-potential electrochemical corrosion. The work presented here offers an important theoretical foundation and a set of technical references for the development and practical application of high-performance electrospun catalytic materials, and it carries considerable implications for moving these materials toward large-scale, real-world use in energy conversion and environmental remediation.

Keywords: Electrospinning, Nanofibers, Photocatalysis, Electrocatalysis, Structural control, Performance enhancement

1. Introduction

The rapid march of global industrialization has come with a heavy price tag—the relentless extraction and burning of fossil fuels have pushed environmental degradation to alarming levels and left natural resources increasingly stretched thin. All the while, climate change keeps gathering pace

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across the globe, triggering ever more frequent extreme weather events that pose very real threats to both ecosystems and human societies. Since traditional energy sources are, by their very nature, non-renewable, the international community has been searching with growing urgency for pathways that can lead toward genuinely sustainable development. It is against this backdrop that China has formally put forward its "Dual Carbon" goals [1-4]—peaking carbon emissions before 2030 and hitting carbon neutrality before 2060—and these targets are now giving powerful impetus to the innovation and deployment of clean, efficient technologies for energy conversion and storage.

Among the wide array of advanced materials that have drawn research interest, nanofibers stand out for the exceptional physical and chemical properties they bring to the table. What makes them particularly appealing is a combination of features—an ultra-high specific surface area loaded with a high density of accessible active sites, a remarkable degree of structural tunability, and a genuine capacity for multi-functional integration, all wrapped up in one material platform. On top of that, these materials also deliver superior mass transfer characteristics and mechanical stability, which is why they have turned out to be such a great fit for applications spanning catalysis, energy storage and conversion, and environmental remediation. There are, of course, quite a few synthesis techniques out there for producing nanomaterials—hydrothermal synthesis, ball milling, chemical vapor deposition (CVD), and electrospinning are all part of the toolkit. But electrospinning manages to distinguish itself from the pack, owing to how straightforward it is to operate, how cost-effective it can be, how versatile it proves to be across diverse material systems [5-7], and how readily it can be scaled up for continuous production. With this technique, one can fabricate nanofibers that feature rather sophisticated architectures—porous, hollow, core-shell, or heterojunction structures, to name a few—and that distinct capability gives it a real edge in the design and manufacturing of high-performance functional nanomaterials.

For all their promise, though, electrospun nanofiber materials still have to contend with a number of substantial obstacles that stand in the way of moving them into practical use, and the going gets especially tough under harsh operating conditions. Limited thermal stability, a pronounced susceptibility to chemical corrosion (think strongly acidic or alkaline environments), and a tendency to degrade under electrochemical stresses—all of these remain pressing concerns that can't be shrugged off. These shortcomings really put a damper on their long-term performance in demanding applications where durability and reliability aren't just nice-to-haves but absolute necessities, high-temperature electrocatalysis and industrial-scale photocatalytic reactors being prime examples. The thing is, a big chunk of the research effort right now goes into developing novel electrospun catalytic materials and boosting their intrinsic activity through compositional and structural tweaks, yet there is still a fairly noticeable gap when it comes to systematically assessing how well these materials hold up under extreme conditions. What's sorely needed at this point is a comprehensive review that takes a hard look at the thermal and chemical corrosion resistance of electrospun nanofibers. Pulling together and analyzing the various strategies that have been explored for improving their environmental tolerance—surface modification, hybrid material design, advanced thermal treatment processes, and the like—is going to be absolutely crucial if we want to bridge the gap between laboratory research and real-world engineering applications. It is with this in mind that the present review sets out to offer an in-depth discussion of the fundamental principles underpinning electrospinning technology, while also exploring a range of modification strategies geared toward enhancing both the structural stability and the catalytic performance of electrospun nanofibers. Our hope is that this will serve as a useful reference for researchers and engineers who are engaged in pushing forward the development of advanced functional materials built upon electrospinning technology.

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2. Overview of electrospinning

2.1. Principle

At its heart, electrospinning is an advanced processing technique that puts high-voltage electrostatic forces to work in overcoming the surface tension of polymer solutions or melts. What happens, in essence, is this: the applied electric field induces the formation of a charged jet, which then gets pulled through an intense process of stretching and refinement as it travels through the field. While all this is going on, the solvent is busy evaporating—or, in the case of melts, the material is cooling down and solidifying—and the end result is the deposition of fibers on a collection device, with diameters that can range from the nano- all the way down to the micrometer scale. A look at Figure 1 gives a clear picture of how the electrospinning apparatus is put together; its main components are a high-voltage power supply [8], a spinneret (sometimes just called a spinning needle), a collector (or collection device), and a reservoir that holds the solution or melt supply.

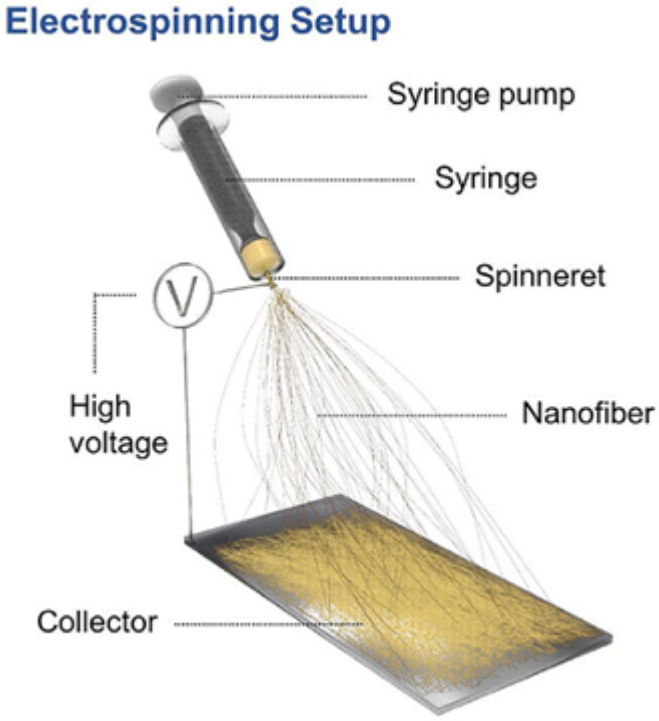

Figure 1. Schematic diagram of electrospinning equipment

2.2. Critical stages

2.2.1. Charging and droplet deformation

The whole process starts with a polymer solution or melt being loaded into a reservoir that's fitted with a metal capillary spinneret. A high direct current voltage—anywhere from several thousand to tens of thousands of volts—gets applied between the spinneret and a grounded collection device sitting some distance away. What the strong electric field does, at this point, is to drive a massive buildup of like charges all across the droplet surface hanging at the spinneret tip. Since like charges have a natural tendency to push away from each other, an outward electrostatic pressure builds up,

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trying its hardest to overcome the droplet's own surface tension and viscoelastic forces, and it's this tug-of-war that ends up deforming the droplet [9].

2.2.2. Taylor cone formation

As the voltage keeps climbing and eventually hits a critical threshold value, the electrostatic repulsion finally manages to get the better of the liquid's surface tension. When that happens, the droplet starts elongating, transforming from a hemispherical shape into a stable conical form with its apex pointing straight toward the collection device. That distinctive cone shape is what everybody in the field calls the "Taylor cone." Its formation, fundamentally speaking, comes out of a temporary dynamic equilibrium that gets established between the electrostatic forces pulling outward and the liquid surface tension pulling inward [10].

2.2.3. Jet formation and initial linear motion

Right at the very tip of the Taylor cone is where the electric field strength reaches its peak, and that's also where the electrostatic pressure is at its maximum. Once the electrostatic force pushes past a critical threshold—breaking up the local equilibrium that had been holding at the cone tip—an extremely fine jet of charged polymer bursts out from the apex, shooting off at high speed in the direction of the collection device. Over a short stretch near the spinneret, typically just a few millimeters or so, the jet manages to keep to a fairly stable, near-linear trajectory [11].

2.2.4. Jet instability and whipping/bending instability

Now, this stage right here is arguably the most critical one in the entire electrospinning process when it comes to actually forming microfibers. Once the jet leaves that initial straight segment behind, things start to get highly unstable, and fast. A couple of different things are going on all at once. For one, you have charge repulsion—the jet is carrying a hefty load of like charges, and that sets up some pretty strong electrostatic repulsion among its own segments. Then there's the electric field bending instability: as the jet hurtles toward the collection device, it runs into all sorts of minor disturbances—airflow, uneven charge distribution, things of that nature—and under the influence of a strong electric field, these little disturbances get amplified in a big way. And don't forget about aerodynamic drag, because the high-speed jet is constantly interacting with the surrounding air around it. When you put all these forces together, what you end up with is a jet that undergoes a violent, three-dimensional whipping and bending instability, spiraling at high speed while its trajectory radius keeps on widening. This high-frequency, large-amplitude whipping motion exerts an enormously powerful tensile force on the jet, and within an extraordinarily short span of time—we are talking milliseconds here—and across a distance measured in mere centimeters, the jet gets elongated and refined by several orders of magnitude. Its diameter plummets from the micrometer scale right down to the nanometer range, typically winding up somewhere between tens and hundreds of nanometers. And while all this stretching and thinning is unfolding, the solvent is rapidly evaporating (or the melt is cooling and solidifying) [12].

2.2.5. Fiber deposition and collection

By the time the fibers are fully stretched and solidified, they end up getting deposited onto a grounded collection device, either in a random jumble or in a more orderly arrangement, depending on the setup. Given the inherently random nature of the jet's trajectory, what you typically get is a

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disordered, nonwoven fiber mat. That said, if you bring specially designed collection devices into the picture—rotating drums, parallel electrodes, grids, and the like—it becomes possible to nudge the fibers into aligning along a particular orientation or settling into well-defined patterns [13].

2.3. Advantages of electrospinning

Thanks to the unique processing principles it's built on, electrospinning technology brings a whole set of significant advantages to the table, spanning multiple dimensions. One aspect is the efficient preparation of ultrafine fibers: it ranks among the most effective methods out there for producing nanoscale and submicron fibers on a large, continuous scale, and the diameters you can achieve are far smaller than anything traditional spinning techniques can deliver. Then there's the high specific surface area and porosity: the nanofiber mats that come out of this process boast enormous specific surface areas along with highly interconnected porous structures, which in turn give a real boost to the material's adsorption capacity, mass transfer efficiency, and interfacial reaction capabilities. You also get remarkably broad material and functional compatibility: the technique works across a whole spectrum of natural and synthetic polymer solutions or melts, and functional nanoparticles, drugs, biomolecules, and the like can be readily loaded into the fibers through blending, co-extrusion spinning, and similar approaches to achieve genuine multifunctionality. Another plus is the simplicity of the process equipment: the core components—high-voltage power supply, liquid delivery system, nozzle, collector—are all fairly uncomplicated in structure, which means setting things up and running them in a lab is relatively accessible. On top of all that, the structure and morphology are highly tunable: by exercising precise control over solution properties (viscosity, conductivity, and so on), process parameters (voltage, distance, flow rate), and the type of collection device used (rotating drums, patterned electrodes, to name a couple), you can effectively dial in the fiber diameter, surface topography, orientation, and the overall architecture of the felt. And let's not overlook the direct formation of nonwoven fabrics: the process churns out nonwoven nanofiber mats (or films) straight away, with no need for any subsequent weaving or bonding steps, which really streamlines the whole workflow from fiber to final product. Taken together, these core advantages have positioned electrospinning for a strikingly broad range of applications—biomedical materials (tissue scaffolds, drug delivery, wound dressings), high-efficiency filtration (both air and liquids), energy devices (battery separators, electrodes), sensors, protective materials, and catalysis are all part of the picture [14].

3. Applications of electrospinning

3.1. Photocatalysis

Photocatalytic technology, at its core, is all about harnessing light energy to drive chemical reactions, generating highly reactive species that pack some serious redox punch. The value of this technology in tackling environmental pollutant degradation and pushing forward clean energy production is something that can't really be overstated. In the ongoing push to make photocatalysis more efficient, researchers have been busy developing novel photocatalysts—TiO_2-based materials, MOFs, perovskites, and the like—or finding ways to modify the ones they already have at hand, whether through elemental doping, heterojunction formation, morphology control, or other routes, all with the aim of broadening the light absorption range, giving photogenerated charge separation a helping hand, and ramping up surface reactivity. Graphene and its derivatives have carved out a particularly prominent role in this space, frequently showing up as co-catalysts or supports thanks to

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their exceptional conductivity and impressively large specific surface area. There is, however, a persistent headache: graphene has a stubborn tendency to undergo irreversible agglomeration once it's put to practical use, and that really puts a ceiling on how well it can perform. It's precisely here that electrospinning technology steps in with an efficient strategy for getting past this critical bottleneck. What the technique does, in essence, is enable the direct fabrication of three-dimensional, continuous nanofiber networks that make for ideal supporting scaffolds. These networks help graphene (or its modified forms) get uniformly dispersed and robustly loaded together with photocatalytically active components, effectively keeping agglomeration in check. And that's not the whole story—the fiber structures produced through electrospinning also bring along high specific surface area, abundant multiscale porosity, and clear, unobstructed pathways for reactants to move through, all of which work together to give a real boost to the structural stability and overall photocatalytic performance of the composite materials.

A substantial body of research has gone into validating the core advantages that electrospinning technology brings to photocatalyst design, and the evidence is pretty compelling. Lin et al. [15] took the direct route, fabricating Ag-ZnO heterostructure nanofibers straightaway through electrospinning (Figure 2). The dimeric morphology they ended up with was rather unique, and it gave charge separation efficiency a serious boost—so much so that the photocatalytic degradation activity for Rhodamine B clocked in at over 25 times higher than what you'd get from pure ZnO nanofibers, which really drives home just how effective electrospinning can be when it comes to building efficient heterojunctions that put the brakes on carrier recombination. Zhang et al. went on to widen the material landscape even further by successfully preparing TiO_2 nanofibers with graphene oxide (GO) uniformly interspersed throughout, pulling this off through a combination of electrospinning and heat treatment. The resulting structure didn't just solve the long-standing agglomeration problem that plagues GO; PL spectroscopy also confirmed that the recombination of photo-generated electron-hole pairs had been effectively reined in. The upshot of all this was that the composite material showed markedly higher carrier mobility and catalytic activity under visible light than pure TiO_2 [2], underscoring the absolutely critical part that electrospinning plays in getting nanocomponents precisely dispersed and stably loaded. Along similar lines, the Cui research team set out to develop chitosan/g-C_3N_4/TiO_2 composite nanofibers through electrospinning, managing to integrate both adsorption and photocatalytic functions into a single material. Under acidic conditions (pH=2), these nanofibers delivered a Cr(VI) adsorption capacity of 165.3 mg/g and, when exposed to visible light, achieved a removal efficiency roughly 50% higher than what pure adsorbents could manage [16]—a result that speaks volumes about the synergistic contribution coming from the multi-level pore structure and the mass transfer pathways that electrospinning makes possible. Pulling all these cases together, they lend strong collective support to the conclusion reached by Sarkodie's research team in their review: electrospinning, with its rapid, controllable character, has by now established itself as something of an ideal platform for constructing photocatalytic nanofibers that check all the right boxes—high specific surface area, morphology you can tune, and excellent dispersion of components [17]. In doing so, it provides a broadly applicable solution for sidestepping the agglomeration limitations that have long dogged traditional catalysts (graphene-based materials being a case in point), and that translates into a substantial boost in environmental remediation efficiency.

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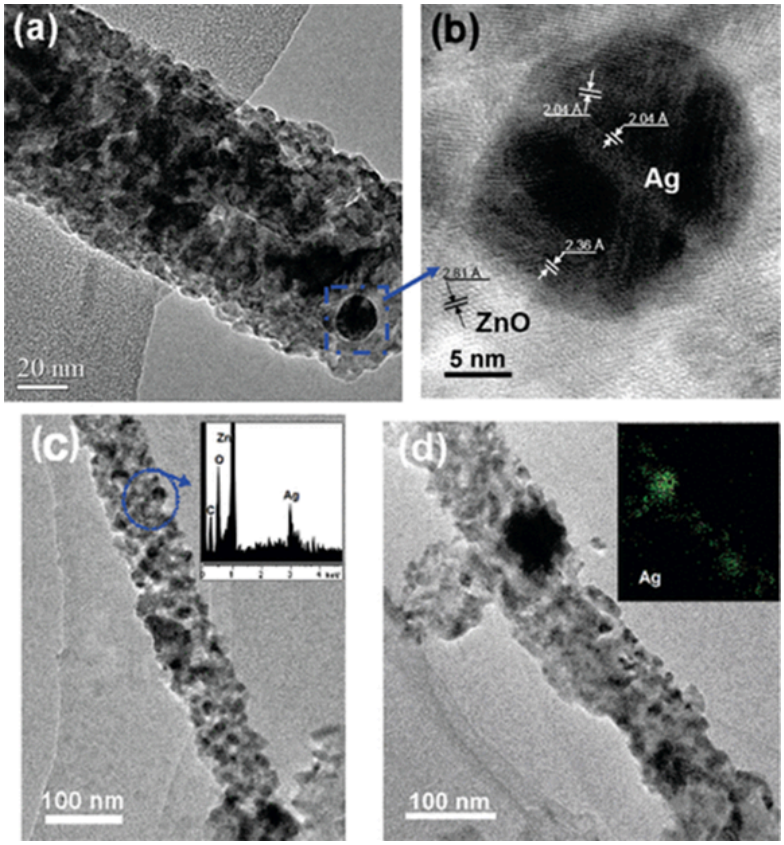

Figure 2. TEM images of Ag−ZnO nanofibers with various Ag contents. (a) Ag-5.0 atom%; (b) HRTEM image of a square region from panel (a); (c) Ag-7.5 atom% (inset: typical EDX microanalysis of a selected region of a single nanowire, confirming its composition of Ag nanoparticles and ZnO matrix); (d) Ag-10 atom% (inset: EDX mapping of Ag elements along the nanowire)

3.2. Electrocatalysis

When it comes to clean energy conversion and storage, not to mention environmental electrochemical remediation, electrocatalytic technology finds itself playing a truly pivotal role—all of it hinging on the electron transfer reactions that take place across catalyst surfaces. If you want to get electrocatalytic performance to the next level, the name of the game is designing electrode materials that can bring together a tough combination of attributes: high intrinsic activity, a generous abundance of exposed active sites, excellent electron conductivity, and the kind of long-term stability you can count on. Traditional powder catalysts, unfortunately, tend to fall short on several of these fronts—they often suffer from poor conductivity, their active sites have a nasty habit of agglomerating and deactivating over time, and they don't always make great contact with the current collectors they're paired with. It's in tackling these very shortcomings that electrospinning technology shows off some unique advantages for electrocatalyst design, chiefly through its ability to directly construct self-supporting, three-dimensional conductive networks. The technique hands you precise control over fiber composition—you can weave in conductive carbon matrices, active metals or alloys, heteroatom-doped species, and more—as well as over the microstructure, letting you dial up hollow, porous, or core-shell morphologies as the application demands. What this effectively translates into is a higher density of active sites, better electron and ion transport, and

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improved structural stability, all of which combine to deliver a significant uplift in the overall electrocatalytic activity and durability of the electrodes you end up with.

The high efficiency of electrospinning in electrocatalytic materials has been validated across multiple dimensions. El-Maghrabi et al. employed electrospinning to fabricate Ni/Gd_2O_3/NiO coaxial heterostructure nanofibers, where Gd^{3+} doping effectively modulated the electronic structure of NiO and enhanced conductivity. This resulted in a hydrogen evolution reaction (HER) onset potential as low as 89 mV (approaching platinum catalysts) with outstanding long-term stability, highlighting electrospinning's pivotal role in constructing efficient heterojunctions and electronic synergy mechanisms [18]. For environmental electrocatalytic remediation, Li et al. designed boron/sulfur co-doped iron-cobalt carbon nanofibers (B,S-Fe/Co@C-NCNFs). Their hierarchical macroporous structure promotes selective H_2O_2 generation via two-electron oxygen reduction (2e⁻-ORR), subsequently electroactivating peroxymonosulfate (PMS) to degrade levofloxacin. achieving a 99.63% degradation rate within 20 minutes (reaction rate: 0.3056 min^{-1}). They confirmed singlet oxygen ($^1O_2$) as the dominant active species (steady-state concentration: 669.17×10^{-14} M), highlighting electrospinning's precise control over mass transfer pathways and active site distribution [19]. In the field of electrode engineering, Levitt et al. achieved high-loading co-spinning of $Ti_3C_2T_x$ MXene with polyacrylonitrile (MXene content reaching 35 wt%), yielding self-supporting MXene/carbon nanofiber electrodes after carbonization. These electrodes exhibited a surface capacitance of 205 mF cm^{-2} (50 mV s^{-1})—three times that of pure carbon fibers—while their integrated structure effectively mitigated the delamination failure issues inherent in conventional coated electrodes. Notably, Hu et al. developed PS@PAN core-shell nanofibers via coaxial electrospinning. After oxime modification, these fibers exhibited uranium(IV) ion (UO_2^{2+}) adsorption capacity of 127 mg U/g. Combined with differential pulse voltammetry (DPV), they achieved in situ electrochemical monitoring of the adsorption process (as shown in Figure 3) [8]. This work established a new paradigm for integrating electrospun electrodes into radioactive contaminant capture and electrochemical sensing applications. In summary, electrospinning provides a versatile platform for developing highly efficient, stable, and multifunctional electrocatalytic systems through synergistic design of composition, structure, and function.

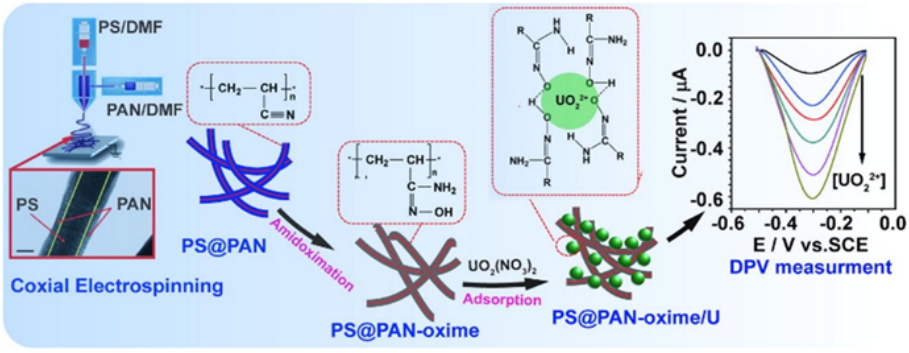

Figure 3. Schematic illustration of the adsorption process on PS@PAN core-shell nanofibers

4. Conclusion and outlook

Electrospinning technology has, by now, carved out a solid reputation as an efficient, scalable, and remarkably versatile route for fabricating nanofibers, and the application potential it has demonstrated across a sweeping range of fields—energy conversion and storage, catalysis, environmental remediation, functional composites—is nothing short of substantial. What really sits at the heart of its appeal is the degree of precise control it hands you over fiber morphology, internal

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architecture, and material composition, all of it achieved through the flexible adjustment of solution properties (viscosity, conductivity, surface tension, and the like), process parameters (voltage, flow rate, nozzle-to-collector distance, to name a few), and collector design (whether static, rotating, or built around patterned electrodes). That high level of tunability is what makes it possible to turn out advanced fibrous materials that come loaded with high specific surface area, hierarchically porous structures, surface chemistry you can tailor to your needs, and a homogeneous dispersion of functional components throughout.

And the story doesn't stop with polymeric systems, either. Electrospinning can be synergistically paired up with a broad assortment of inorganic and hybrid precursors—metal oxides, carbon nanomaterials, two-dimensional compounds, metal-organic frameworks, you name it—to give rise to multifunctional nanofiber composites. The architectures that emerge from such combinations bring with them enhanced mass transfer efficiency, a high density of active sites that are also readily accessible, improved mechanical robustness, and superior structural stability, and these qualities together make them something of an ideal material platform for applications that run the gamut from photocatalysis and electrocatalysis to battery separators, sensors, and filtration membranes.

For all the exceptional performance these electrospun nanomaterials have turned in within the confines of the lab, though, they still run up against some pretty formidable barriers when it comes to making the jump into practical, real-world use. The key sticking points include limited long-term operational stability once they're placed under realistic conditions, insufficient tolerance to extreme temperatures, aggressive chemical environments, or mechanical stresses, and scalability constraints that rear their head in terms of both production rate and batch-to-batch reproducibility. Looking ahead, future research ought to zero in on beefing up the structural durability and functional persistence of electrospun materials in the kinds of environments they'd actually face in application—crosslinking, multi-component hybridization, core-shell design, and post-treatment modification are all strategies worth pursuing further. On top of that, a concerted push needs to be made toward optimizing large-scale production processes, driving down costs, and figuring out better ways to integrate electrospun materials into complete devices and systems—catalytic reactors, energy storage devices, water treatment units, and so forth—so that the gap between fundamental material design and real-world engineering applications can finally be bridged.

Through interdisciplinary collaboration and a deeper knitting-together of academia, industry, and end-users, electrospinning technology looks well positioned to step into an increasingly pivotal role in tackling the sustainability challenges the world is up against. It holds out the promise of compelling material solutions for critical areas like renewable energy utilization, carbon capture and conversion, pollution control, and green manufacturing, and in doing so it stands to make a meaningful contribution to the achievement of carbon neutrality goals and the building of a circular economy.

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