

REVIEW

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Coaxial electrospinning as a promising technique for fabricating advanced materials for energy storage applications

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Abstract

As the demand for efficient, high-performance energy storage systems intensifies, the need for innovative materials that can enhance energy density, power output, and cycle stability has become paramount. Coaxial electrospinning, a versatile nanofabrication technique, has emerged as a powerful method for producing advanced core-shell nanofibers with tailored properties specifically designed for energy storage applications. This review delves into the principles of coaxial electrospinning, highlighting its advantages over conventional fabrication techniques in creating multifunctional materials for batteries and supercapacitors. By manipulating the core and shell compositions, coaxial nanofibers offer superior ion/electron transport, mechanical stability, and electrochemical performance. The review discusses the latest breakthroughs in the field, including material selection, fiber design strategies, and the resulting improvements in energy storage capacity and durability. Challenges and future opportunities for scaling coaxial electrospinning to meet commercial demands are also explored, positioning this technique as a promising frontier for next-generation energy storage solutions.

Keywords Coaxial electrospinning, Energy storage applications, Advanced material fabrication, Nanofiber, Electrochemical performance optimization

1 Introduction

The accelerating global transition toward renewable energy sources has intensified the demand for efficient, durable, and sustainable energy storage systems. Technologies such as lithium-ion batteries, supercapacitors, and emerging hybrid devices have become indispensable in addressing the inherent intermittency of solar and wind power, ensuring a stable and reliable electricity supply across residential, industrial, and grid-scale applications [1, 2]. Central to the advancement of these technologies is the continued development of high-performance electrode and electrolyte materials capable of



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delivering improved energy and power densities, enhanced cycling stability, and greater safety, while remaining environmentally benign and scalable for mass production [3].

Although significant strides have been made in electrochemical energy storage research, conventional materials and fabrication methods still fall short of meeting the increasingly stringent performance requirements of next-generation devices [4–6]. Many existing materials suffer from structural instability, limited conductivity, sluggish ion transport, and incompatibility among constituent components, all of which undermine their long-term performance and reliability [7]. As the energy storage landscape evolves, there is a growing imperative to explore innovative material design strategies that enable hierarchical structuring, controlled interfacial engineering, and the integration of multifunctional components at the nanoscale [8–10].

Electrospinning has emerged as one of the most versatile and scalable techniques for fabricating continuous one-dimensional nanofibers with precisely controlled morphology and composition [11]. These nanostructures, characterized by large specific surface area, high porosity, and short diffusion pathways, have shown considerable promise in enhancing the electrochemical performance of energy storage devices [12, 13]. However, conventional single-fluid electrospinning remains limited in its ability to incorporate multiple functional materials or to create complex architectures capable of simultaneously addressing multiple performance bottlenecks [11, 14]. This limitation has stimulated interest in coaxial electrospinning, an advanced variant of the technique that enables the fabrication of core-shell nanofibers by simultaneously extruding two distinct solutions.

Coaxial electrospinning represents a significant evolution of the electrospinning process, offering an unprecedented degree of architectural control and material tunability [15–17]. By decoupling the properties of the core and shell layers, this approach allows the rational design of nanofibers that combine complementary functionalities and exploit synergistic interactions [16, 18, 19]. This capability is particularly well suited to addressing the major challenges that have long limited energy storage materials. For instance, the core-shell structure can buffer active materials against mechanical degradation and parasitic reactions during repeated cycling, thereby enhancing durability [16]. The inclusion of conductive components in either layer improves electron transport and interfacial charge transfer, while the high surface area and interconnected porosity of the fibers promote efficient ion diffusion and maximize active material utilization [20, 21]. Furthermore, coaxial electrospinning facilitates the integration of otherwise incompatible materials by spatially separating them within the fiber, allowing for controlled interface formation and stable operation [22].

In addition to its functional advantages, coaxial electrospinning remains a cost-effective and scalable process, compatible with a wide range of materials including polymers, carbonaceous compounds, transition metal oxides and sulfides, and hybrid composites [23]. These attributes make it highly attractive for real-world applications ranging from flexible electronics to large-scale grid storage [24]. Yet, despite its promise, the field is still in a relatively early stage of development. Research to date has tended to focus narrowly on specific material systems or device configurations, and a systematic understanding of optimal design strategies, structure-function relationships, and pathways to performance optimization remains underdeveloped [20, 25]. Existing reviews have either treated electrospinning broadly, without adequately distinguishing the unique

capabilities of the coaxial variant, or concentrated on isolated chemistries, leaving unexplored the broader potential of coaxial electrospinning as a transformative fabrication method for energy storage materials [16, 26].

This review seeks to address that gap by providing a comprehensive and critical synthesis of recent progress in coaxial electrospinning for energy storage applications. We examine the underlying principles of core–shell nanostructure formation, analyze recent advances in materials and device performance, and discuss the strategic considerations that govern materials selection, processing parameters, and integration into functional devices. At the same time, we identify key challenges, knowledge gaps, and opportunities for further innovation, offering a coherent perspective on how this technique can evolve to meet the demands of future energy technologies. By situating coaxial electrospinning within the broader context of energy storage research and articulating its distinctive advantages and limitations, this review aims to inspire new research directions, foster interdisciplinary collaboration, and accelerate the development of sustainable, high-performance energy storage solutions.

2 Coaxial electrospinning and its advancements

Electrospinning is a versatile and scalable technique for producing ultrafine polymer fibers, first conceptualized in the pioneering patents of Formhals during the 1930s [27, 28]. Initially, its use was limited due to the lack of suitable applications and materials. However, the resurgence of nanotechnology in the 1990s renewed interest in electrospinning as an effective method to fabricate nanofibrous materials with unique properties and high surface-to-volume ratios [29]. Early implementations predominantly relied on blend electrospinning, where two or more polymers were dissolved in a common solvent to produce homogenous composite fibers. This approach was straightforward and widely adopted, but it suffered from significant limitations, notably the inability to control the spatial distribution of individual components within the fiber matrix, and the potential incompatibility of mixed materials at the molecular level [27].

To address these challenges, researchers developed more advanced fiber architectures. A major breakthrough occurred in the early 2000s with the advent of coaxial electrospinning (and its analogous technique, coaxial electrospraying, when forming particles). This method, first reported by Sun et al. in 2003, utilized a concentric spinneret with two independently fed fluid streams to produce fibers with a distinct core–shell structure [11]. By physically separating the core and sheath materials during spinning, coaxial electrospinning enabled the encapsulation of functional or incompatible components within protective shells, vastly expanding the range of achievable nanofiber functionalities and opening new opportunities in encapsulation, controlled release, and surface modification.

Subsequent innovations led to the development of modified coaxial electrospinning, which further broadened the technique's applicability. In this variant, even unspinnable or low-viscosity fluids such as pure small-molecule drugs, oils, or aqueous solutions could serve as the core material, stabilized and encapsulated by a spinnable polymer sheath [30]. This adaptation allowed the inclusion of otherwise challenging-to-process materials within nanofibers, greatly enhancing the versatility of the technology in biomedical, pharmaceutical, and functional material applications.

Building on the coaxial configuration, researchers introduced tri-axial electrospinning, in which three distinct fluids were fed through a specialized spinneret to produce nanofibers with three concentric layers: an inner core, an intermediate layer, and an outer shell [31]. This more sophisticated architecture allows even finer control over material distribution and release kinetics, and enables multifunctional fibers with hierarchical structural features. While technically more demanding, tri-axial electrospinning exemplifies the progressive evolution of nanofiber fabrication toward greater complexity and functionality.

More recently, novel hybrid approaches have emerged, notably the combination of coaxial and side-by-side electrospinning. This technique enables the production of hybrid fibers with asymmetrical (Janus-type) morphologies that integrate both core–shell and side-by-side domains within a single fiber [32]. Such designs offer anisotropic properties, dual functionalities, and synergistic performance that are unattainable with traditional symmetric fibers, making them highly attractive for advanced applications requiring directional properties or compartmentalized functionalities. Collectively, these advancements underscore the remarkable evolution of electrospinning technology, transitioning from simple blend fibers to sophisticated, hierarchical, and tunable nanostructures. Coaxial, modified coaxial, tri-axial, and hybrid electrospinning strategies continue to push the boundaries of nanofiber design, enabling tailored materials for emerging applications in energy storage, biomedicine, environmental remediation, and beyond [33].

2.1 Strategies from electrospun Core–Sheath nanofibers for developing functional materials

Electrospinning, particularly the coaxial (or triaxial) variant producing core–sheath nanofibers, has emerged as a versatile platform for engineering functional materials with tailored structures and properties. This approach enables spatial separation of components into distinct regions (core and sheath) at the nanoscale, which can be exploited for controlled release, protection, encapsulation, or enhanced interfacial functionality. Several innovative strategies have been developed [34, 35].

Rather than abrupt boundaries, creating a *gradient distribution* of active components across the core–sheath structure has shown significant potential for applications requiring controlled and sustained functionality. Dong et al. (2024) demonstrated gradient release of bioactive compounds by tuning polymer solubility and diffusivity, achieving improved release kinetics and bioavailability [36]. Similarly, Chen and co-workers designed nanofibers with gradually distributed antioxidants, enhancing the protection of sensitive biomolecules and reducing burst release [37]. Such gradient designs improve the functional performance by mimicking natural concentration profiles and enabling staged functionality.

The use of a “blank” or inert sheath to encapsulate the functional core is another strategy to enhance stability and control release. Guo et al. (2024) demonstrated this by using a blank coating of biocompatible polymer around an encapsulated active, which acted as a protective barrier, preventing premature degradation while still allowing diffusion over time [38]. Such coatings are also effective at shielding sensitive components from environmental stressors (moisture, light, oxidation), making them suitable for food packaging and biomedical applications.

Creating hollow core–sheath nanofibers by selectively removing the core material offers unique advantages in applications requiring high surface-to-volume ratio, light weight, and selective permeability. These hollow fibers can act as micro- or nano-reservoirs for further loading, or as conduits for selective separation. For example, Wang et al. (2024) reported hollow nanofibers enabling efficient separation of gas mixtures due to their tailored porosity and selective barrier properties [39].

One of the hallmark advantages of core–sheath electrospinning is the high encapsulation efficiency of active compounds, even for sensitive or poorly soluble ingredients. The separation of active-loaded core from the external environment minimizes loss and degradation. Deng et al. (2025) reported core–sheath nanofibers encapsulating antimicrobial agents with >90% loading efficiency and sustained activity over prolonged periods [40]. This is particularly attractive for pharmaceuticals, nutraceuticals, and agrochemicals where precise dosing and stability are critical.

The above strategies illustrate the versatility of electrospun core–sheath nanofibers in creating functional materials with tailored release, protection, encapsulation, and separation properties. Gradient distributions mimic natural systems, blank coatings offer robust barriers, hollow fibers enhance surface area and selectivity, and the high encapsulation efficiency ensures optimal functionality. Future work could focus on scaling up these approaches, improving reproducibility, and integrating smart (stimuli-responsive) functionalities to further broaden application horizons in healthcare, food, environmental remediation, and beyond.

The unique nano core–sheath structure attainable through coaxial electrospinning has been a driving force behind its rising popularity in the fabrication of advanced functional materials. As highlighted by a recent literature [41], the ability to spatially organize two or more materials at the nanoscale within a single fiber offers distinct advantages: protection of sensitive actives, controlled release kinetics, enhanced interfacial interactions, and synergistic functionalities not achievable with homogeneous nanofibers. These advantages have opened up wide-ranging applications in drug delivery, tissue engineering, food preservation, sensors, and environmental remediation.

The key logic behind the success of the nano core–sheath architecture lies in its ability to decouple different functional roles into physically distinct regions: the core can serve as a reservoir for actives or provide mechanical strength, while the sheath can act as a barrier, modulate release, or interact with the environment. This design flexibility has made coaxial (and triaxial) electrospinning an increasingly attractive and widely used technique for material scientists and engineers [35]. However, despite these advances, one of the most critical gaps in the field remains a detailed understanding of the process–structure–performance relationships. Many studies focus on demonstrating functionality but provide limited mechanistic insights into how processing parameters (e.g., solution properties, flow rates, voltage, collector type) dictate the resulting core–sheath morphology, and how these structural features in turn influence the final material performance [29].

3 Energy applications

Coaxial electrospun nanofibers have found application in diverse energy storage technologies, with high potential in energy-related applications including Li-ion batteries, hydrogen generation, capacitors, etc. (Fig. 1) owing to the exceptional physicochemical

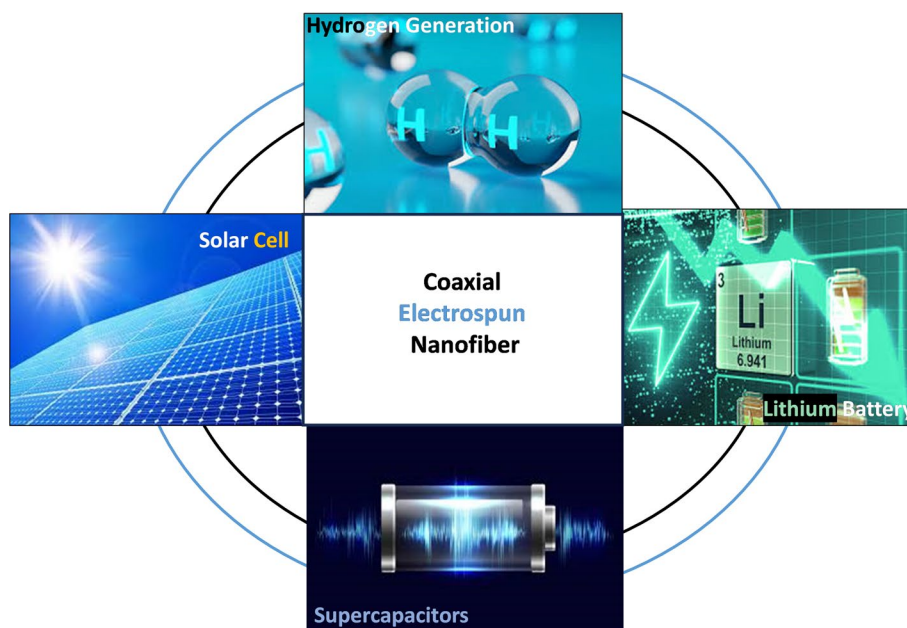


Fig. 1 Applications of Coaxial electrospun nanofiber for energy Storage devices

properties and flexible nature of their core-sheath structures, allowing for customized qualities [16, 42]. Their enormous surface area and adjustable porosity make them excellent for sensors and flexible energy devices.

More so, these nanofibers have applications in fields such as energy storage, conversion, and harvest. They improve electrode materials in batteries and supercapacitors by increasing electrical conductivity, ion mobility, and overall stability, resulting in more energy storage and longer device life [43–45]. Their structure facilitates the use of different materials, allowing for more control over electrochemical behavior. Studies have shown that coaxial nanofibers function as efficient catalysts and light-absorbing layers in fuel cells and solar cells, improving performance and durability. The adaptability of coaxial electrospinning creates numerous options for enhancing energy technologies, making them more sustainable and efficient.

3.1 Lithium battery

Advances in battery technology have expanded beyond lithium-ion systems, necessitating the development of improved materials that improve energy capacity, power, lifespan, and safety [16, 46, 47]. The materials utilized in today's batteries vary in size, shape, and structure, yet they still fall short of the performance requirements for next-generation technology. Electrospinning, a versatile and efficient technology for producing very thin fibers, has been widely used to create and design nanofibers from useful materials for application in batteries [16, 48]. That being said, it is worth noting that in the world of portable electronic devices, lithium-ion batteries (LIB) have evolved as a pervasive component, serving as a viable alternative and clean energy solution in lieu of fossil fuels [35, 49]. Renewable energy source demands high energy and power density, but despite the LIB's extremely high energy density ($\sim 3860 \text{ mAhg}^{-1}$), its metallic nature imposes limitations on its use as an anodic material due to significant concerns related to its low melting point, high reactivity with electrolytes, and propensity for dendrite growth

[50]. In 1991, carbon materials such as graphite garnered attention for their potential to mitigate negative concerns associated with lithium-ion batteries (LIBs) due to their low cost, durability, eco-friendliness, capacity, and low electrochemical reactivity against lithium metals [51]. However, they faced a setback due to limited capacity ($\sim 372 \text{ mA}\cdot\text{h g}^{-1}$) compared to LIB for variable applications that required higher energy, additionally, their poor recycling efficiency and the dendritic lithium metal growth around the anode remained unaddressed. Non-graphitic (hard) carbon exhibits a higher capacity ($400\text{--}500 \text{ mA}\cdot\text{h g}^{-1}$), yet its application in LIBs is restricted by its limited retention capacity and rapid capacity attenuation [52]. Therefore, addressing this challenge involves employing composite materials with intrinsic electrochemical capacity and advancing the development of nano- and micro-porous anode materials. Extensive research has focused on selecting materials with intrinsic capacities, such as ZnO , TiO_2 , SnO_2 , and GeOx , which demonstrate high stability and theoretical capacities of 978, 335, 782, and $2152 \text{ mA}\cdot\text{h g}^{-1}$, respectively [49]. However, these materials suffer from poor electrical conductivity and significant volume expansion, leading to issues such as material pulverization, loss of electrical contact, and increased internal resistance. The use of composite carbon/metal oxide materials also offers a promising solution by enhancing both electrochemical properties and mitigating large-volume expansion [53].

In this vein, the synergistic effect of composites also improves their capacity and mechanical properties this is corroborated by Jin-Hua Liu and co-workers who reported that nanofibers prepared by electrospinning have many advantages, including small diameters, large specific surface area, small pore sizes, high porosity, and good pore connectivity as shown in Fig. 2 [46, 54]. Liu et al. reported the design of a solid-state electrolyte for LIBs using aramid (ANFs) nanofibers/polyethylene oxide (PEO) Lithium bis(trifluoromethanesulfonyl)imide (TFSI). PEO served as a soft polymer electrolyte capable of dissolving lithium salts, while ANFs acted as nano-additive organic fillers. The composite electrolyte was constructed using hydrogen-bond interactions

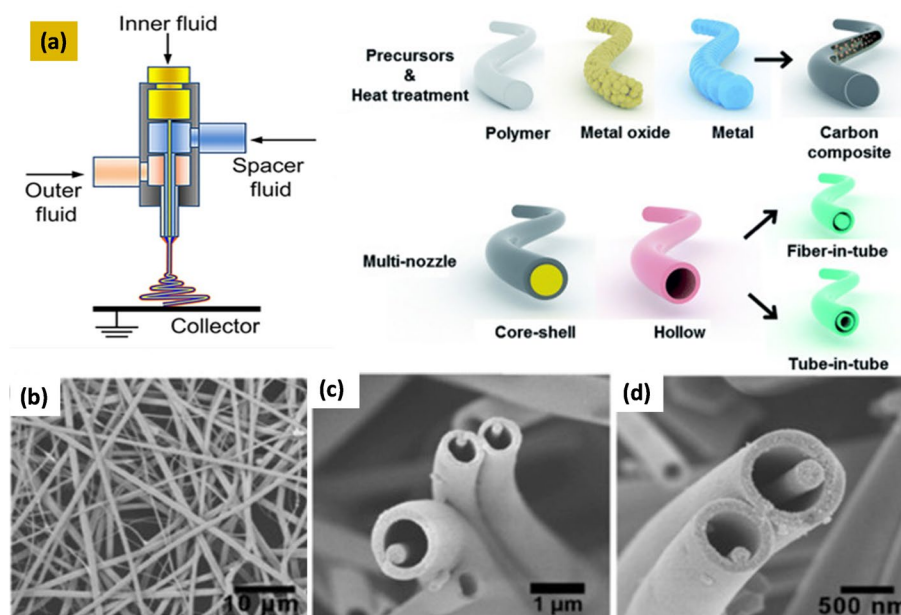


Fig. 2 Coaxial electrospinning process and Probable schematics for electrospun composites for lithium-ion batteries (a); SEM images of coaxial electrospun core-shell, hollow and tube-in-tube nanofibres (b–d) [46, 54]

between ANFs, PEO chains, and TFSI anions. This design strategy extended ion transport pathways, achieving a superior ionic conductivity of $8.8 \times 10^{-5} \text{ Scm}^{-1}$ and a cyclic stability of 135 mAhg^{-1} after 100 cycles at 0.4 C. Overall, the electrolyte demonstrated improved ion conductivity, mechanical and electrochemical stability, and resistance to lithium dendrite formation [55]. Li et al. reported the fabrication of hierarchical CaCo_2O_4 (CCO) nanofibers (NFs) via electrospinning, which were investigated as anode materials for lithium-ion batteries (LIBs) [56]. Similarly, Zou et al. utilized an electrospinning process for the fabrication of porous carbon nanofiber films embedded with Sn/SnOx nanoparticles within the pores, showcasing their potential for advanced energy storage applications. The nanofibers are composed of porous carbon with encapsulated Sn/SnOx nanoparticles with electrochemical performance, achieving capacities of 735 mA h g^{-1} in the first cycle and 510 mA h g^{-1} after 40 cycles [57]. Wang et al. reported the evaluation of electrospun carbon silicon (C/Si) composite nanofibers as anode materials for LIBs. The electrochemical properties were evaluated using 2032-coin cells, with metallic lithium serving as the counter electrode. The C/Si composite nanofibers were coated onto a copper foil using a PVDF binder to form working electrodes with a loading density of approximately 1.3 mg cm^{-2} . The C/Si (77/23, w/w) nanofibers demonstrated a high reversible capacity of up to 1240 mA h g^{-1} and excellent capacity retention, highlighting their potential for advanced battery applications [58]. Choi et al. explored the impact of different surrounding confinements on the electrochemical performance of Si nanoparticle-based anodes for LIBs [59]. Three confinement strategies were: Si nanoparticles embedded in carbon nanofibers (Si@CNF) via electrospinning, carbon nitride-encapsulated Si nanoparticles with a core/shell structure (Si@CND), and a binder-enriched Si nanoparticle-based anode (Si@RBD). Among these, Si@CNF, characterized by conductive hard confinements, and Si@RBD demonstrated notable reversible specific capacities of 620 mA h g^{-1} and 1200 mA h g^{-1} , respectively, after 30 cycles [59]. Lin et al. also reported the fabrication of MnOx/carbon nanofiber composites (MnOx/CNFs) via the electrodeposition of MnOx nanoparticles onto carbon nanofibers [60]. Hosono et al. reported synthesized carbon-coated LiFePO_4 nanowires and triaxial LiFePO_4 nanowires featuring a carbon nanotube core and a carbon shell, employing the electrospinning method for their preparation [61]. Similarly, Toprakci et al. reported the synthesis of LiFePO_4/C composite by combining electrospinning and sol-gel techniques. Polyacrylonitrile (PAN) served as both the electrospinning medium and the carbon source. The LiFePO_4 precursor/PAN fibers underwent heat treatment, during which the LiFePO_4 precursor transformed into the energy-storing LiFePO_4 material, while PAN was converted into carbon [62]. Cheah et al. reported the synthesis of one-dimensional vanadium pentoxide (V_2O_5) nanofibers (VNFs) through electrospinning of a vanadium sol-gel precursor containing vanadyl acetylacetonate and poly(vinylpyrrolidone) (PVP), followed by sintering. The electrospun VNFs demonstrated an initial discharge capacity of approximately 316 mAhg^{-1} ($\sim 2.2 \text{ Li per V}_2\text{O}_5$) within a voltage range of 1.75–4.0 V vs. Li/Li^+ at a 0.1 C rate [63]. Liang et al. reported that separators for LIBs with high ionic conductivity at room temperature, excellent electrochemical stability, and stable cycling performance were achieved by preparing PVDF fiber membranes through electrospinning combined with heat treatments [64]. Polyvinylidene fluoride-co-chlorotrifluoroethylene (PVDF-CTFE) and PVDF-CTFE/PVDF-HFP have been widely used for the fabrication of nanofiber composite membranes via electrospinning and utilized as

separator membranes for LIBs [56]. Jayaraman et al. reported the fabrication of electrospun PVDF-HFP nanofiber membrane that exhibited liquid-like conductivity of approximately 2.9 mS cm^{-1} under ambient conditions. When used as a separator in LIBs, the full cell demonstrated excellent cyclability and high rate capability, attributed to enhanced ionic transport [52].

However, significant volume expansion and low conductivity serve as another hurdle in their LIB applications. Interestingly, the combination of carbon-based materials emerged as an advantage to enhance the LIB performance. Among various nanomaterials, electrospun one-dimensional NF membranes have garnered significant interest owing to their remarkable flexibility in dimensions and structures, diverse material options, and robust physical stability [65]. To achieve this, the coaxial electrospinning technique has emerged, offering further benefits such as (a) core-sheath or hollow-structured NFs and (b) a multilayered architecture for nanoparticle integration. In electrochemical reactions, the effective incorporation of nanoparticles into carbon NFs holds a significant role as the production of free-standing electro-active electrodes via electrospinning helps develop a binder- and additive-free LIB that enhances its electrochemical performance. By so doing, several reports have demonstrated the fabrication of NFs using coaxial electrospinning and their applications in lithium-ion batteries, as summarized in Table 1 [49].

Also, in the try to address the growing demand for portable and wearable electronics, researchers are also focusing on flexible and foldable LIBs with faster charging and longer discharging capabilities because convectional LIBs often lack flexibility due to their rigid structure and heavy weight. Therefore, overcoming this step back, a study was conducted on free-standing, foldable vanadium oxide/multichannel carbon nanofiber ($\text{V}_2\text{O}_3/\text{MCCNF}$) composites prepared via electrospinning (Fig. 3). The free-standing $\text{V}_2\text{O}_3/\text{MCCNF}$ composites demonstrated a remarkable performance, delivering a high capacity of 881.1 mAhg^{-1} at 0.1 Ag^{-1} and 487.8 mAhg^{-1} at 5 Ag^{-1} . These electrodes maintained stability over 240 cycles and 5000 cycles, with a low capacity decay rate of 0.00323% [79].

3.2 Supercapacitor

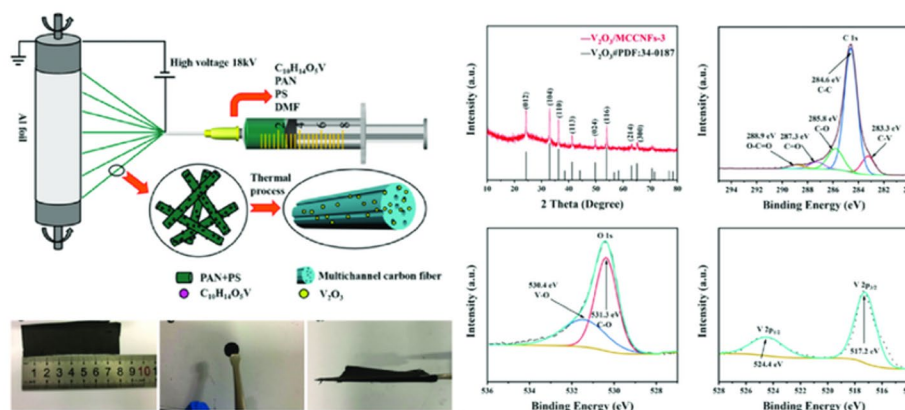
Supercapacitors emerge as a viable alternative to conventional batteries as another form of clean energy storage owing to their high power density and rapid charge-discharge capabilities. Simple construction, eco-friendliness, and a long life cycle offer supercapacitors a wide range of applications [80–82]. Conventional capacitors rely on solid dielectrics or air gaps for energy storage, while supercapacitors utilize electrolytes to form electric double layers or undergo fast redox reactions [83]. This pathway enables them to achieve higher energy densities while maintaining high power densities. Electrode materials such as metal oxides and conducting polymers have been explored to enhance supercapacitor performance, but they have been found to have one or two shortcomings. Lokhande et al. and Chuang et al. reported that RuO_2 exhibits a large electrochemical capacitance of $150\text{--}260 \text{ F cm}^{-2}$ which is ten times higher than that of carbon, and also provides easy room for protons and electron mobility within the capacitor, but its huge nanostructure resists charge transfer [84, 85]. Likewise, polyaniline and polypyrrole were observed to have excellent conductivity with high pseudo-capacitance, but they are less mechanically stable to withstand electrochemical repetitive charge-discharge

Table 1 Electrospun nanofiber for lithium-ion battery applications

Core	Sheath	Type of separator/elctrode	Composition	Cell Configu-ration	Key findings	Ref.
PVP	PVP + Co(Ac) ₂	Celgard 2400 polypropylene membrane	Core: Hollow Sheath: Porous tubular cobalt oxide	CR2016 cointype halfcell assembly	1826.2 mA-hg ⁻¹ at 300 mA-g ⁻¹ after 100 Cycles	[66]
PAN/PMMA + Si	PVP + MW-CNTs	Celgard 2025 polyethylene	Core: Si NPs in porous carbon Sheath: Carbon with MWCNTs (Honeycomb-cobweb structure)	Coin-type half cells (2025 type) C	903 mA-h/g at 0.2 Ag ⁻¹ 89% after 100 cycles at 200 mA-g ⁻¹	[66]
PMMA + GeOx	PAN	Celgard 2025 polyethylene film	Core: GeOx Sheath: Carbon	Coin-type half cells (2025 type) C	875 mA-hg ⁻¹ at 160 mA-g ⁻¹ after 400 cycles 513 mA-hg ⁻¹ at 1600 mA/g after 500 cycles	[67]
PAN/PS + Si NPs	PAN	Polypropylene (Celgard 2250)	Core: Si NPs in porous carbon Sheath: Carbon Honeycomb-like structure	Coin-type half cells CR2032	997 mA-hg ⁻¹ at 200 mA-g ⁻¹ 71% after 150 cycles 603 mA-hg ⁻¹ after 300 cycles at 500 mA-g ⁻¹	[68]
Mineral oil + Ag NPs	PVP + Ti(OiPr) ₄	Microporous polypropylene film (Celgard, 2400)	Core: Hollow structure incorporating Ag NPs. Sheath: TiO ₂ sheath after calcination.	Swagelok-type	130 mA-hg ⁻¹ at 1 C discharge rate 77% after 50 cycles	[69]
SAN	SAN-island PAN emulsion	Not specified	Core: sacrificial layer Sheath: porous carbon wall	Not specified	620 (pore) vs. 352 (no pore) mA-hg ⁻¹ at 50mA g ⁻¹ 81% after 10 cycles	[70]
PAN SAN + Si NPs	PAN	Celgard	Core: Carbon core Middle: SAN Sheath: Carbon	Coin-type half (2032 type)	1210.7 mA-h g ⁻¹ 1 at 50 mA/g 75% after 100 cycles	[71]
PMMA	PS + Ti(OiPr) ₄	Celgard 2400 film	Core: Sacrificial layer Sheath: Carbon + TiO ₂	Coin-cell (CR 2032)	~800 mA-h g ⁻¹ at 100 mA/g, 85% after 250 cycles	[72]

Table 1 (continued)

Core	Sheath	Type of separator/electrode	Composition	Cell Configuration	Key findings	Ref.
Si NPs + mineral oil	PAN	ITO anode and Al cathode.	Core: Si Sheath: Carbon	Not specified	1300 mA-h/g (95%) after 80 cycles at 0.5 C. 1013 mA h g ⁻¹ at 2 C.	[73]
PMMA	PAN	FTO glass	Core: Sacrificial layer for meso-hollow fiber. Sheath: Sublimed sulfur microporous carbon	Two-electrode cell C	815 mA-h g ⁻¹ @ 0.1 C 88% after 70 cycles	[74]
SnCl ₄ + PAN	PAN	Celgard 2300 film	Core: Tin carbon composite core Sheath: Carbon wall	CR2032 button cells	626 mA-h g ⁻¹ at 50 mA g ⁻¹ 73% after 50 cycles	[75]
SnO ₂ NPs + PMMA	Sheath – PAN	Typical LiPF ₆ -based electrolyte with standard polyolefin separator	Core: SnO ₂ NPs & Hollow core. Sheath: Carbon wall	Li-ion halfcell (anode vs. Li metal)	1002 mA-h g ⁻¹ for initial cycle at 100 mA g ⁻¹ 833 mA-h g ⁻¹ after 500 cycles at 600 mA g ⁻¹	[76]
Zn(OAc) ₂ + PMMA solution	Graphene oxide (GO) + PAN	poly(propylene) membrane	Core: ZnO NPs Sheath: rGO incorporated glassy carbon	2032 coin cell C	815 mA-h g ⁻¹ at 50 mA g ⁻¹ 80% after 100 cycles	[77]
Fe ₂ O ₃	NiO	Micro-porous (Celgard 2300)	Core: Fe ₂ O ₃ NPs Sheath: NiO nanosheets	coin-type half cells (CR 2025)	1047.2 mAhg ⁻¹ after 50 cycles	[78]

**Fig. 3** Electrospinning fabrication process of V₂O₅/MCCNF composites, XRD and XPS spectra [79]

energy storage [86, 87]. This prompts the choice of inorganic fillers such as silica, carbon nanotubes, and graphite oxide with a high specific surface area to form nanocomposites, which can demonstrate an endured electrochemical energy storage performance and high capacitance in their thin film structures [85, 88]. Hence, the use of coaxial electrospun NFs is a promising avenue for enhancing supercapacitor performance, as different studies showed that coupling coaxially electrospun nanotubes into polymer films helped to improve the dielectric properties, stability, and energy density of supercapacitors owing to their core-sheath porous structure. Zhou et al. report showed that titanium nitride core exhibits a low rate capability and electronic conductivity with vanadium nitride sheath is vice-verse, while the core-sheath porous NFs fabrication (combination) poses a capacitance of 247.5 Fg^{-1} at the scan rate of 2 mVs^{-1} and a better rate capability of 160.8 Fg^{-1} at the higher scan rate of 50 mV/s [66]. Pan et al. reported the improvement of dielectric properties and energy density by coating the surface of BaTiO_3 nanotubes with dopamine layers capped into PVDF films. The results show that the composite exhibits a dielectric constant of 47.5 compared to pristine PVDF and BaTiO_3 nanotubes of 8.26 and 5.7 respectively, with an energy density of 7.03 Jcm^{-3} at a relatively lower field of 330 MV/m [89]. Furthermore, Yingbo Xiao et al., [90] reported the synthesis of free-standing porous coaxial carbon nanofiber (PCCNF) membranes with a large surface area ($648 \text{ m}^2\text{g}^{-1}$) and an appropriate pore size distribution was made using a simple coaxial electrospinning and template method. These PCCNF membranes demonstrate excellent capacitance, with values of 261 Fg^{-1} and 48 Fg^{-1} at 1 Ag^{-1} in three-electrode and two-electrode systems, respectively. This leads to an impressive energy density of $48.6 \pm 3 \text{ Whkg}^{-1}$ and power density of $67.5 \pm 1 \text{ Wh kg}^{-1}$. The findings of the study show that the supercapacitors made from PCCNF membranes show outstanding flexibility, as well as strong electrochemical and mechanical stability.

More so, Lei Wang et al., [91] reported the design of new coaxial electrospun polyetherimide@polyaniline core-shell fibrous membranes as self-supporting flexible electrodes for supercapacitors, the work shows that an innovative polyetherimide@polyaniline (PEI@PANI) core-shell fibrous membranes (CFMs) were synthesized using a straightforward coaxial electrospinning method, along with secondary doping with 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPS). Polyetherimide facilitated the ease and smooth coating of a dense layer of emeraldine base polyaniline (EB-PANI) onto the fiber surfaces without the need for additional spinning aids. These results showed an excellent porous hydrophilic material, with good electrical conductivity, and exceptional mechanical flexibility. The combined effects of the structure and materials allow these flexible PEI@PANI CFMs to offer more accessible electrochemical active sites and lower ion diffusion resistance. As a result, PEI@PANI CFMs exhibit an impressive areal capacitance of 1159.9 mFcm^{-2} and an energy density of $46.91 \text{ } \mu\text{W h/cm}^2$, making them highly promising for use in flexible energy storage applications. Jeong et al. reported a template free hierarchical porous carbon nanofibers/manganese oxide (MnO_2) fabricated eletrospun polyacrylonitrile/cyclodextrin (CD) composite $\text{PMnCD}(\beta)$ using β -CD phase. The composite porous structure, making it a promising material for supercapacitor electrodes. Thus, the combination of nano-sized MnO_2 and carbon nanofibers demonstrated high pseudocapacitance alongside excellent electronic conductivity. The fabricated $\text{PMnCD}(\beta)$ electrode featured a large specific surface area and mesopores enriched with nitrogen groups, enabling efficient ion accumulation and rapid ion diffusion. The

β phase of CD nanofibers contributed to the hierarchical porous structure, achieving a specific surface area of $499 \text{ m}^2\text{g}^{-1}$ and a total pore volume of $0.32 \text{ cm}^3\text{g}^{-1}$. These characteristics enhanced the adsorption efficiency and facilitated the accumulation of hydrated molecules, thereby improving double-layer formation. The PMnCD(β) electrode exhibited outstanding electrochemical performance, including a maximum energy density of $25.3\text{--}16.0 \text{ Whkg}^{-1}$ across a power density range of $400\text{--}10,000 \text{ Wkg}^{-1}$. It also delivered a high specific capacitance of 228 Fg^{-1} at 1 mAcm^{-2} and excellent cycling stability, retaining 94% of its capacitance after 10,000 cycles [92]. Synthesis of metallized nickel-plated carbon nanofiber (Ni@CNF) designed with 2D nickel gallium sulfide (NiGa_2S_4) nanosheets was developed by Kim et al. schematic formation process shown in (Fig. 4). In their study, they reported that the presence of nanofibers facilitated the pseudocapacitance and energy density of the nanosheets, which, in turn, enhanced energy storage capacity and overall electrochemical performance. The device demonstrated exceptional long-term stability, retaining 109% of its capacitance after 20,000 cycles, and achieved a maximum specific capacitance of 488 Fg^{-1} with a potential window of 1.1 V at a current rate of 0.5 Ag^{-1} . Additionally, the flexibility of the device was confirmed through cyclic voltammetry tests after 2,000 bending cycles, demonstrating favorable results [93]. Yan et al. [94] reported the synthesis of MnO_2 nanoshoots grown on NiCo_2O_4 nanotubes, yielding improved electrochemical activity and high electronic conductivity. The resulting $\text{NiCo}_2\text{O}_4@\text{MnO}_2$ heterostructures exhibited a strong synergistic effect, enhancing their performance as electrodes for supercapacitors. These materials achieved a specific capacitance of 706.7 Fg^{-1} at a current density of 3 A g^{-1} , demonstrating a high rate capability with approximately 84.9% retention of the initial capacitance. Furthermore, they exhibited exceptional cycling stability, retaining 136.3% of their initial capacitance after 10,000 charge-discharge cycles [95].

Activated porous carbon nanofibers were synthesized by An et al. [96] with three distinct porous structures controlled by incorporating 1, 4, and 8 wt% of Sn-poly(vinylpyrrolidone) precursors in the core region, and 7 wt% PAN/PVP precursors in the shell region, using a co-electrospinning technique followed by H_2 reduction. These activated porous CNFs, designed for use as electrodes in high-performance

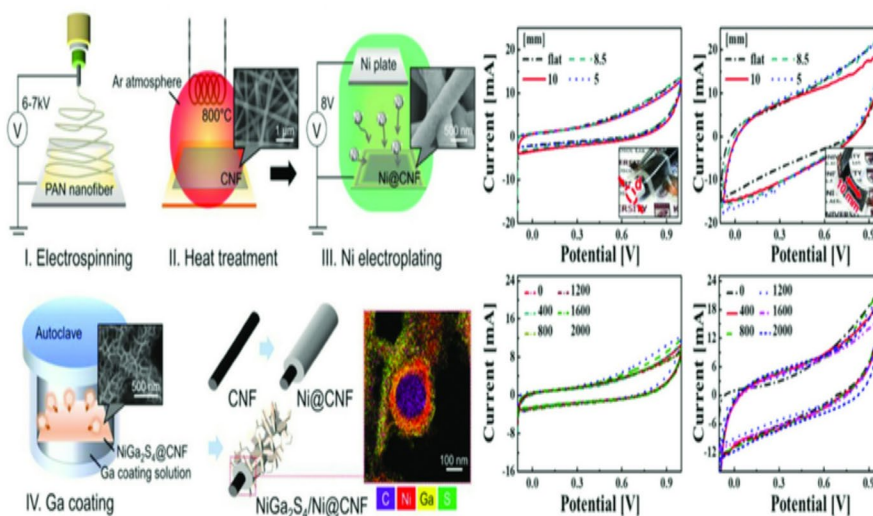


Fig. 4 Fabrication process of $\text{NiGa}_2\text{S}_4/\text{Ni@CNF}$ for supercapacitors, CV curves with varying curvature radii (mm) liquid and solid electrolyte [93]

electrochemical capacitors, exhibited excellent capacitances 289.0 F g^{-1} at 10 mV s^{-1} , superior cycling stability, and high energy densities, outperforming conventional CNFs attributed to the synergistic effects of improved porous structures and the formation of activated states on the CNF surfaces. Poly(3,4-ethylenedioxythiophene) (PEDOT) nanofibers have been reported fabricated combining electrospinning with vapor-phase polymerization. With diameters of around 350 nm and soldered intersections, the fibers exhibited strong dimensional stability. These nanofiber mats demonstrated a conductivity of $60 \times 10 \text{ S cm}^{-1}$ and were incorporated into all-textile flexible supercapacitors, using carbon cloths as current collectors and electrospun PAN nanofibrous membranes as separators. The textile layers were embedded in a solid electrolyte containing an ionic liquid and PVDF-co-HFP. The resulting supercapacitors were fully flexible and showed stable performance under ambient conditions [97]. Zhi et al. [98] developed porous activated carbon nanofibers by electrospinning a polyacrylonitrile precursor containing H_3PO_4 . With less than 1 wt% H_3PO_4 as the activation agent during carbonization, the resulting activated carbon nanofibers exhibited a large surface area $\sim 709 \text{ m}^2 \text{ g}^{-1}$ and high porosity $0.356 \text{ cm}^3 \text{ g}^{-1}$. Achieved high specific capacitance of 156 F g^{-1} at 0.5 A g^{-1} and an energy density of $10.98 \text{ W h kg}^{-1}$ at a power density of 10 kW kg^{-1} , about nine times higher than that of non-activated carbon nanofibers. This significant improvement is attributed to the H_3PO_4 -based activation process, which enhances the micropore volume and the ratio of mesopores to micropores. Zhou et al. [98] reported the synthesis and electrochemical performance of carbon nanofibers surface-grown with carbon nanotubes (CNT) and nanostructured polyaniline films (PANI/CNT/CNF) for use as high-performance electrode materials in pseudosupercapacitors. Li and co-workers [99] developed flexible NiFe_2O_4 nanofiber-based in-plane micro-supercapacitors (MSCs) designed to serve as energy storage units for powering a portable graphene pressure sensor. The NiFe_2O_4 nanofiber electrodes exhibited a specific capacitance of 2.23 F cm^{-3} at a scan rate of 100 mV s^{-1} and demonstrated excellent cycling stability, retaining 93.6% of their capacitance after 10,000 charge/discharge cycles. These in-plane MSCs showcased remarkable flexibility and durability, maintaining outstanding performance even after repeated charge/discharge cycles under convex and concave bending conditions. The MSCs provided a high energy density of $0.197 \text{ mW h cm}^{-3}$ and a power density of up to 2.07 W cm^{-3} . Additionally, the researchers integrated the MSCs with a graphene pressure sensor in a micro-system to test its pressure response function, using MATLAB for simulation. The system showed stable pressure responses, with simulated results closely matching experimental data, demonstrating the feasibility of these systems in wearable electronic devices (Fig. 5) [98, 99]. Table 2 below summarized electrospun nanofiber for supercapacitor.

3.3 Solar cells and luminescence

Coaxial electrospun fiber emerges as a promising material in solar cells and luminescence applications, as scientists push towards developing clean and renewable energy sources in response to the adverse environmental effects and finite nature of fossil fuels. Solar energy, renowned for its regenerative capacity and environmental friendliness, has become a focal point of research. However, the efficiency of solar cells is often hampered by charge recombination, primarily at the anode compartment [80, 108]. Interestingly, various research studies have demonstrated that the use of core-sheath nanofibers

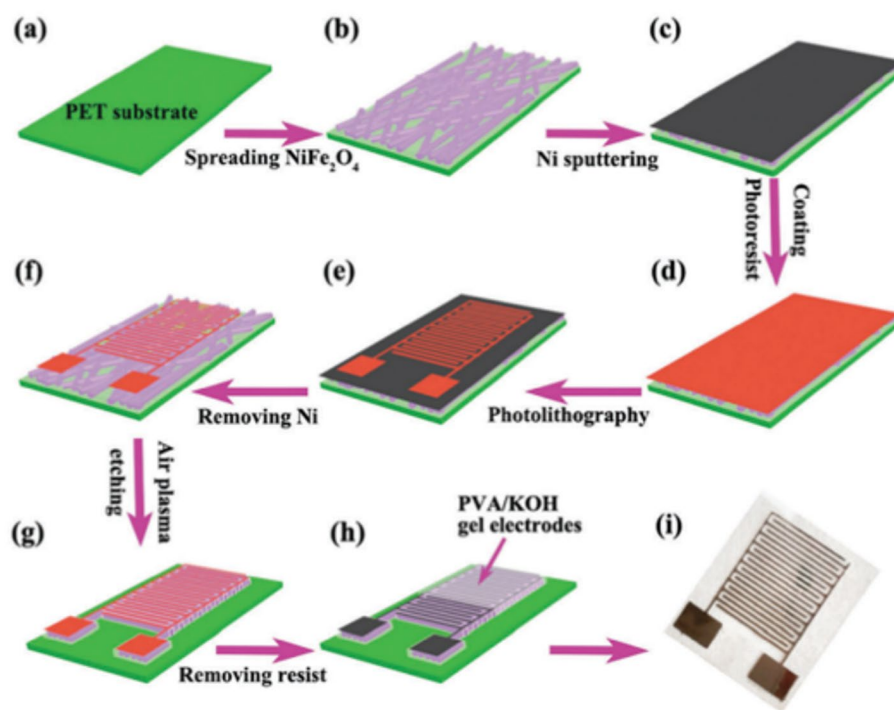


Fig. 5 Schematic diagram illustrating the fabrication process of flexible in-plane MSCs with NiFe_2O_4 nanofiber electrodes on a PET substrate. **a** Plasma cleaning of the PET surface, **b** deposition of NiFe_2O_4 nanofibers, **c** sputtering of Ni onto the substrate, **d** coating with photoresist, **e** photolithography process, **f** removal of Ni, **g** air plasma etching, **h** removal of the resist, and **i** a digital image of the MSC device [99]

Table 2 Electrospun nanofiber for supercapacitor

Electrospun	Separator	Cell Configuration	Key findings	Ref.
Co_3O_4 + CNF	Standard porous separator	Two-electrode hybrid supercapacitor (pseudocapacitive + EDLC)	586 F g^{-1} at a current density of 1 A g^{-1}	[100]
CNF + CNT	PVA/ H_2SO_4 gel solid-state medium	Symmetric solid state	315 F g^{-1} at 1 A g^{-1} , 5.1 Wh kg^{-1} at 10.1 kW kg^{-1} cycling stability 92% after 10,000 cycles at 2 A g^{-1}	[101]
As-spun hybrid NFs	Polyolefin micro-porous membrane, wetted by electrolyte	CR2032 coin-type two-electrode half cell	360.7 F g^{-1} at a current density of 1 A g^{-1}	[102]
PANI-NF	Standard porous separator	Symmetric two-electrode cell: Pt-nanofiber electrode	$\sim 230 \text{ F g}^{-1}$ at the 1000th cycle	[103]
Pt fiber mat	Porous filter paper soaked in gel electrolyte	Asymmetric hybrid supercapacitor	412 S cm^{-1} , $\sim 409.4 \text{ F g}^{-1}$	[104]
Polyacrylonitrile/polyaniline	PVA-based Li_2SO_4 gel	Symmetric/sandwich	335 F g^{-1} at a current density of 0.5 A g^{-1} , 175 F g^{-1} at 32 A g^{-1}	[105]
Ni + Carbon		Three-electrode CV/GCD	164 F g^{-1}	[106]
PANI + CNFs	Porous separator between identical PANI/CNF electrodes	Symmetric two-electrode supercapacitor	264 F g^{-1}	[107]

effectively addresses this issue, leading to improved solar cell efficiency [109–112]. Solar cells play a crucial role in converting light into electricity, while incandescence and luminescence offer alternative means of generating light, often referred to as ‘cool light’. Luminescence can be classified as chemiluminescence, electroluminescence, triboluminescence, and bioluminescence, depending on the source energy. For instance, fluorescence arises from energy emitted by ultraviolet radiation, or X-rays. The concerted effort of scientists towards the development of sensors with high efficiency and detection accuracy in the field of science led to the discovery of luminescent materials such as transition metal ions, rare earth metal complexes, heavy metals, quartz, feldspar, some organic materials, and aluminum oxide with electron-hole pairs. Thereby, giving room for new discovery of luminescent materials with lower energy consumption and good brightness as an alternative to conventional light-emitting diodes (LEDs) [43, 113]. On this premise, the use of core-sheath NFs has also attracted the attention of researchers [109, 114, 115]. Nicholas M. Bedford et al., [116] reported the synthesis of poly(3-hexylthiophene) and phenyl-C61-butyric acid methyl ester (P3HT) through coaxial electrospinning process, which was used in bulk heterojunction organic photovoltaics (BHJ–OPV), are created through a. Since P3HT blends cannot be directly electrospun, polycaprolactone (PCL) is used as an electrospinnable outer layer, allowing the formation of P3HT fibers. After electrospinning, the PCL sheath is easily removed using cyclopentanone, leaving pure P3HT fibers with an average diameter of 120 ± 30 nm. These fibers are then incorporated into the active layer of BHJ–OPV devices, leading to improvements in short-circuit current density, fill factor, and power conversion efficiency (PCE) compared to devices with thin-film active layers of the same chemical composition. The highest-performing fiber-based devices show a PCE of 4.0%, while the best thin-film devices achieve a PCE of 3.2%. Resulting in enhanced optical absorption and exciton generation. The setup for the probable application of coaxial electrospun nanofiber is shown in Fig. 6.

More so, studies have shown that coaxial electrospun fibers in solar cells can enhance charge separation, transport, and light absorption. The core material frequently functions as an effective electron or hole transport layer, whilst the shell material can function as a light-harvesting layer. This improves the cell's efficiency by increasing charge mobility and lowering recombination losses [42, 117]. Furthermore, the fibers' high surface-area-to-volume ratio enables more efficient light trapping, improving overall power conversion efficiency. These characteristics accord coaxial electrospun fibers the

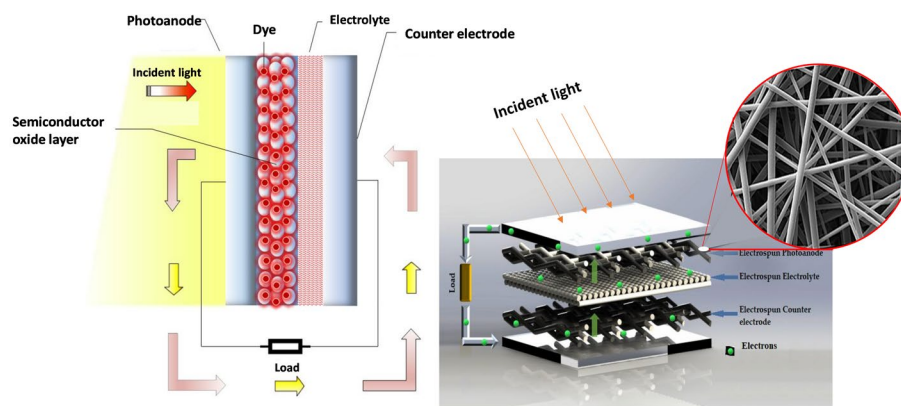


Fig. 6 Coaxial electrospun fiber scheme and setup for solar cell application [16]

potential for next-generation solar cell application. Based on the above, Nguyen Trung Hieu et al. [118] reported the use of a coaxial electrospinning process to synthesize titanium dioxide/carbon nanofibers (TCNFs) for use as anodes in dye-sensitized solar cells (DSSCs). The core material was polyacrylonitrile, and the shell was a blend of titanium isopropoxide and polyvinylpyrrolidone. The photovoltaic performance of DSSCs containing TCNF-based photoanodes was evaluated using current density-voltage (J-V) measurements, incident photon-to-current conversion efficiency (IPCE), and electrochemical impedance spectroscopy (EIS). The TCNF-based DSSC has a power conversion efficiency (PCE) of 7.5%, outperforming DSSCs using TiO₂ nanofiber (TNF) and TiO₂ nanoparticle (TNP) photoanodes. The improvement was ascribed to the carbon core and nanocrystalline TiO₂ shell structure, which improved electron transport and reduced charge recombination. Moreover, Pingfan Du et al. (2012) developed novel TiO₂/ZnO core-sheath nanofibers (NFs) utilizing a specialized coaxial electrospinning approach. These nanofiber films were used as photoanodes in dye-sensitized solar cells. The study revealed that DSSCs with TiO₂/ZnO core-sheath NFs performed better than those with bare TiO₂ NFs. Specifically, energy conversion efficiency increased from 4.47 to 5.17%. Table 3 below showed electrospun nanofiber for solar cell applications.

3.4 Hydrogen generation

The inefficiency of conventional nanoparticles like platinum pivots on the use of coaxial electrospun nanofibers for hydrogen generation [128]. Hydrogen generation serves as an ideal clean energy source owing to its large energy density. Currently, hydrogen is sourced from fossil fuels, particularly natural gas (methane CH₄), via a process that significantly increases carbon dioxide emissions [128]. Consequently, electrochemical water splitting emerges as a promising alternative method for hydrogen generation [127]. At the cathode, hydrogen gas is produced (through a process known as hydrogen evolution reaction (HER)) electrochemical water spitting cathodic half reaction (Eq. 1). For optimum energetic efficiency in water splitting, an electrocatalyst is required to initiate the electrochemical reaction.

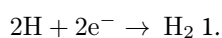


Table 3 Electrospun nanofiber for solar cell applications

Core	Sheath	Type of separator/electrode	Cell Configuration	Key findings	Ref.
TiO ₂	FePt	FTO glass	Sandwich-type	100 mWcm ⁻² , 16% PCE	[119]
PU	PAN	Silver nanowires	p-i-n (inverted)	4.06% PCE	[120]
Ag	CNFs	Silver nanowires	Flexible OPV structure	500 bending cycles, LTE: 3.37 × 10 ⁻⁶ K ⁻¹	[121]
BT NPs	PVDF	Carbon nanotubes	Cantilever	1020 V, 29 μA, 2.2 Wm ⁻²	[122]
rGO/GO	PVDF	Paired flexible metal electrode	Sandwich structure	16 V, 700 nA	[123]
NiFe ₂ O ₄	PVDF	Aluminum metal	Flexible sandwich-type	1.46 μCcm ⁻² , 4.8 V	[124]
BHJ-OPV	P3HT: PCBM	ITO anode and aluminum cathode	Standard bulk heterojunction	4.0% PCE	[125]
C ₆	Polythiophene	ITO glass	Single layer architecture	5.58% PCE	[126]
PANI	Carbon	FTO glass	Sandwich	0.5 Ω cm ²	[127]

Table 4 Electrospun nanofiber for hydrogen generation

Electrospun	Key findings	Ref.
Ni + CNFs	– 0.17 V, 3.05 mA cm ^{–2} at η = 200 mV	[132]
Ru + CNF	Ea: 30.1 kJmol ^{–1} , conversion (> 99%)	[133]
Ni-NC + NFs-Pt	47, 22, and 84 mV at j = 10 mAcm ^{–2} , in 0.5 M H ₂ SO ₄ , 1 M KOH and 0.1 M phosphate buffer solution	[134]
CNFs + MoS ₂	– 0.30 V	[135]
MoS ₂ + NCNF	38 mV	[136]
CoSe ₂ + CNF	100 mA cm ^{–2} at ~180 mV	[137]
CNF + CoS ₂	– 40 mV, 10.0 mA cm ^{–2} at η = 110 mV	[138]
NiCoP + CNF	10 mA cm ^{–2} , 130 mV	[139]
PAN + CA	440 mV at – 80 mAcm ^{–2} , and > 100000s	[140]

Yu et al. reported the use of low-cost and effective electrocatalyst hollow nitrogen-doped carbon NFs with single-layered tungsten disulfide (WS₂@HNCNFs) with excellent durability, providing a lower overpotential of 280 mV to achieve 10 mAcm^{–2} with a lower charge transfer resistance of 24 Ω [129]. Sun and co-workers developed a highly efficient electrocatalyst for large-scale hydrogen production, made up of two-dimensional (2D) platinum (Pt) and molybdenum disulfide (MoS₂) nanosheets attached to one-dimensional (1D) cobalt nanoparticles embedded in carbon hollow nanofibers (Co@CHNF) [130]. The resulting Pt-MoS₂-Co@CHNF catalyst had a large surface area of 44.5 m² per gram. The Pt-MoS₂-Co@CHNF catalyst exhibited an overpotential of just 91 mV at a current density of 10 mAcm^{–2} and 258 mV at 200 mAcm^{–2} in 1 M potassium hydroxide (KOH) solution, maintaining stable catalytic activity over 14 h of continuous use. This demonstrates its excellent long-term durability, outperforming other Co-based or Mo-based catalysts. Notably, the self-supporting, binder-free Pt-MoS₂-Co@CHNF electrode reached a very high current density of 500 mA/cm² at a low overpotential of 301 mV, showing no degradation after 24 h of operation in 1 M KOH seawater electrolyte, highlighting its strong potential for large-scale seawater-based hydrogen production. Furthermore, Longzhu Li et al., [131] worked on MoS₂/CoS₂ with heterostructure in situ grown on the surface of an electrospinning carbon nanotube for efficient hydrogen evolution reaction. The produced electrospun carbon nanotubes were used as a substrate for the in-situ growth of a MoS₂/CoS₂ hybrid. These carbon nanotubes have a large length-to-diameter ratio, resulting in a conductive network. The MoS₂/CoS₂ compound was consistently spread on the nanotubes' surfaces, increasing active site exposure. Furthermore, the heterostructure of MoS₂ and CoS₂ resulted in a considerable electron transfer. More so, DFT investigation revealed that the MoS₂/CoS₂ composite had a significantly reduced hydrogen adsorption-free energy as reported [131]. The findings of the work show that the catalyst demonstrated remarkable long-term stability and performed well in hydrogen evolution reaction, with an overpotential of just 124 mV at 10 mA/cm² and a Tafel slope of 88.7 mV/decade in 1 M KOH. Table 4 below displayed summarized electrospun nanofiber for hydrogen generation.

4 Current development challenges and perspectives in coaxial electrospinning for energy storage applications

Coaxial electrospinning has gained considerable attention as a versatile and effective technique for fabricating nanostructured materials tailored to energy storage devices, including batteries and supercapacitors. By enabling the formation of

core–sheath fibers with distinct compositional and functional domains, this method allows for enhanced control over properties such as mechanical integrity, electrical conductivity, and electrochemical stability. Despite these advantages, several critical challenges remain that limit the broader applicability and industrial translation of coaxial electrospinning in energy storage. One major challenge concerns the precise control and reproducibility of fiber morphology and uniformity. The coaxial electrospinning process is highly sensitive to numerous parameters including solution viscosities, flow rates, applied voltage, and environmental conditions. This sensitivity often results in fibers with inconsistent diameters, bead defects, or incomplete core–sheath structures, which can detrimentally affect ion transport pathways and overall electrode performance [141]. To address this, integration of real-time process monitoring combined with machine learning algorithms could enable dynamic optimization of processing parameters, thus improving fiber consistency. Additionally, exploring solvent systems and solution additives that enhance jet stability can further refine fiber morphology.

Another significant limitation is the restricted range of compatible material combinations for the core and sheath layers. The necessity for both materials to be electrospinnable and chemically compatible constrains the incorporation of certain high-performance but challenging materials such as inorganic nanoparticles or polymers with limited solubility [142]. Modified coaxial electrospinning techniques that employ unspinnable sheath fluids or multichannel fluid systems present promising avenues to expand the material palette. Surface functionalization of nanomaterials and the use of supramolecular interactions may also improve compatibility while maintaining fiber integrity. Scaling up coaxial electrospinning from laboratory to industrial production remains a critical bottleneck due to the inherently low throughput of conventional single-needle systems and difficulties in preserving fiber uniformity at larger scales [29]. Development of multi-needle or needleless coaxial electrospinning configurations, combined with continuous roll-to-roll collectors, offers potential routes to increase production rates substantially and facilitate commercial viability. Post-processing treatments required to enhance electrochemical properties, such as thermal annealing or chemical crosslinking, pose additional challenges. These treatments can induce fiber deformation or damage the core–sheath architecture, undermining the benefits conferred by the nanostructure [28]. Investigating low-temperature, photochemical, or in situ curing methods may provide gentler alternatives that preserve fiber morphology while improving material stability and functionality.

Finally, effective integration of coaxial electrospun materials into practical energy storage devices demands overcoming issues related to electrode adhesion, electrical connectivity, and mechanical robustness under operational stresses. Designing composite fiber mats incorporating conductive networks or binder-free architectures could enhance mechanical and electrical integration. Hierarchical architectures combining coaxial fibers with complementary nanomaterials may further optimize device performance and durability.

While coaxial electrospinning represents a powerful platform for engineering advanced energy storage materials, addressing these development challenges through innovative process control, expanded material compatibility, scalable manufacturing, gentle post-treatments, and device-focused design is essential. Future research efforts

guided by these strategies will be critical to translating coaxial electrospun materials from the laboratory to commercial energy storage applications.

It is important to mention that there is growing interest in alternative or complementary architectures that can further enhance performance in advanced applications such as energy storage. This perspective highlights recent developments in side-by-side electrospinning/Janus nanofibers, coaxial/side-by-side electrospraying, and more complex tri-chamber and integrated core–sheath–Janus structures, which offer unique structural and functional advantages. The side-by-side electrospinning technique, producing so-called Janus nanofibers, creates fibers with two distinct hemispheres of different materials, exposed simultaneously to the environment. This architecture enables orthogonal properties on each side of the fiber, such as hydrophobic/hydrophilic surfaces, or electron donor/acceptor functionalities, making them particularly suited for asymmetric energy storage devices.

For instance, Yu and co-workers reported Janus nanofibers tailored for supercapacitor electrodes, demonstrating improved charge storage and cycling stability due to synergistic dual-material interfaces [143].

Beyond fibers, **electrospraying** variants of coaxial and side-by-side configurations produce particulate or bead-on-string structures with similar multi-compartment functionality. These morphologies can enhance electrolyte uptake, ion transport pathways, and surface area, all critical to high-performance batteries and supercapacitors. Chen et al. (2025) demonstrated coaxial/side-by-side electrosprayed particles as versatile building blocks for high-capacity, fast-charging electrodes [144]. Pushing complexity further, **tri-chamber core–sheath fibers** incorporate three separate functional domains within a single fiber. As shown by Wan [145], such structures allow simultaneous integration of multiple active materials with distinct roles such as an energy-storing core, a conductive sheath, and a protective or catalytic outer layer to optimize energy storage performance and longevity. More recently, **integrated core–sheath/Janus hybrid structures** have emerged as promising architectures combining the advantages of both approaches. For example, Yu et al. (2024) [146] and Wang et al. (2025) [147] reported hybrid nanofibers and membranes designed for high-power energy storage and conversion devices, demonstrating improved charge transport, interfacial stability, and multifunctionality [146, 147].

The evolution of fiber architectures beyond conventional coaxial electrospinning represents a fertile ground for innovation in the energy storage field. Side-by-side (Janus), coaxial/side-by-side electrospraying, tri-chamber, and integrated hybrid designs enable the integration of disparate functionalities in a single nanostructure, addressing challenges such as poor conductivity, limited ion diffusion, and low energy density. Future research should focus on scalable fabrication, precise structural control, and systematic performance evaluation of these emerging architectures in real devices.

5 Conclusion

Coaxial electrospinning has emerged as a transformative technique for fabricating advanced materials with core-shell nanostructures, offering significant advantages in energy storage applications. By allowing precise control over the composition and architecture of nanofibers, this method has demonstrated remarkable potential in enhancing the performance of batteries, supercapacitors, and other energy storage devices. The versatility of coaxial electrospinning enables the development of materials with high

surface area, enhanced conductivity, and improved mechanical stability key attributes needed for high-energy-density systems with long cycle life. The ability to fine-tune the core and shell materials opens new avenues for optimizing energy storage capabilities, making coaxial electrospun nanofibers a promising candidate for next-generation energy storage solutions.

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Author contributions

Yakubu Adekunle Alli conceptualized and led the development of the review, defined the scope, coordinated author contributions, and drafted the initial manuscript. Abayomi Bamisaye and Akinsanmi S. Ige contributed significantly to the literature review and critical analysis of coaxial electrospinning techniques and their applications in energy storage. Rabi Elabor and Oluwatobi Ife-Adediran assisted with data compilation, visualization, and drafting sections related to electrochemical performance metrics. Adanlawo Olayinka Samson and Samuel Oluwadadepo Oni were responsible for reviewing and editing the sections on material design strategies and comparative performance analysis across different energy storage systems. Alfred Yeboah and Owolabi Mutolib Bankole contributed to the theoretical framework and future outlook section, offering insights into interdisciplinary integration and industrial relevance. Dele Peter Fapojuwo provided critical revisions to improve intellectual content and ensure clarity and coherence of the manuscript. Adeniyi Sunday Ogunlaja offered expert supervision, contributed to manuscript structuring, and ensured alignment with journal standards. All authors reviewed and approved the final version of the manuscript.

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Declarations

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Not applicable.

Consent for publication

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Competing interests

The authors declare no competing interests.

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References

1. Ngoy KR, Lukong VT, Yoro KO, Makambo JB, Chukwuati NC, Ibegbulam C, et al. Lithium-ion batteries and the future of sustainable energy: A comprehensive review. *Renew Sustain Energy Rev.* 2025;223:115971. <https://doi.org/10.1016/J.RSER.2025.115971>.
2. Njema GG, Ben R, Ouma O, Kibet JK. A review on the recent advances in battery development and energy. *Storage Technol* 2024. <https://doi.org/10.1155/2024/2329261>
3. Bhosale SV, Bhosale SV. Advancements in supercapacitors: breaking barriers and enabling amazing applications 2025. <https://doi.org/10.1039/d5sc01955a>
4. Rezić I, Meštrović R, Škoc MS. Nanofiber-Based Innovations in Energy Storage Systems 2025. <https://doi.org/10.3390/polym>
5. Zhang Q, Soham D, Liang Z, Wan J, Med. -X 123AD. <https://doi.org/10.1007/s44258-024-00048-w>

6. Zhao J, Chen L, Ma A, Bai X, Zeng Y, Liu D, et al. Recent advances in coaxial electrospun nanofibers for wound healing. *Mater Today Bio*. 2024;29:101309. <https://doi.org/10.1016/j.mtbio.2024.101309>.
7. Zhu Z, Liu Y, Zhang H, Xu Y, Shao Z, Ge L, et al. Emerging trends in electrochemical energy storage: a focus on low-temperature pseudocapacitors. *Energy Reviews*. 2025;4:100118. <https://doi.org/10.1016/J.ENREV.2024.100118>.
8. Islam MM, Nafees A. Emerging Next-generation nanomaterials in energy storage: advancement and challenges, 2024, pp. 27–61. <https://doi.org/10.1021/bk-2024-1484.ch002>
9. Al-Amiery AA, Fayad MA, Abdul Wahhab HA, Al-Azzawi WK, Mohammed JK, Majidi HS. Interfacial engineering for advanced functional materials: surfaces, interfaces, and applications. *Results Eng*. 2024;22:102125. <https://doi.org/10.1016/J.RINENG.2024.102125>.
10. Njema GG, Kibet JK, Ngari SM. A review of interface engineering characteristics for high performance perovskite solar cells. *Measurement: Energy*. 2024;2:100005. <https://doi.org/10.1016/j.meae.2024.100005>.
11. Cho Y, Won Beak J, Sagong M, Ahn S, Nam JS, Kim I-D. Hall of Fame www.advmater.de Electrospinning and Nanofiber Technology: Fundamentals, Innovations, and Applications 2025. <https://doi.org/10.1002/adma.202500162>
12. Getaneh SA, Temam AG, Workneh GA, Nwanya AC, Ejikeme PM, Ezema FI. Advances in MoS₂-Based ternary nanocomposites for high-performance electrochemical energy storage. *Hybrid Adv*. 2024;7:100333. <https://doi.org/10.1016/J.HYBADV.2024.100333>.
13. Prashanth GK, Rao S, Lalithamba HS, Bhagya NP, Swamy MM, Yashodha SR, et al. Smart nanomaterials for semiconductor applications: recent advances in energy storage and biosensing technologies. *Next Mater*. 2025;9:100964. <https://doi.org/10.1016/J.NXMATE.2025.100964>.
14. Joshi B, Samuel E, Kim Y, il, Yarin AL, Swihart MT, Yoon SS. Progress and potential of electrospinning-derived substrate-free and binder-free lithium-ion battery electrodes. *Chem Eng J*. 2022;430:132876. <https://doi.org/10.1016/J.CEJ.2021.132876>.
15. Wei W, Wildy M, Xu K, Schossig J, Hu X, Choon Hyun D et al. Downloaded via 41.165.67.75 on 2025;12:14. <https://doi.org/10.1021/acs.langmuir.3c01038>
16. Alli YA, Bamişaye A, Onawole AT, Oladoye PO, Bankole OM, Koivisto B, et al. Coaxial electrospinning: design, characterization, mechanistic insights and their emerging applications in solar cells. *Nano Energy*. 2024;131:110203. <https://doi.org/10.1016/J.NANOEN.2024.110203>.
17. Jeon D, Sagong M, Soo Kim M, Seok Nam J, Park H, Kim I-D. Electrospun carbon nanofibers clean energy applications. *Compr Rev*. 2025;7:12517. <https://doi.org/10.1002/eom.2.12517>.
18. Adabavazeh Z, Johari N, Baino F. Electrospun conductive polymer scaffolds: tailoring fiber diameter and electrical properties for tissue engineering applications. *Mater Today Commun*. 2025;46. <https://doi.org/10.1016/J.MTCOMM.2025.112596>.
19. Al-Abduljabbar A, Farooq I. Electrospun polymer nanofibers: processing, properties, and applications 2022. <https://doi.org/10.3390/polym15010065>
20. Li D, Shen C, Zheng Y, Xu J. Electrochemo-Mechanical degradation and failure of active particles in high energy density batteries: A review. *Small*. 2025;21. <https://doi.org/10.1002/sml.202407740>.
21. Mohamed Ismail KB, Arun Kumar M, Mahalingam S, Jayavel R, Arivanandhan M, Kim J. Conducting polymer based electrodes in metal-ion batteries: A state-of-the-art review. *Renew Sustain Energy Rev*. 2025;222:115982. <https://doi.org/10.1016/J.RSER.2025.115982>.
22. Jiang H, Wang L, Zhu K. Coaxial electrospinning for encapsulation and controlled release of fragile water-soluble bioactive agents. *J Controlled Release*. 2014;193:296–303. <https://doi.org/10.1016/J.JCONREL.2014.04.025>.
23. Liang J, Bu LT, Cao WG, Chen T, Cao YC. Facile fabrication of coaxial-cable like Mn₂O₃ nanofiber by electrospinning: application as electrode material for supercapacitor. *J Taiwan Inst Chem Eng*. 2016;65:584–90. <https://doi.org/10.1016/J.JTICE.2016.06.005>.
24. Kaushik P, Bharti R, Sharma R, Verma M, Olsson RT, Pandey A. Progress in synthesis and applications of Polyaniline-Coated nanocomposites: A comprehensive review. *Eur Polym J* 2024;221. <https://doi.org/10.1016/j.eurpolymj.2024.113574>
25. Song J, Lin X, Liang J, Ee Y, Fong S, Li Y, et al. A review on electrospinning as versatile supports for diverse nanofibers and their applications in environmental sensing. *Adv Fiber Mater*. 2023;5:429–60. <https://doi.org/10.1007/s42765-022-00237-5>.
26. Pillai VV, Ramasubramanian B, Sequerth O, Pilla S, Wang T, Mohanty AK, et al. Nanomaterial advanced smart coatings: emerging trends shaping the future. *Appl Mater Today*. 2025;42:102574. <https://doi.org/10.1016/J.APMT.2024.102574>.
27. Keirouz A, Wang Z, Reddy S, Nagy K, Vass P, Buzgo M et al. The history of electrospinning: past, present, and future developments 2023. <https://doi.org/10.1002/admt.202201723>
28. Xue J, Wu T, Dai Y, Xia Y. Electrospinning and electrospun nanofibers: methods, materials, and applications. *Chem Rev*. 2019;119:5298–415. <https://doi.org/10.1021/acs.chemrev.8b00593>.
29. Haider A, Haider S, Kang IK. A comprehensive review summarizing the effect of electrospinning parameters and potential applications of nanofibers in biomedical and biotechnology. *Arab J Chem*. 2018;11:1165–88. <https://doi.org/10.1016/J.ARJ.2015.11.015>.
30. Khan J, Khan A, Khan MQ, Khan H. Applications of co-axial electrospinning in the biomedical field. *Next Mater*. 2024;3:100138. <https://doi.org/10.1016/J.NXMATE.2024.100138>.
31. Yu D-G, Li X-Y, Wang X, Yang J-H, Bligh SWA, Williams GR. Nanofibers fabricated using triaxial electrospinning as zero order drug delivery systems. *ACS Appl Mater Interfaces*. 2015;7:18891–7. <https://doi.org/10.1021/acsami.5b06007>.
32. Si Y, Shi S, Zhi C, Lei L, Hu J, Yang L. Janus Electrospun Membr Adv Mater. 2025. <https://doi.org/10.1002/adma.202507498>.
33. Al-Abduljabbar A, Farooq I. Electrospun polymer nanofibers: processing, properties, and applications. *Polym (Basel)*. 2022;15:65. <https://doi.org/10.3390/polym15010065>.
34. Nayl AA, Abd-Elhamid AI, Awwad NS, Abdelgawad MA, Wu J, Mo X, et al. Review of the recent advances in electrospun nanofibers applications in water purification. *Polym (Basel)*. 2022;14:1594. <https://doi.org/10.3390/polym14081594>.
35. Han D, Steckl AJ. Coaxial electrospinning formation of complex polymer fibers and their applications. *ChemPlusChem*. 2019;84:1453–97. <https://doi.org/10.1002/cplu.201900281>.
36. Dong R, Gong W, Guo Q, Liu H, Yu D-G. Synergistic effects of radical distributions of soluble and insoluble polymers within electrospun nanofibers for an extending release of Ferulic Acid 2024. <https://doi.org/10.3390/polym16182614>
37. Chen Y, Gong W, Zhang Z, Zhou J. Reverse gradient distributions of drug and polymer molecules within electrospun Core-Shell nanofibers for Sustained Release 2024. <https://doi.org/10.3390/ijms25179524>
38. Shell S, Gong W, Wang M-L, Liu Y, Yu D-G, Wan Annie Bligh S, Citation. Gong, W shell distribution of vitamin K3 within reinforced electrospun nanofibers for improved photo-Antibacterial Performance 2024. <https://doi.org/10.3390/ijms25179556>

39. Wang W, Yang X, Yin H, Lu Y, Dou H, Liu Y, et al. Polymeric nanofibers via green electrospinning for safe food engineering. *Macromol Rapid Commun*. 2025;46. <https://doi.org/10.1002/marc.202401152>.
40. Deng W, Liu Y, He C, Xiong X, Zhang R, Yan T, et al. Synergistic improvements of properties of cellulose acetate based curcumin@TiO₂ nanofibers via triaxial electrospinning. *Chem Eng J*. 2025;506:160117. <https://doi.org/10.1016/J.CEJ.2025.160117>.
41. Zhao Y-S, Huang J, Yang X, Wang W, Yu D-G, He H et al. Electrospun nanofibers and their application as sensors for health-care 2025. <https://doi.org/10.3389/fbioe.2025.1533367>
42. Hieu NT, Baik SJ, Jun Y, Lee M, Chung OH, Park JS. Electrospun coaxial titanium dioxide/carbon nanofibers for use in anodes of dye-sensitized solar cells. *Electrochim Acta*. 2014;142:144–51. <https://doi.org/10.1016/j.electacta.2014.07.032>.
43. Du P, Song L, Xiong J, Yuan Y, Wang L, Xi Z, et al. TiO₂/nb 2O₅ core-sheath nanofibers film: Co-electrospinning fabrication and its application in dye-sensitized solar cells. *Electrochem Commun*. 2012;25:46–9. <https://doi.org/10.1016/j.elecom.2012.09.013>.
44. Xu F, Tan H, Fan J, Cheng B, Yu J, Xu J. Electrospun TiO₂-Based photocatalysts. *Solar RRL*. 2021;5:2000571. <https://doi.org/10.1002/solr.202000571>.
45. Liu J-H, Wang P, Gao Z, Li X, Cui W, Li R, et al. Review on electrospinning anode and separators for lithium ion batteries. *Renew Sustain Energy Rev*. 2024;189:113939. <https://doi.org/10.1016/j.rser.2023.113939>.
46. Hebbar V, Viji M, Ghosh S, Sudakar C. Co-axially electrospun Li-rich layered oxide@spinel core-shell heterostructure nanofibers for enhanced stability and electrochemical performance. *Mater Res Bull*. 2024;180:113057. <https://doi.org/10.1016/J.MATERRESBULL.2024.113057>.
47. Zha J, Zheng D, Wang Y, Xie Z, Wu G, Qi J, et al. Coaxial electrospinning synthesis free-standing Sn/TiO₂ flexible carbon fibers with sheath/core structure for advanced flexible lithium/potassium-ion batteries. *Electrochim Acta*. 2024;500:144745. <https://doi.org/10.1016/J.ELECTACTA.2024.144745>.
48. Li ZY, Gao R, Zhang J, Zhang X, Hu Z, Liu X. New insights into designing high-rate performance cathode materials for sodium ion batteries by enlarging the slab-spacing of the Na-ion diffusion layer. *J Mater Chem Mater*. 2016;4:3453–61. <https://doi.org/10.1039/c5ta10589g>.
49. Song MK, Park S, Alamgir FM, Cho J, Liu M. Nanostructured electrodes for lithium-ion and lithium-air batteries: the latest developments, challenges, and perspectives. *Mater Sci Eng R: Rep*. 2011;72:203–52. <https://doi.org/10.1016/j.mser.2011.06.001>.
50. Dell RM. Batteries - fifty years of materials development. *Solid State Ion*. 2000;134:139–58. [https://doi.org/10.1016/S0167-2738\(00\)00722-0](https://doi.org/10.1016/S0167-2738(00)00722-0).
51. Ghosh S, Zaid M, Dutta J, Parvin M, Martha SK. Soft carbon in non-aqueous rechargeable batteries: a review of its synthesis, carbonization mechanism, characterization, and multifarious applications 2024. <https://doi.org/10.1039/d4ya00174e>
52. Deng J, Dai Y, Xiao Z, Song S, Dai H, Li L, et al. Bulk-like SnO₂-Fe₂O₃@carbon composite as a high-performance anode for lithium ion batteries. *Nanomaterials*. 2020;10:1–19. <https://doi.org/10.3390/nano10020249>.
53. Wang N, Zhao Y. Chapter 5 - Coaxial electrospinning. In: Ding B, Wang X, Yu J, editors. *Electrospinning: nanofabrication and applications*. William Andrew Publishing; 2019. pp. 125–200. <https://doi.org/10.1016/B978-0-323-51270-1.00005-4>.
54. Liu L, Lyu J, Mo J, Yan H, Xu L, Peng P, et al. Comprehensively-upgraded polymer electrolytes by multifunctional aramid nanofibers for stable all-solid-state Li-ion batteries. *Nano Energy*. 2020;69:104398. <https://doi.org/10.1016/j.nanoen.2019.104398>.
55. Li L, Cheah Y, Ko Y, Teh P, Wee G, Wong C, et al. The facile synthesis of hierarchical porous flower-like NiCo₂O₄ with superior lithium storage properties. *J Mater Chem Mater*. 2013;1:10935. <https://doi.org/10.1039/c3ta11549f>.
56. Zou L, Gan L, Lv R, Wang M, Huang Z, Kang F, et al. A film of porous carbon nanofibers that contain sn/sno nanoparticles in the pores and its electrochemical performance as an anode material for lithium ion batteries. *Carbon NY*. 2011;49:89–95. <https://doi.org/10.1016/j.carbon.2010.08.046>.
57. Wang L, Ding CX, Zhang LC, Xu HW, Zhang DW, Cheng T, et al. A novel carbon-silicon composite nanofiber prepared via electrospinning as anode material for high energy-density lithium ion batteries. *J Power Sources*. 2010;195:5052–6. <https://doi.org/10.1016/j.jpowsour.2010.01.088>.
58. Choi HS, Lee JG, Lee HY, Kim SW, Park CR. Effects of surrounding confinements of Si nanoparticles on Si-based anode performance for lithium ion batteries. *Electrochim Acta*. 2010;56:790–6. <https://doi.org/10.1016/j.electacta.2010.09.101>.
59. Lin Z, Ji L, Woodroof MD, Zhang X. Electrodeposited mnox/carbon nanofiber composites for use as anode materials in rechargeable lithium-ion batteries. *J Power Sources*. 2010;195:5025–31. <https://doi.org/10.1016/j.jpowsour.2010.02.004>.
60. Hosono E, Wang Y, Kida N, Enomoto M, Kojima N, Okubo M, et al. Synthesis of triaxial lifepo₄ nanowire with a VGCF core column and a carbon shell through the electrospinning method. *ACS Appl Mater Interfaces*. 2010;2:212–8. <https://doi.org/10.1021/am900656y>.
61. Toprakci O, Ji L, Lin Z, Toprakci HAK, Zhang X. Fabrication and electrochemical characteristics of electrospun LiFePO₄/carbon composite fibers for lithium-ion batteries. *J Power Sources*. 2011;196:7692–9. <https://doi.org/10.1016/j.jpowsour.2011.04.031>.
62. Cheah YL, Aravindan V, Madhavi S. Electrochemical lithium insertion behavior of combustion synthesized V₂O₅ cathodes for lithium-ion batteries. *J Electrochem Soc*. 2012;159:A273–80. <https://doi.org/10.1149/2.071203jes>.
63. Liang Y, Cheng S, Zhao J, Zhang C, Sun S, Zhou N, et al. Heat treatment of electrospun polyvinylidene fluoride fibrous membrane separators for rechargeable lithium-ion batteries. *J Power Sources*. 2013;240:204–11. <https://doi.org/10.1016/j.jpowsour.2013.04.019>.
64. Jayaraman S, Aravindan V, Suresh Kumar P, Chui Ling W, Ramakrishna S, Madhavi S. Exceptional performance of TiNb₂O₇ anode in all One-Dimensional architecture by electrospinning. *ACS Appl Mater Interfaces*. 2014;6:8660–6. <https://doi.org/10.1021/am501464d>.
65. Cao Y, Geng K, Geng H, Ang H, Pei J, Liu Y, et al. Metal-Oleate Complex-Derived bimetallic oxides nanoparticles encapsulated in 3D graphene networks as anodes for efficient lithium storage with pseudocapacitance. *Nanomicro Lett*. 2019;11:1–14. <https://doi.org/10.1007/s40820-019-0247-3>.
66. Li W, Chen S, Yu J, Fang D, Ren B, Zhang S. In-situ synthesis of interconnected SWCNT/OMC framework on silicon nanoparticles for high performance lithium-ion batteries. *Green Energy Environ*. 2016;1:91–9. <https://doi.org/10.1016/j.gee.2016.04.005>.

67. Zhang H, Qin X, Wu J, He YB, Du H, Li B, et al. Electrospun core-shell silicon/carbon fibers with an internal honeycomb-like conductive carbon framework as an anode for lithium ion batteries. *J Mater Chem Mater*. 2015;3:7112–20. <https://doi.org/10.1039/c4ta06044j>.
68. Yuan T, Zhao B, Cai R, Zhou Y, Shao Z. Electrospinning based fabrication and performance improvement of film electrodes for lithium-ion batteries composed of TiO₂ Hollow fibers†. *J Mater Chem*. 2011;21:15041–8. <https://doi.org/10.1039/c1jm11483b>.
69. Ramachandran J, Lu M, Arias-Monje PJ, Kirmani MH, Shirolkar N, Kumar S. Towards designing strong porous carbon fibers through gel spinning of polymer blends. *Carbon N Y*. 2021;173:724–35. <https://doi.org/10.1016/j.carbon.2020.10.029>.
70. Lee BS, Yang HS, Jung H, Jeon SY, Jung C, Kim SW, et al. Novel multi-layered 1-D nanostructure exhibiting the theoretical capacity of silicon for a super-enhanced lithium-ion battery. *Nanoscale*. 2014;6:5989–98. <https://doi.org/10.1039/c4nr00318g>.
71. Li X, Chen Y, Zhou L, Mai YW, Huang H. Exceptional electrochemical performance of porous TiO₂-carbon nanofibers for lithium ion battery anodes. *J Mater Chem Mater*. 2014;2:3875–80. <https://doi.org/10.1039/c3ta14646d>.
72. Paquin F, Rivnay J, Salleo A, Stingelin N, Silva C. Multi-phase semicrystalline microstructures drive exciton dissociation in neat plastic semiconductors. *J Mater Chem C*. 2015;3:10715–22. <https://doi.org/10.1039/b000000x>.
73. Kaerkitcha N, Chuangchote S, Sagawa T. Control of physical properties of carbon nanofibers obtained from coaxial electrospinning of PMMA and PAN with adjustable inner/outer nozzle-ends. *Nanoscale Res Lett*. 2016;11:186. <https://doi.org/10.1186/s11671-016-1416-7>.
74. Chen S, Zhou R, Chen Y, Li P, Song Y, Wang L. Lithium-Ion batteries anodic performance of porous Sn/C-ZnO core-shell structures derived from ZIF-8. *Int J Electrochem Sci*. 2016;11:10522–35. <https://doi.org/10.20964/2016.12.62>.
75. Dong Y, Zhao Z, Wang Z, Liu Y, Wang X, Qiu J. Dually fixed SnO₂ nanoparticles on graphene nanosheets by polyaniline coating for superior lithium storage. *ACS Appl Mater Interfaces*. 2015;7:2444–51. <https://doi.org/10.1021/am506818h>.
76. Shilpa, Basavaraja BM, Majumder SB, Sharma A. Electrospun Hollow glassy carbon-reduced graphene oxide nanofibers with encapsulated ZnO nanoparticles: A free standing anode for Li-ion batteries. *J Mater Chem Mater*. 2015;3:5344–51. <https://doi.org/10.1039/c4ta07220k>.
77. Xiong Q, Tu J, Xia X, Zhao X, Gu C, Wang X. A three-dimensional hierarchical Fe₂O₃@NiO core/shell Nanorod array on carbon cloth: a new class of anode for high-performance lithium-ion batteries. *Nanoscale*. 2013;5:7906. <https://doi.org/10.1039/c3nr02258g>.
78. Zhang T, Zhang L, Zhao L, Huang X, Li W, Li T, et al. Free-Standing, foldable V 2 O 3 /Multichannel carbon nanofibers electrode for flexible Li-Ion batteries with ultralong lifespan. *Small*. 2020;16. <https://doi.org/10.1002/smll.202005302>.
79. Faisal M, Nasir F, Shabbir F, Ud Z, Babar D, Saleem MF et al. Supercapacitors: An Emerging Energy Storage System 2025. <https://doi.org/10.1002/aesr.202400412>
80. Dissanayake K, Kularatna-Abeywardana D. A review of supercapacitors: materials, technology, challenges, and renewable energy applications. *J Energy Storage*. 2024;96:112563. <https://doi.org/10.1016/j.est.2024.112563>.
81. Zhang J, Gu M, Chen X. Supercapacitors for renewable energy applications: a review. *Micro Nano Eng*. 2023;21:100229. <https://doi.org/10.1016/j.mne.2023.100229>.
82. Snook GA, Kao P, Best AS. Conducting-polymer-based supercapacitor devices and electrodes. *J Power Sources*. 2011;196:1–12. <https://doi.org/10.1016/j.jpowsour.2010.06.084>.
83. Chuang CM, Huang CW, Teng H, Ting JM. Hydrothermally synthesized RuO₂/carbon nanofibers composites for use in high-rate supercapacitor electrodes. *Compos Sci Technol*. 2012;72:1524–9. <https://doi.org/10.1016/j.compscitech.2012.05.024>.
84. Lokhande CD, Dubal DP, Joo OS. Metal oxide thin film based supercapacitors. *Curr Appl Phys*. 2011;11:255–70. <https://doi.org/10.1016/j.cap.2010.12.001>.
85. Wei H, Yan X, Li Y, Gu H, Wu S, Ding K, et al. Electrochromic poly(DNTD)/WO₃ nanocomposite films via electropolymerization. *J Phys Chem C*. 2012;116:16286–93. <https://doi.org/10.1021/jp304127z>.
86. Wei S, Mavinakuli P, Wang Q, Chen D, Asapu R, Mao Y, et al. Polypyrrole-Titanium nanocomposites derived from different oxidants. *J Electrochem Soc*. 2011;158:K205. <https://doi.org/10.1149/2.048111jes>.
87. Hu Z, Zu L, Jiang Y, Lian H, Liu Y, Li Z, et al. High specific capacitance of polyaniline/mesoporous manganese dioxide composite using KI-H₂SO₄ electrolyte. *Polym (Basel)*. 2015;7:1939–53. <https://doi.org/10.3390/polym7101491>.
88. Zhou X, Shang C, Gu L, Dong S, Chen X, Han P, et al. Mesoporous coaxial titanium nitride-vanadium nitride fibers of core-shell structures for high-performance supercapacitors. *ACS Appl Mater Interfaces*. 2011;3:3058–63. <https://doi.org/10.1021/am200564b>.
89. Xiao Y, Xu Y, Zhang K, Tang X, Huang J, Yuan K, et al. Coaxial electrospun free-standing and mechanically stable hierarchical porous carbon nanofiber membranes for flexible supercapacitors. *Carbon N Y*. 2020;160:80–7. <https://doi.org/10.1016/j.carbon.2020.01.017>.
90. Wang L, Zhang C, Cao X, Xu X, Bai J, Zhu J, et al. Construction of novel coaxial electrospun polyetherimide@polyaniline core-shell fibrous membranes as free-standing flexible electrodes for supercapacitors. *J Power Sources*. 2024;602:234305. <https://doi.org/10.1016/j.jpowsour.2024.234305>.
91. Jeong JH, Kim YA, Kim B-H. Electrospun polyacrylonitrile/cyclodextrin-derived hierarchical porous carbon nanofiber/MnO₂ composites for supercapacitor applications. *Carbon N Y*. 2020;164:296–304. <https://doi.org/10.1016/j.carbon.2020.03.052>.
92. Kim Y, Samuel E, Joshi B, Park C, Lee H-S, Yoon SS. Flexible metallized carbon nanofibers decorated with two-dimensional NiGa₂S₄ nanosheets as supercapacitor electrodes. *Chem Eng J*. 2021;420:130497. <https://doi.org/10.1016/j.cej.2021.130497>.
93. Yan A-L, Wang W-D, Chen W-Q, Wang X-C, Liu F, Cheng J-P. The synthesis of NiCo₂O₄-MnO₂ Core-Shell nanowires by electrodeposition and its supercapacitive properties. *Nanomaterials*. 2019;9:1398. <https://doi.org/10.3390/nano9101398>.
94. Li L, Zhang X, Zhang Z, Zhang M, Cong L, Pan Y, et al. A bismuth oxide nanosheet-coated electrospun carbon nanofiber film: a free-standing negative electrode for flexible asymmetric supercapacitors. *J Mater Chem Mater*. 2016;4:16635–44. <https://doi.org/10.1039/C6TA06755G>.
95. An G-H, Ahn H-J. Activated porous carbon nanofibers using Sn segregation for high-performance electrochemical capacitors. *Carbon N Y*. 2013;65:87–96. <https://doi.org/10.1016/j.carbon.2013.08.002>.
96. Laforge A. All-textile flexible supercapacitors using electrospun poly(3,4-ethylenedioxythiophene) nanofibers. *J Power Sources*. 2011;196:559–64. <https://doi.org/10.1016/j.jpowsour.2010.07.007>.

97. Zhi M, Liu S, Hong Z, Wu N. Electrospun activated carbon nanofibers for supercapacitor electrodes. *RSC Adv.* 2014;4:43619–23. <https://doi.org/10.1039/C4RA05512H>.
98. Zhou Z, Wu X-F, Hou H. Electrospun carbon nanofibers surface-grown with carbon nanotubes and polyaniline for use as high-performance electrode materials of supercapacitors. *RSC Adv.* 2014;4:23622–9. <https://doi.org/10.1039/C4RA00964A>.
99. Reddy VS, Tian Y, Zhang C, Ye Z, Roy K, Chinnappan A, et al. A review on electrospun nanofibers based advanced applications: from health care to energy devices. *Polym (Basel).* 2021;13:3746. <https://doi.org/10.3390/polym13213746>.
100. Abouali S, Akbari Garakani M, Zhang B, Xu Z-L, Kamali Heidari E, Huang J, et al. Electrospun carbon nanofibers with in situ encapsulated Co_3O_4 nanoparticles as electrodes for High-Performance supercapacitors. *ACS Appl Mater Interfaces.* 2015;7:13503–11. <https://doi.org/10.1021/acsami.5b02787>.
101. Miao F, Shao C, Li X, Wang K, Lu N, Liu Y. Electrospun carbon nanofibers/carbon nanotubes/polyaniline ternary composites with enhanced electrochemical performance for flexible Solid-State supercapacitors. *ACS Sustain Chem Eng.* 2016;4:1689–96. <https://doi.org/10.1021/acssuschemeng.5b01631>.
102. Hu CL, Yi HH, Wang FX, Xiao SY, Wu YP, Wang D, et al. Boron doping at P-site to improve electrochemical performance of LiMnPO_4 as cathode for lithium ion battery. *J Power Sources.* 2014;255:355–9. <https://doi.org/10.1016/j.jpowsour.2013.12.040>.
103. Choi S-H, Hyun T-S, Lee H, Jang S-Y, Oh S-G, Kim I-D. Facile synthesis of highly conductive platinum nanofiber Mats as conducting core for high rate redox supercapacitor. *Electrochem Solid-State Lett.* 2010;13:A65. <https://doi.org/10.1149/1.3369539>.
104. Zhang L, Ding Q, Huang Y, Gu H, Miao Y-E, Liu T. Flexible hybrid membranes with $\text{Ni}(\text{OH})_2$ nanoplatelets vertically grown on electrospun carbon nanofibers for High-Performance supercapacitors. *ACS Appl Mater Interfaces.* 2015;7:22669–77. <https://doi.org/10.1021/acsami.5b07528>.
105. Miao F, Shao C, Li X, Wang K, Liu Y. Flexible solid-state supercapacitors based on freestanding nitrogen-doped porous carbon nanofibers derived from electrospun polyacrylonitrile@polyaniline nanofibers. *J Mater Chem Mater.* 2016;4:4180–7. <https://doi.org/10.1039/C6TA00015K>.
106. Jang J, Bae J, Choi M, Yoon S-H. Fabrication and characterization of polyaniline coated carbon nanofiber for supercapacitor. *Carbon N.Y.* 2005;43:2730–6. <https://doi.org/10.1016/j.carbon.2005.05.039>.
107. Santangelo S. Electrospun Nanomaterials for Energy Applications: Recent Advances 2019. <https://doi.org/10.3390/app9061049>.
108. Nagamine S, Ishimaru S, Taki K, Ohshima M. Fabrication of carbon-core / TiO_2 -sheath nano Fibers by carbonization of Poly (vinyl alcohol)/ TiO_2 composite nano Fibers prepared via electrospinning and an interfacial sol -. *Gel Reaction.* 2011;65:3027–9. <https://doi.org/10.1016/j.matlet.2011.06.067>.
109. Bedford NM, Dickerson MB, Drummy LF, Koerner H, Singh KM, Vasudev MC et al. Nanofiber-Based Bulk-Heterojunction organic solar cells. Using Coaxial Electrospinning 2012:1–9. <https://doi.org/10.1002/aenm.201100674>.
110. Links DA. Nanoscale photocatalytic materials † 2012:1707–16. <https://doi.org/10.1039/c2nr11251e>.
111. Huang HJ, Nan HR, Yang YG, Gao XY, Chen F, Chen Z. Improved performance of Thick films based binary and ternary bulk heterojunction organic photovoltaic devices incorporated with electrospinning. *Processed Nanofibers.* 2018;1800914:1–10. <https://doi.org/10.1002/admi.201800914>.
112. Liu Q, Liu Y, Ding Y, Peng Z, Yu Q, Tian X, et al. Synthesis and characterization of novel blue emitting $\text{Na}_2\text{CaSiO}_4:\text{Ce}^{3+}$ phosphor. *J Solgel Sci Technol.* 2014;71:276–82. <https://doi.org/10.1007/s10971-014-3371-z>.
113. Li C, Chen H, Hua Y, Yu L, Jiang Q, Deng D, et al. Photoluminescence and energy transfer studies on $\text{Ce}^{3+}/\text{Eu}^{2+}$ -co-doped $\text{Ba}_3\text{Si}_6\text{O}_{12}\text{N}_2$ phosphor for white light-emitting-diodes. *Opt Commun.* 2013;295:129–33. <https://doi.org/10.1016/j.optcom.2012.12.090>.
114. Guo P, Aegerter MA. $\text{Ru}(\text{II})$ sensitized Nb_2O_5 solar cell made by the sol-gel process. *Thin Solid Films.* 1999;351:290–4. [https://doi.org/10.1016/S0040-6090\(99\)00215-1](https://doi.org/10.1016/S0040-6090(99)00215-1).
115. Nano LC. Light-Emitting Coaxial Nano fibers 2012:622–8.
116. López-Covarrubias JG, Soto-Muñoz L, Iglesias AL, Villarreal-Gómez LJ. Electrospun nanofibers applied to dye solar sensitive cells: A review. *Materials.* 2019;12. <https://doi.org/10.3390/ma12193190>.
117. Mostofizadeh M, Pitcher ML, Sheikh A. Coaxial electrospinning. *Electrospun and Nanofibrous Membranes: Principles and Applications* 2022:105–26. <https://doi.org/10.1016/B978-0-12-823032-9.00006-4>.
118. Nien Y-H, Yong Z-R, Ho C-S, Chou J-C, Lai C-H, Kuo P-Y, et al. Preparation and characterization of the Dye-Sensitized solar cell with modified photoanode by FePt/TiO_2 nanofibers. *IEEE Trans Nanotechnol.* 2021;20:507–11. <https://doi.org/10.1109/TNANO.2021.3088954>.
119. Zhai J, Yin X, Song L, Chen W-H, Du P, Xiong J. Preparation of fabric-like transparent electrode for flexible perovskite solar cell. *Thin Solid Films.* 2021;729:138698. <https://doi.org/10.1016/j.tsf.2021.138698>.
120. Lin P-C, Hsieh C-T, Liu X, Chang F-C, Chen W-C, Yu J, et al. Fabricating efficient flexible organic photovoltaics using an eco-friendly cellulose nanofibers/silver nanowires conductive substrate. *Chem Eng J.* 2021;405:126996. <https://doi.org/10.1016/j.cej.2020.126996>.
121. Yang Z, Zhou S, Zu J, Inman D. High-Performance piezoelectric energy harvesters and their applications. *Joule.* 2018;2:642–97. <https://doi.org/10.1016/j.joule.2018.03.011>.
122. Yang J, Zhang Y, Li Y, Wang Z, Wang W, An Q, et al. Piezoelectric nanogenerators based on graphene oxide/pvdf electrospun nanofiber with enhanced performances by In-Situ reduction. *Mater Today Commun.* 2021;26:101629. <https://doi.org/10.1016/j.mtcomm.2020.101629>.
123. Prasad PD, Hemalatha J. Energy harvesting performance of magnetoelectric poly(vinylidene fluoride)/ NiFe_2O_4 nanofiber films. *J Magn Magn Mater.* 2021;532:167986. <https://doi.org/10.1016/j.jmmm.2021.167986>.
124. Bedford NM, Dickerson MB, Drummy LF, Koerner H, Singh KM, Vasudev MC, et al. Nanofiber-Based Bulk-Heterojunction organic solar cells using coaxial electrospinning. *Adv Energy Mater.* 2012;2:1136–44. <https://doi.org/10.1002/aenm.201100674>.
125. Pierini F, Lanzi M, Nakielski P, Pawłowska S, Urbanek O, Zembrzycki K, et al. Single-Material organic solar cells based on electrospun Fullerene-Grafted polythiophene nanofibers. *Macromolecules.* 2017;50:4972–81. <https://doi.org/10.1021/acs.macromol.7b00857>.
126. Chen J, Li B, Zheng J, Zhao J, Jing H, Zhu Z. Polyaniline nanofiber/carbon film as flexible counter electrodes in platinum-free dye-sensitized solar cells. *Electrochim Acta.* 2011;56:4624–30. <https://doi.org/10.1016/j.electacta.2011.02.097>.

127. Ojha K, Saha S, Dagar P, Ganguli AK. Nanocatalysts for hydrogen evolution reactions. *Phys Chem Chem Phys*. 2018;20:6777–99. <https://doi.org/10.1039/c7cp06316d>.
128. Balat M, Balat M. Political, economic and environmental impacts of biomass-based hydrogen. *Int J Hydrogen Energy*. 2009;34:3589–603. <https://doi.org/10.1016/j.ijhydene.2009.02.067>.
129. Yu S, Kim J, Yoon KR, Jung JW, Oh J, Kim ID. Rational design of efficient electrocatalysts for hydrogen evolution reaction: single layers of WS₂ nanoplates anchored to Hollow Nitrogen-Doped carbon nanofibers. *ACS Appl Mater Interfaces*. 2015;7:28116–21. <https://doi.org/10.1021/acsami.5b09447>.
130. Sun C, Wang C, Han G, Zhang Y, Zhao H. Pt atomic clusters/MoS₂ nanosheets/Co-doped Hollow carbon nanofibers for high-current-density alkaline hydrogen production. *Chem Eng J*. 2024;496:153665. <https://doi.org/10.1016/j.cej.2024.153665>.
131. Li L, Yu M, Gao C, Yan X, Zhang N, Bao J, et al. MoS₂/CoS₂ with heterostructure in-situ grown on the surface of electrospinning carbon nanotube for efficient hydrogen evolution reaction. *J Alloys Compd*. 2024;1003:175530. <https://doi.org/10.1016/j.jallcom.2024.175530>.
132. Ding Q, Liu M, Miao Y-E, Huang Y, Liu T. Electrospun nickel-decorated carbon nanofiber membranes as efficient electrocatalysts for hydrogen evolution reaction. *Electrochim Acta*. 2015;159:1–7. <https://doi.org/10.1016/j.electacta.2015.01.197>.
133. Khalily MA, Yurderi M, Haider A, Bulut A, Patil B, Zahmakiran M, et al. Atomic layer deposition of ruthenium nanoparticles on electrospun carbon nanofibers: A highly efficient nanocatalyst for the hydrolytic dehydrogenation of methylamine borane. *ACS Appl Mater Interfaces*. 2018;10:26162–9. <https://doi.org/10.1021/acsami.8b04822>.
134. Li M, Zhu Y, Song N, Wang C, Lu X. Fabrication of Pt nanoparticles on nitrogen-doped carbon/ni nanofibers for improved hydrogen evolution activity. *J Colloid Interface Sci*. 2018;514:199–207. <https://doi.org/10.1016/j.jcis.2017.12.028>.
135. Zhang C, Wang Z, Bhoyate S, Morey T, Neria B, Vasiraju V, et al. MoS₂ decorated carbon nanofibers as efficient and durable electrocatalyst for hydrogen evolution reaction. *C (Basel)*. 2017;3:33. <https://doi.org/10.3390/c3040033>.
136. Zhu H, Du M, Zhang M, Zou M, Yang T, Wang S, et al. S-rich single-layered MoS₂ nanoplates embedded in N-doped carbon nanofibers: efficient co-electrocatalysts for the hydrogen evolution reaction. *Chem Commun*. 2014;50:15435–8. <https://doi.org/10.1039/C4CC06480A>.
137. Wang K, Xi D, Zhou C, Shi Z, Xia H, Liu G, et al. CoSe₂ necklace-like nanowires supported by carbon fiber paper: a 3D integrated electrode for the hydrogen evolution reaction. *J Mater Chem Mater*. 2015;3:9415–20. <https://doi.org/10.1039/C5TA01143D>.
138. Gu H, Huang Y, Zuo L, Fan W, Liu T. Electrospun carbon nanofiber@cos₂ core/sheath hybrid as an efficient all-pH hydrogen evolution electrocatalyst. *Inorg Chem Front*. 2016;3:1280–8. <https://doi.org/10.1039/C6QI00229C>.
139. Surendran S, Shanmugapriya S, Sivanantham A, Shanmugam S, Kalai Selvan R. Electrospun carbon nanofibers encapsulated with nicop: A multifunctional electrode for supercapattery and oxygen reduction, oxygen evolution, and hydrogen evolution reactions. *Adv Energy Mater*. 2018;8. <https://doi.org/10.1002/aenm.201800555>.
140. Ji D, Peng S, Lu J, Li L, Yang S, Yang G, et al. Design and synthesis of porous channel-rich carbon nanofibers for self-standing oxygen reduction reaction and hydrogen evolution reaction bifunctional catalysts in alkaline medium. *J Mater Chem Mater*. 2017;5:7507–15. <https://doi.org/10.1039/C7TA00828G>.
141. Abdulhussain R, Adebisi A, Conway BR, Asare-Addo K. Electrospun nanofibers: exploring process parameters, polymer selection, and recent applications in pharmaceuticals and drug delivery. *J Drug Deliv Sci Technol*. 2023;90:105156. <https://doi.org/10.1016/j.jddst.2023.105156>.
142. Pillay V, Dott C, Choonara YE, Tyagi C, Tomar L, Kumar P, et al. A review of the effect of processing variables on the fabrication of electrospun nanofibers for drug delivery applications. *J Nanomater*. 2013;2013. <https://doi.org/10.1155/2013/789289>.
143. Yu D-G, He W, He C, Liu H, Yang H. Versatility of electrospun Janus wound dressings. *Nanomedicine*. 2025;20:271–8. <https://doi.org/10.1080/17435889.2024.2446139>.
144. Chen S, Wu X, Ding X. One-step side-by-side electrospinning of Janus particles for durable multifunctional coatings on cotton textiles. *Colloids Surf Physicochem Eng Asp*. 2025;710:136227. <https://doi.org/10.1016/j.colsurfa.2025.136227>.
145. Wang M, Hou J, Yu D-G, Li S, Zhu J, Chen Z. Electrospun tri-layer nanodepots for sustained release of acyclovir. *J Alloys Compd*. 2020;846:156471. <https://doi.org/10.1016/j.jallcom.2020.156471>.
146. Yu D-G, Zhou J. Electrospun multi-chamber nanostructures for sustainable biobased chemical nanofibers. *Next Mater*. 2024;2:100119. <https://doi.org/10.1016/j.nxmater.2024.100119>.
147. Wang M, Huang C, Chen Y, Ji Y, Yu D-G, Bligh SWA. Medicated tri-layer fibers based on cellulose acetate and Polyvinylpyrrolidone for enhanced antibacterial and wound healing properties. *Carbohydr Polym*. 2025;348:122856. <https://doi.org/10.1016/j.carbpol.2024.122856>.

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