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Electrospun Nanofibers-Based Moist-Electric Generators

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Abstract

Moisture-electric generators provide an innovative and sustainable method for harvesting electricity directly from ambient atmospheric humidity through hygroscopic interactions and ion transport processes. Among diverse architectures, those based on electrospun nanofibers are particularly promising due to their high surface area, superior breathability, mechanical flexibility, and seamless integration into wearable systems. This review provides a comprehensive summary of recent advances in electrospun nanofiber moisture-electric generators, with a focus on fabrication techniques via electrospinning, material optimization through functional additives, device performance metrics, and emerging applications in self-powered wearable electronics, sensors, and smart textiles. Significant improvements in power output and durability have been reported in hybrid designs. Nonetheless, challenges in long-term reliability, manufacturing scalability, and conversion efficiency hinder widespread adoption. Future directions include multifunctional materials, asymmetric device designs, and scalable production strategies to enable practical, battery-free power sources for next-generation wearable technologies.

Keywords: Electrospun nanofibers; Moisture-electric generators; Functional nanomaterials; Self-powered sensors; Wearable power sources

1. INTRODUCTION

The growing need for sustainable and decentralized energy sources is driven by the surge in portable electronics, wearable devices, and remote monitoring systems [1]. Global energy consumption for such applications is projected to grow exponentially, exacerbating reliance on conventional batteries that pose environmental concerns due to limited lifespan, toxic components, and disposal challenges. Traditional energy harvesting technologies [2–5]—such as photovoltaic, thermoelectric, piezoelectric, and triboelectric—have improved significantly but still face limitations: they often depend on sunlight or movement, suffer from mechanical wear, or perform poorly in everyday indoor conditions.

In this context, moisture-driven electricity generation, also called moist-electric generation (MEG), emerges as a highly promising solution [6–9]. This technology harnesses water vapour that is always present in the air—even at low relative humidity levels—to produce electrical power passively and continuously, without the requiring of external mechanical input, light, or heat gradients [10]. By exploiting the natural interaction between hygroscopic materials and water vapor, MEG devices generate voltage through ion dissociation, charge separation, and directed ion transport, offering a truly "green" and widely available energy option suitable for diverse environments, including indoor settings and humid regions.

Among the diverse material platforms explored—including hydrogels, carbon-based nanomaterials (e.g., graphene oxide, MXene), and metal-organic frameworks—fibrous architectures based on electrospun nanofibers have become especially important. These nanofibers offer unique advantages: high specific surface area (often > 100 m^2/g), interconnected porous networks for rapid moisture diffusion, tunable hygroscopicity through chemical functionalization, and inherent mechanical flexibility and breathability ideal for wearable applications [11–14].

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Electrospun mats facilitate efficient water molecule adsorption/desorption cycles, enhancing ion mobility and sustaining charge gradients even at moderate RH [15].

The electrospinning technique plays a central role for these advances. This versatile, industrially scalable method involves applying high voltage to a polymer solution or melt, forming ultrafine fibers (diameters 50–1000 nm) collected as non-woven mats [16]. Parameters such as applied voltage, flow rate, collector distance, and environmental humidity allow precise control over fiber morphology—ranging from aligned yarns to random mats, bead-free structures, or core-shell configurations via coaxial spinning. These features enable the creation of advanced designs like Janus (asymmetric) membranes, bilayer composites, and gradient-functionalized fibers, which direct ion flow unidirectionally for enhanced voltage output [17,18].

Recent achievements illustrate the rapid progress of electrospun nanofiber-based MEGs. For example, devices with cellulose acetate and tree-like pores significantly improve moisture transport; crosslinked PVA/sodium alginate bilayers demonstrate enhanced long-term stability; and fully electrospun Janus structures achieve operation longer than 600 hours with voltages around 1.0 V and currents in the microampere range. Stretchable and flame-resistant versions further expand applicability to human-body-integrated electronics. Scanning electron microscopy (SEM) images consistently reveal the highly porous and connected nanofiber networks that are essential for good performance [11,19].

This review focuses specifically on electrospun nanofiber-based MEGs, highlighting their fabrication, material optimization, working mechanisms, device performance, and applications. We aim to provide a comprehensive overview of recent progress while identifying key challenges and future directions for scalable, practical implementation.

2. MECHANISMS OF ELECTRICITY GENERATION

In electrospun nanofiber-based moist-electric generators, electricity generation depends on the interaction between atmospheric moisture and the functional groups on the nanofiber surfaces. Recent studies classify the main mechanisms into two primary categories: ion concentration gradient (also known as ionic diffusion or concentration gradient-driven) and streaming potential [8,20]. These mechanisms frequently operate together in porous nanofiber systems, creating synergistic effects that lead to higher and more stable output performance.

The ion concentration gradient mechanism arises from the creation of an uneven distribution of mobile ions, often protons H^+ or other cations and anions, across the material thickness. When moisture adsorbs onto the nanofiber surfaces, water molecules weaken bonds in oxygen-containing functional groups such as carboxyl (–COOH) or hydroxyl (–OH), leading to ion dissociation and the release of free ions. These ions then diffuse from regions of high concentration to low concentration, generating a potential difference and driving current through the external circuit.

This gradient forms through several approaches in nanofiber-based devices. In single-material systems, asymmetrical treatment during fabrication creates a gradient of functional groups, for example through controlled functionalization or processes similar to moisture-electric annealing adapted to nanofibers, resulting in one side having higher density of hygroscopic groups and stronger ion release on the moist-exposed side. Another way involves asymmetrical moisture absorption, often achieved with asymmetrical electrodes or uneven exposure, where one side absorbs more water, causing uneven swelling and enhanced ion mobility. In multilayer or composite systems, bilayer or Janus electrospun structures offer greater design flexibility by the incorporation of different polymers or additives on each layer, further strengthening the gradient [21]. In nanofiber MEGs, porous and asymmetric designs such as tree-like pores or Janus architectures particularly reinforce this mechanism by the promotion of directional ion diffusion and minimizing back-diffusion.

The second major mechanism—streaming potential—occurs when moisture flow or capillary action transports ions through narrow channels in the nanofibers [7,8]. Charged functional groups on the nanofiber walls attract counter-ions from the adsorbed water layer, forming an electrical double layer (EDL) at the solid-liquid interface. As moist air flow or pressure drives fluid movement through the nanopores, these counter-ions are dragged along, producing a streaming current and corresponding voltage.

Several factors strongly influence the streaming potential. Nanopore size relative to the Debye length (the thickness of the EDL) plays a critical role: when the pore diameter approaches or falls below the Debye length, overlapping EDLs develop, enabling high ion selectivity and a stronger potential. The overall porous structure of electrospun nanofibers, with abundant nanochannels and high porosity, significantly amplifies these streaming effects, especially in hierarchically porous or tree-like designs. Experimental evidence demonstrates that voltage can persist even after direct moisture flow stops, due to residual contributions from the EDL and trapped ions.

In many electrospun nanofiber MEGs, both mechanisms function simultaneously, resulting in synergistic enhancement where the ion concentration gradient initiates diffusion and the streaming potential in nanopores boosts overall output and long-term stability. This dual action appears particularly clearly in functionalized composites,

such as those based on PVA/phytic acid or cellulose, and in asymmetric Janus structures, where the built-in gradient prevents ion back-diffusion while the pores support robust EDL formation [20,22,23].

3. ELECTROSPINNING PROCESS AND OPTIMIZATION

Electrospinning serves as the primary fabrication technique for producing nanofibers in MEGs. Researchers favor this method for its simplicity, versatility, and potential for industrial-scale production. It enables the creation of non-woven mats featuring high porosity, large surface area, and tunable chemical properties, all of which prove essential for the effective moisture adsorption and for the ion transport in MEG devices [24,25].

The electrospinning process (Fig. 1) works by applying a high electric field to a polymer solution or melt. A typical setup includes three main parts: a high-voltage power supply (usually 10–30 kV), a syringe pump to control the flow of the solution, a spinneret (often a metal needle), and a grounded collector (such as a flat plate, rotating drum, or roller) [26].

The polymer solution is loaded into a syringe and pushed out at a constant flow rate (typically 0.1–5.0 mL/h). When high voltage is applied, electrostatic forces overcome the surface tension of the droplet at the needle tip, forming a Taylor cone. From this cone, a charged jet is ejected. The jet undergoes whipping instability due to electrostatic repulsion, stretching and thinning rapidly while the solvent evaporates. Finally, solid nanofibers are deposited on the collector as a random or aligned mat.

Several key parameters significantly affect fiber quality and morphology (Tables 1–3, [27]). Applied voltage strengthens the electrostatic force, often resulting in thinner fibers, though excessive levels can cause bead defects. The distance from tip to collector, ideally 10–20 cm, provides sufficient time for solvent evaporation and jet stretching; shorter distances yield wet fibers, while longer

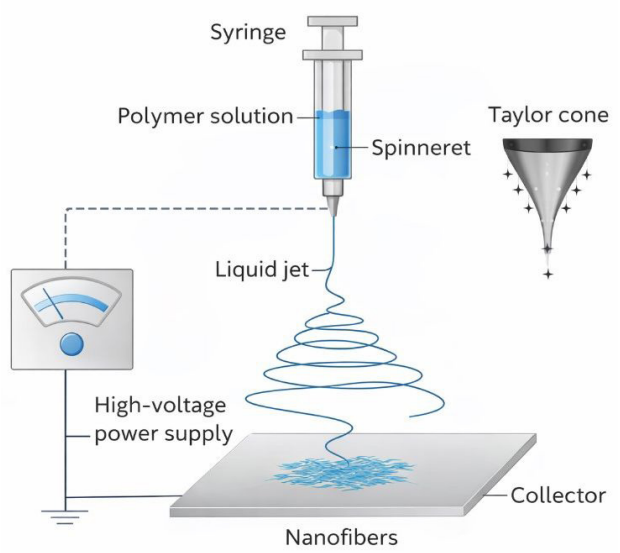

Fig. 1. Electrospinning setup.

ones reduce efficiency. Flow rate influences uniformity, with lower rates promoting smooth fibers and higher rates leading to thicker diameters or beads.

Solvent characteristics, including volatility, conductivity, and viscosity, determine jet stability—for instance, mixtures like dimethylformamide, acetone, or water/ethanol suit hygroscopic polymers such as PVA or cellulose acetate. Environmental conditions, particularly humidity and temperature, regulate evaporation; elevated humidity during spinning can induce porous surfaces on individual fibers [28].

These parameters directly shape nanofiber structure in ways critical for MEG performance. Fiber diameter generally spans 50 nm to 1.0 μm, decreasing with higher voltage or lower solution concentration due to enhanced stretching, which in turn increases surface area for moisture interaction. Porosity develops through controlled evaporation or ambient humidity, producing nanopores on fiber surfaces and interconnected voids within the mat that improve moisture diffusion and ion pathways. Collectors influence

Table 1. Technological parameters and their influence on the process and fiber morphology. Reproduced with permission from Ref. [27], © 2024 John Wiley and Sons.

Parameter	Increase ↑	Decrease ↓
Applied voltage	Smaller Taylor cone, thinner fibers, smaller pores Very high voltage causes multiple jets and may result in the formation of beads	Larger Taylor cone, thicker fibers, larger pores Voltage below spinning threshold stops jet formation
Flow rate	Thicker fibers, larger pores Excessive flow rate causes a bloated Taylor cone and wet fibers	Thinner fibers, smaller pores Too little causes the Taylor cone to retreat into the nozzle
Tip-to-collector distance (TCD)	Causes an effective decrease in electrical density, resulting in thicker fibers A large TCD may not be suitable for solvents with fast evaporation	Decrease in TCD causes an effective increase in electrical density A minimum distance is required for the formation of fibers

Table 2. Solvent characteristics and their influence on the process and fiber morphology. Reproduced with permission from Ref. [27], © 2024 John Wiley and Sons.

Parameter	Increase ↑	Decrease ↓
Polymer concentration	Thicker fibers, larger pores Very high concentration stops electrospinning A medium concentration gives a combination of beads and fibers	Thinner fibers, smaller pores Very low concentration results in the formation of beads If the polymer is sufficiently conductive, electrospraying is possible at fairly low concentrations
Electrical conductivity	Thinner fibers, smaller pores Solutions with extremely high conductivities may be unstable during electrospinning and are likely to produce multiple jets	Thicker fibers, larger pores produced A minimum conductivity is required for electrospinning
Viscosity	Thicker fibers, larger pores Extremely viscous solutions cannot be electrospun	Thinner fibers, smaller pores Very low viscosity causes the formation of beads
Surface tension	Makes it harder to electrospun and results in instability of jets Solutions with very high surface tension cannot be electrospun	Very low surface tension increases the tendency of jet breakage and results in drops
Molecular weight	Beads reduced if any, thicker fibers produced	Fiber thickness decreases Very low molecular weight forms beads

Table 3. Environmental conditions and their influence on the process and fiber morphology. Reproduced with permission from Ref. [27], © 2024 John Wiley and Sons.

Parameter	Increase ↑	Decrease ↓
Temperature	Fiber diameter decreases	Fiber diameter increases
Relative humidity	Higher humidity causes thinner fibers due to slower solvent evaporation Increases the incidence and size of circular pores on fibers No useable fibers produced over a critical limit	Lower humidity allows for better and faster solvent evaporation, resulting in thicker fibers

orientation, with static ones yielding random mats and rotating or patterned ones creating aligned fibers that can support directional ion movement. For MEG applications, the optimization focuses on achieving porosity above 80%, specific surface area exceeding 100 m^2/g, and consistent mat thickness to ensure reliable electricity generation.

Advanced variants of electrospinning allow for sophisticated structures and enhanced functionalization suited to MEG requirements. Coaxial electrospinning employs concentric needles to process two solutions at once, yielding core-shell fibers that encapsulate hygroscopic additives or create asymmetric surface chemistry for better ion dissociation and durability [29]. Multi-needle configurations boost productivity and enable polymer blending within a single mat, producing composites with superior conductivity or moisture affinity [30]. Needleless approaches utilize rotating spinners, wires, or gas bubbles to initiate multiple jets simultaneously, facilitating large-scale output of uniform thick mats [31]. Researchers frequently apply these modifications to build asymmetry, including Janus structures with contrasting hydrophilicity on opposing sides.

Electrospun nanofiber mats are particularly effective for moisture-electric generation due to their ultraporous, nonwoven architecture composed of nanoscale fibers. Fibers with diameters around 100 nm can provide surface areas approaching ~ 1000 m^2/g, while typical electrospun mats exhibit porosity above 90% [32]. This structure exposes a high density of polar functional groups (e.g., –OH, –COOH), enabling rapid moisture adsorption and ionization. Interconnected nanochannels promote overlapping electrical double layers and support efficient proton (H_3O^+) diffusion and streaming-charge transport [33].

As a result, electrospun MEGs can simultaneously operate via concentration-gradient diffusion and streaming-current mechanisms. For example, Sun et al. [33] demonstrated that an electrospun polyacrylonitrile fabric generated an open-circuit voltage of 0.83 V, which at the time exceeded all reported polymer-based MEGs.

In addition to high electrical output, electrospun nanofiber mats are mechanically soft, bendable, and breathable, allowing air and moisture transport without blocking ion flow. These properties make them well suited for wearable

and textile-integrated devices, as they conform to curved surfaces and remain comfortable during use [34].

Moreover, directional (Janus or multilayer) architectures are easy to implement by sequential electrospinning: a hydrophilic side can continuously absorb moisture and a hydrophobic side can promote evaporation. This built-in asymmetry drives unidirectional ion flow and long-lasting output. In one all-electrospun Janus film (PVA/LiCl layer vs. a PVDF/PVB layer), the MEG produced ~ 0.60 V and ~ 44 μA/cm^2 (at 95% RH) continuously for over 30 days [17].

Finally, electrospinning is a mature, scalable process: it can process a wide range of polymers into continuous nanofibers and easily produce large-area mats. In summary, electrospun mats combine high porosity and surface area, tunable asymmetry, and mechanical flexibility/breathability, making them especially effective and practical for durable MEGs.

4. COMPARISON WITH OTHER MEG PLATFORMS

Several other MEG material platforms have been explored, each with distinct strengths and weaknesses relative to nanofiber devices. Hydrogel-based MEGs (HMEGs), for instance, use thick polymer gels (e.g. PVA–alginate, polyacrylamide) that swell with moisture. These hydrogels can absorb very large amounts of water and form continuous ion-conducting networks. Indeed, advanced hydrogels have achieved record currents: Yang et al. reported a PVA–alginate supramolecular gel that produced 1.30 V and an exceptionally high short-circuit current of 1.31 mA·cm^{-2} [35]. Such high currents (milliamp scale) far exceed those of typical fibrous MEGs (usually microampere-scale). However, hydrogel devices are bulky and often require ionic dopants or high salt content to achieve performance. They also lose flexibility and breathability when swollen. In contrast, electrospun fiber mats remain air-permeable and lighter. Indeed, hydrogels must rely on techniques like protonation doping to boost output, whereas nanofiber platforms can achieve large voltages with less material [36].

Carbon- and inorganic-based MEGs form another category. Graphene oxide (GO) films and graphene networks were among the first MEGs studied. While a GO film with an oxygen gradient can convert moisture into electricity (even at ≈ 62% energy conversion efficiency [37]), such devices typically deliver only intermittent voltage spikes under strong humidity gradients. Integration of graphene or graphene oxide into three-dimensional porous carbon networks has been reported to improve moisture adsorption and ion transport pathways, leading to open-circuit voltages typically on the order of several hundred millivolts (≈ 0.3–0.4 V) [20]. Inorganic nanowires (e.g. TiO_2) have also been tested: Shen et al. [38] developed a TiO_2 nanowire MEG with a power density up to ~ 47 μW·cm^{-2}. These rigid nanostructures can be efficient under ideal conditions, but they lack the open, moisture-permeable porosity of fiber mats. Carbon nanotube (CNT)-coated fabrics are a hybrid example: Faramarzi et al. [39] showed that coating a stretchable nanofiber mat with CNTs produced up to ~ 0.8 V and 13 μA (≈ 10 μW) of power when wetted. While this boosted conductivity and stretchability, the device still relied on an electrospun fiber scaffold.

Two-dimensional materials and hybrids, such as MXenes and composite films, have shown promising high outputs. For instance, Wang et al. [40] integrated conductive MXene nanosheets into a moisture-generator design, achieving a volumetric power density of 3.47 mW·cm^{-3}—about 2.2 times higher than previous records. This MXene-based MEG could be printed onto textile and powered wearable electronics. Likewise, bilayers combining bacterial cellulose and reduced graphene oxide produced ~ 1.1 V and 53 μA on a 1.0 cm^2 device [41]. These composite films can exploit synergistic hygroscopic/carbon interfaces but tend to be thicker and less breathable than nanofiber meshes. Polyelectrolyte film devices are another competing platform: for example, a precisely engineered bilayer of oppositely charged polymer films delivered ~ 0.95–1.38 V per unit (depending on humidity) and could be stacked into kilovolt-scale arrays [42]. However, such devices usually generate very low currents and require complex multilayer integration for the practical power output.

Finally, textile and biopolymer MEGs (e.g., cotton cloth, cellulose membranes, protein nanowires) offer natural fiber platforms. An “all-fabric” MEG made from breathable cloth was recently demonstrated, highlighting comfort for wearable use [34]. Cellulose-based MEGs (sometimes doped with salts or combined with graphene) can produce steady voltages around 1.0 V and show excellent stability in variable weather. Bacterial protein nanowires have even been used as a thin active layer, reaching ~ 0.5 V and 200 nA [43]. These biologically inspired materials are biodegradable and low-cost, but typically require sophisticated processing and provide only moderate output.

In summary, each platform has trade-offs. Hydrogels excel in ionic conduction; rigid carbon/ceramic devices can achieve high power under gradients; engineered polymer films yield large voltage; natural fibers are eco-friendly and robust. Electrospun nanofibers uniquely combine many advantages: they are lightweight and stretchable like fabrics, have hydration channels like gels, and when doped can approach voltages of engineered films. This combination of high output, continuous operation, and wearable form-factor sets electrospun nanofiber MEGs apart from other systems.

5. MATERIALS AND FUNCTIONALIZATION

The choice of polymer and its additives is critical for electrospun MEGs. A base polymer must be highly hygroscopic, mechanically robust, and electrospinnable. Common choices include:

• Polyvinyl alcohol (PVA): Rich in –OH groups, PVA is extremely hygroscopic and easily crosslinked to provide the stability. Electrospun PVA fibers are flexible, biocompatible and form uniform mats (diameters ~ 100–500 nm). They strongly adsorb moisture and release protons, boosting output.

• Cellulose acetate (CA): A biopolymer derived from cellulose, CA is biodegradable and naturally porous. Electrospun CA often forms hierarchical/tree-like fiber networks that channel moisture deeply. Partially regenerated cellulose (by the deacetylation) has even more –OH groups, further improving water uptake. Annealing CA mats to tune pore size has been shown to raise an open circuit voltage from 0.08 to 0.30 V, illustrating the impact of porous structure [44].

• Polyacrylonitrile (PAN): PAN yields very strong, smooth nanofibers and is thermally stable. It is often carbonized after the spinning to make conductive mats (as in water-evaporation devices). Pure PAN fibers provide a robust scaffold; after the carbonization they retain high porosity and can yield stable open circuit voltage (~ 0.5 V) and μA currents without structural loss [18].

• Polyvinylidene fluoride (PVDF): PVDF is hydrophobic and ferroelectric. In MEGs it is usually paired with hydrophilic layers (Janus design) or blended, contributing piezoelectric effects and directing evaporation. A PVDF layer can help to maintain a moisture gradient.

• Polyethylene oxide (PEO): PEO has mobile polymer chains and readily solvates ions. It can swell with water and enhance proton mobility, often used in blends (e.g., PVA/PEO) to improve ionic conductivity.

Combinations (e.g., PVA/PEO, PVA/CA) are also common to balance flexibility and hygroscopicity. In all cases the electrospinning process itself is compatible with the addition of various functional agents. Key functional additives include:

• Salts (e.g., tetrabutylammonium bromide, LiCl): These dissolve in the adsorbed water, providing extra mobile ions. For example, a PVA/LiCl fiber layer supplies abundant H^+/Cl^- under humidity. More ions amplify the streaming potential.

• Acids (e.g., phytic acid): Organic acids like phytic acid (a phosphorous-rich natural molecule) graft proton-donating groups ($–PO_3H$) onto the fiber. MEG, doping PVA fibers with phytic acid raised output (0.81 V, ~ 3.1 μA on 2 cm^2) by promoting proton hopping [11].

• Nanoparticles and nanocarbon materials, including carbon nanotubes, graphene oxide, silica, and metal oxides, are widely incorporated into electrospun nanofibers to enhance surface charge density, ion–water interactions, and moisture transport pathways. Xu et al. [45] demonstrated that oxidized carbon nanotubes integrated onto polyacrylonitrile (PAN) nanofibers via a synergistic electrospinning–electrospraying process provide abundant oxygen-containing functional groups that electrostatically interact with protons and metal ions, while the three-dimensional porous fiber network facilitates efficient water transport, leading to stable electricity generation in evaporation-induced devices. In a related study, Tabrizizadeh et al. [18] reported that carbonized electrospun PAN nanofiber mats used as porous scaffolds for water-evaporation-induced generators achieved an areal power density of approximately 83 $nW \cdot cm^{-2}$, nearly an order of magnitude higher than some previously reported porous materials.

• Polyelectrolytes and hydrogels: Incorporating ionic polymers (e.g. alginate, poly(acrylic acid), or supramolecular networks) can enhance water retention and provide internal ion reservoirs. Such networks can swell and gradually release ions under humidity, smoothing out the output over time.

By tuning these additives (typically 1.0–20 wt.% in solution), researchers can greatly increase conductivity and charge carrier density. Crucially, electrospinning is a "top-down" process that easily accommodates these dopants during the fiber formation.

Finally, structural design is used to sustain ion gradients and reduce back-diffusion:

• Janus bilayers: Two layers with opposite affinities (one hygroscopic, one moisture-repellent) drive ions unidirectionally. For example, in Janus nanofiber film, the PVA/LiCl side absorbed moisture and generated H^+, while a PVDF/PVB side drove evaporation. This architecture gave ~ 0.60 V and 44 μA/cm^2 continuously for > 30 days [17].

• Sandwich/multilayer stacks: The modulation of the moisture uptake and the protection of active fibers may be achieved by the addition of one or more intermediate or protective layers (e.g., a wettable polymer sandwiched between porous electrodes).

• Gradients: Fiber mats can be made with gradually varying composition or porosity (via sequential electrospinning or coaxial spinning). For instance, core–shell fibers with an inner charged core (fixed potential) and outer ion-rich shell have been shown to yield exceptional outputs (0.8 V, > 1 mA/cm^2) because of built-in electric fields and local ion concentration.

• Yarn or network shapes: Aligning fibers or twisting them into yarns can create continuous flow channels for water, enhancing streaming effects. Such macroscopic organization can also improve the mechanical strength and the handling.

Overall, careful material selection and functionalization allow electrospun MEGs to achieve balanced hygroscopicity, ion mobility, and durability. Advanced electrospun designs regularly reach open-circuit voltages in the 0.5–1.0 V range and currents from μA up to mA per cm^2 (under ambient RH). These devices can sustain operation for days to weeks. In practice, electrospun MEGs have powered small sensors and wearable electronics by harvesting only humidity.

6. APPLICATIONS

Moist-electric generators (MEGs) are being actively explored as sustainable power sources for wearable and portable devices. For example, Sun et al. [33] developed an electrospun nanofiber fabric MEG that successfully powered self-powered respiratory monitoring, wind-speed detection, and touch sensing. Likewise, Zhao and Tang [34] noted that MEGs "are a fascinating and promising candidate to supply renewable and clean power for next-generation portable electronics," highlighting recent demonstrations of breathable, all-fabric MEGs for smart clothing. In a recent advance, Chen et al. [17] fabricated an all-electrospun nanofiber "Janus" MEG that was integrated into self-powered circuits for the breath detection. These works illustrate how electrospun nanofiber MEGs can be woven into textiles or incorporated into conformal wearables, enabling self-powered wearable electronics.

Electrospun MEGs have also been used directly for the physiological monitoring. Sun et al. [33] used their breathable MEG to track the breathing patterns, and Chen et al. [17] achieved self-powered sensing of exhaled breath on a nanofiber device. In the related work, Wu et al. [46] engineered a bilayer nanofiber membrane MEG with enhanced stability; they emphasized that "electrospinning nanofiber membranes, favored for their large surface area, micro-nano channel networks, and facile fabrication, serve as ideal platforms for MEGs". In this study the MEG enabled "multifunctional integration for real-time moisture detection, respiratory health monitoring, activity tracking, and energy harvesting in self-powered wearable systems". Thus, electrospun MEGs have been tailored to sense subtle physiological humidity changes (e.g. respiration, sweat), opening the applications in health monitoring and human–machine interfaces [47].

Beyond wearables, electrospun MEGs are proposed for environmental sensing and distributed IoT power. Kwon et al. [48] review evaporation-driven nanofiber MEGs and note that such devices have potential uses in humidity sensors, portable monitoring, and even desalination. Because moisture is ubiquitous (indoor air, environment), MEGs can serve as self-powered environmental monitors. For instance, Sun et al. [33] demonstrated wind-speed sensing as one application of their MEG. Importantly, Yang et al. [35] showed that the integrated banks of MEGs can directly drive real electronics: a 9 cm^2 MEG unit produced enough current (~ 65 mA in parallel) to charge a smartwatch, light a bulb, and run a clock continuously, showcasing feasibility for Internet-of-Things (IoT) devices. They explicitly remark that high-power, scalable MEGs "chart the course towards … broad IoTs applications and wearable applications". Feng and Xia [49] similarly emphasized that MEGs "may become an energy source that can be utilized in daily life", suggesting broad deployment (from smart homes to sensors in remote locations).

Electrospun MEGs have been increasingly explored for integration into biomedical systems for specific sensing and stimulation tasks. Wu et al. [46] highlighted that biocompatible nanofibrous MEGs are well suited for applications such as real-time moisture detection and respiratory health monitoring in wearable health patches, owing to their flexibility, breathability, and sensitivity to humidity variations. In a related demonstration, Gao et al. [50] reported a paper-based moist-electric generator that exploits moisture gradients within a nanoporous cellulose substrate to produce sustained electrical output under ambient conditions. The flexible, lightweight, and disposable nature of this paper-like MEG suggests its potential use in wearable medical sensing platforms and other body-worn or skin-conformal electronic systems. Proposed applications also extend to building-integrated sensors and smart textiles; for example, Zhao and Tang [34] pointed out that MEGs embedded in fabrics could enable smart clothing capable of harvesting electricity from human breath and perspiration to support on-body power supply.

In summary, recent experimental studies illustrate the versatility of electrospun nanofiber MEGs. Demonstrated applications include self-powered respiratory monitors, humidity and airflow sensors, wearable touch detectors, and even self-powered transistors. Theoretical proposals extend to powering distributed IoT networks and environmental monitors (e.g. soil moisture or greenhouse sensors), as well as the integration into medical devices. These advances are enabled by the unique properties of electrospun nanofibers – high porosity, large surface area, and tunable chemistry – which facilitate moisture–ion interactions for sustained power. As noted by Yang et al. [35], scaling up MEG systems to practical IoT and wearable systems is a key goal, and first demonstrations (charging watches, running electronics) show this path is viable. Overall, electrospun nanofiber MEGs are emerging as flexible, lightweight harvesters for low-power electronics across wearables, healthcare, environmental sensing, and IoT applications [33,35,46,49].

7. CHALLENGES AND OUTLOOK

Electrospun nanofiber MEGs have shown remarkable proof-of-concept performance, but several fundamental

limitations remain difficult to solve. In particular, these devices tend to produce very low power and current densities. For example, Yang et al. [35] explicitly noted that "majority of MEGs suffer from very low current density and ungratified power density". In practice, most reported electrospun MEGs generate only microampere-level currents per square centimeter, and power densities of order 10^{-4}–10^{-1} mW·cm^{-2}—far below what is needed for practical electronics. Even when open-circuit voltages are high, sustaining a continuous high short-circuit current is difficult. Chen et al. [17] observed that although many MEGs achieve steady voltages, "it has been proven to be a challenge to maintain a continuous relatively high short-circuit current". This intrinsic low output constrains applications to only ultra-low power sensors or requires very large-area devices.

Another inherent challenge is the strong dependence on ambient humidity. MEGs harvest energy from moisture gradients, so their output typically rises sharply with humidity. In one study, output current increased monotonically as RH rose from 10% to 80% [35]. Below about 20% RH, currents become very small (often below 0.1 mA·cm^{-2}) and the devices essentially stop working. Many designs therefore only function well in high–humidity conditions (e.g., above 60–70% RH) and produce negligible power in arid or fluctuating environments. Performance also tends to plateau or even decrease if RH becomes too high (> 90%), as the driving ionic gradients vanish. Thus, MEGs generally require a moist environment to operate, which limits their reliability outdoors or in dry climates.

Long-term stability and durability pose additional difficulties. In the lab, MEGs are usually tested over minutes to days, but real-world deployment would demand years of operation under cycling humidity, temperature changes, and mechanical wear. For hydrogel-based MEGs (common in nanofiber systems), drying out or freezing causes loss of performance. Repeated moisture cycles can degrade the polymer matrix or leach ions. Even dry, electrospun fiber mats have limited mechanical robustness: Kwon et al. [48] found that a thin PAN nanofiber mat was durable under a static load, but "its ability to retain shape may not be guaranteed when… fully covered with moisture". In practice, wet fibers can swell, deform, or crack unless supported on rigid substrates. Metal electrodes in contact with water can undergo corrosion, which significantly influences the performance and stability of moist-electric generators. Pi et al. [51] investigated hydrogel-based MEGs with porous carbon and metallic electrodes and found that corrosion reactions occurring at the metal–electrolyte interface play a critical role in enhancing the instantaneous voltage and current output, while also introducing instability over prolonged operation. Their corrosion tests showed that electrochemical degradation of the electrodes can contribute to electrical signals but ultimately undermines long-term durability. Therefore, ensuring stable output over months or years —resistant to drying, temperature swings, and electrode degradation—remains an open challenge in MEG design.

Finally, scalability and integration are major practical barriers. Most reported MEGs are laboratory-scale (cm^2); scaling to meter-scale sheets or clothing is nontrivial. Electrospinning itself is inherently slow (typically ~ 0.01–1.0 g of fiber per hour) [52], so mass production requires advanced multi-jet or roll-to-roll systems, which are only now emerging. Even if large-area fiber mats are fabricated, maintaining uniform porosity, moisture uptake, and electrode contact over a big area is challenging. Device integration also meets the difficulties: early MEGs used sandwich structures with the separate electrodes, but these are bulky. Efforts toward fully printed or planar configurations encounter mechanical-mismatch issues: differences in stiffness and thermal expansion between electrodes and wet fibers can cause cracking or delamination. As Li et al. [53] pointed out, the translating single MEG units into a compact array or system will require new architectures (for example origami-folded or packed layouts) to minimize the internal resistance and maintain the robust interconnections. In summary, at the present the manufacturing and integration technology for large-scale, reliable electrospun MEGs is immature, which hinders their practical deployment.

Despite these hurdles, a number of forward-looking strategies are under active exploration. A major focus is on new materials and chemical designs. Researchers are developing novel polymers, composites and dopants to enhance ion transport and water affinity. For instance, doping PVA fibers with strong acids or salts can dramatically boost proton conductivity. Zhang et al. [36] reviewed polymer engineering strategies in hydrogel-based moisture-electric generators, including the incorporation of proton-donating acids such as phytic acid, hygroscopic salts (e.g., LiCl), or sulfonic-acid monomers into polymer networks to enhance ionic conductivity and water uptake. These dopants significantly improve electrical output by increasing the supply of mobile ions, and in some supramolecular hydrogel systems—such as PVA blended with sodium alginate—current densities approaching or exceeding the milliampere per square centimeter (1.0 mA·cm^{-2}) level have been reported under optimized humidity conditions. In electrospun membranes, controlling microstructure is key: Lyu et al. [15] showed that optimizing pore size and porosity in cellulose acetate nanofibers led to higher moist-electric output. Likewise, introducing inorganic fillers or nanochannels (e.g., carbonized polymer dots, liquid-metal networks, or 3D scaffolds) has been proposed to improve scalability and enable higher voltages. Overall, material innovation—from ionic liquids and nanofillers to flexible

electrode inks—aims to raise the intrinsic energy conversion of MEG materials.

Complementing materials research, there is growing interest in computational design and machine learning. As Li et al. [53] note, AI techniques could greatly accelerate MEG development: machine-learning models might analyze published data to identify the most effective material combinations or fiber geometries. In principle, one could train models on existing MEG outputs versus humidity/temperature and use them to predict which polymer blends or nanostructures maximize ion gradients. Reinforcement learning could even incorporate weather forecasts, determining optimal operating schedules or the best times for device regeneration to maximize energy harvested. Though still nascent, these data-driven approaches offer a path to optimize MEGs without exhaustive trial-and-error.

Another direction is hybrid energy systems. By pairing MEGs with other harvesters, one can mitigate the weaknesses of each technology. For example, a recent device integrated a moist-electric generator with a triboelectric nanogenerator: a porous PTFE layer allowed simultaneous harvesting of water-droplet triboelectricity and moisture-driven ionic currents. Under periodic water impacts this hybrid generator produced both AC and DC outputs ~ 0.55 V and 120 μA from the MEG component plus higher voltage AC from the water-based triboelectric generator (TEG) [54]. Such MEG–TEG hybrids can deliver more stable power, using the moisture channel for DC steady output and the TEG for bursts from raindrops or fluid motion. In principle, MEGs could also be combined with solar or thermoelectric elements: for example, moisture–photovoltaic hybrids (using humidity-responsive materials under sunlight) have been demonstrated on a building scale [55]. Although these concepts are at an early stage, they illustrate how multi-source harvesters could extend running time and improve total energy yield under variable conditions.

Finally, commercialization potential and barriers should be considered. MEGs have attractive features (they harvest ubiquitous, "free" energy and can operate in darkness), suggesting potential in remote sensors, wearable electronics, or IoT nodes. Some prototype demonstrations are encouraging: for instance, a scaled array of supramolecular hydrogel MEGs recently powered a 2.5 W light bulb and continuously charged a smartwatch from ambient humidity [35]. Nonetheless, the gap to market remains large. Typical household devices require on the order of 10–100 W, whereas even the most advanced MEG units today yield milliwatts. As Li et al. [53] emphasize, closing this gap will require robust power management systems, reliable long-term performance under realistic environments, and sustainable fabrication processes. Cost and material biocompatibility are also concerns if MEGs are to be widely deployed (for example, safe skin-contact materials for wearables). Thus, while the concept of moisture-powered electronics is compelling, practical adoption will depend on demonstrating consistent, large-area energy harvesting at competitive cost and integrating MEGs seamlessly into end-user devices.

In summary, electrospun nanofiber MEGs face intertwined challenges of low output, environmental sensitivity, and scaling, but current literature data also point to promising research directions. Advances in functional materials (ionic polymers, nanocomposites), data-driven design, and hybrid device architectures are steadily improving performance [36]. With sustained effort, the community aims to bridge the remaining gaps between laboratory prototypes and real-world applications. For example, Li et al. [53] predicted that integrating MEGs with flexible electronics and sustainable design practices will be key to "market-demand-oriented development". Ultimately, a balanced approach that continues to address fundamental limitations while exploring new design paradigms will be essential to realizing the potential of MEGs as green power sources.

8. CONCLUSION

In conclusion, electrospun nanofiber-based moisture-electric generators (MEGs) have emerged as a highly promising class of energy-harvesting devices that convert ubiquitous atmospheric moisture into usable electricity through sustainable, green mechanisms. This review systematically examined the key aspects of these systems, including advanced fabrication techniques via electrospinning, strategic material optimization (such as functionalization with CNTs, MXene, reduced graphene oxide, and bacterial cellulose), underlying working mechanisms (primarily ion gradient-driven diffusion, streaming potentials, and hygroscopic effects), performance metrics (including output voltage, power density, and responsiveness), and diverse applications in wearable electronics, self-powered sensors, and textile-integrated power sources.

Significant progress has been achieved in recent years, with devices demonstrating enhanced power output (reaching hundreds of microwatts per square centimeter in some cases), improved mechanical flexibility, breathability, and environmental stability. These advancements have positioned electrospun nanofiber-based MEGs as ideal candidates for powering next-generation portable and IoT devices without the reliance on traditional batteries.

Nevertheless, several critical challenges remain to be addressed for scalable and practical implementation. These include limited long-term stability under fluctuating humidity conditions, relatively modest power densities for high-demand applications, complexities in large-scale manufacturing, and the need for better integration with existing textile and electronic systems while maintaining cost-effectiveness and environmental benignity.

Looking ahead, future research should prioritize the development of hybrid multifunctional materials, intelligent device architectures (e.g., multilayer or asymmetric designs), and scalable roll-to-roll electrospinning processes. Additionally, in-depth mechanistic studies using advanced characterization techniques, combined with real-world field testing and standardization efforts, will be essential to bridge the gap between laboratory prototypes and commercial viability. With continued innovation, electrospun nanofiber-based MEGs hold tremendous potential to contribute meaningfully to sustainable energy solutions, enabling a new era of autonomous, moisture-powered wearable technologies.

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Генераторы электричества из атмосферной влаги на основе электроформованных волокон

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Аннотация. Генераторы электрической энергии из атмосферной влаги представляют собой перспективный и экологический подход к прямому преобразованию энергии окружающей среды за счёт гигроскопических взаимодействий и процессов ионного транспорта. Среди различных архитектур особый интерес вызывают устройства на основе нановолокон, полученных методом электроформования, благодаря их высокой удельной поверхности, высокой воздухопроницаемости, механической гибкости и возможности интеграции в переносные электронные устройства. В настоящем обзоре систематизированы современные достижения в области генераторов электричества из влаги на основе электроформованных нановолокон. Рассмотрены методы их получения с использованием электроспиннинга, подходы к оптимизации материалов с введением функциональных добавок, таких как углеродные нанотрубки, MXene, восстановленный оксид графена и бактериальная целлюлоза, а также основные физические механизмы генерации электрического отклика, включая диффузию ионов в градиенте концентрации, возникновение стримингового потенциала и ионизацию поверхностных функциональных групп. Проанализированы ключевые эксплуатационные характеристики устройств, такие как выходное напряжение, плотность мощности и долговременная стабильность, а также их применение в автономных переносимых устройствах, сенсорных системах и текстильной электронике. Показано, что использование гибридных архитектур позволяет существенно повысить выходную мощность и долговечность устройств. Вместе с тем остаются нерешёнными проблемы, связанные с обеспечением долгосрочной надёжности, масштабируемости технологических процессов и повышением эффективности преобразования энергии, что в настоящее время ограничивает широкое практическое внедрение данных систем. Перспективными направлениями дальнейших исследований являются разработка многофункциональных материалов, асимметричных архитектур устройств и масштабируемых технологий производства, направленных на создание практических автономных источников питания для технологий следующего поколения.

Ключевые слова: нановолокна, полученные методом электроформования; генераторы электричества из атмосферной влаги; функциональные наноматериалы; автономные сенсоры; источники питания для носимой электроники