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Green electrospinning of sustainable nanofibers: a sustainable frontier for next-generation materials

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K E Y W O R D S

Renewable Materials

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Eco-Friendly

Recycling

Electrospinning

A B S T R A C T

To fulfil the demand for eco-friendly nanomaterials, electrospinning offers a viable method for creating sustainable nanofibers. This mini review focuses on environmentally friendly and sustainability aspect of nanofibers produced via electrospinning. It examines difficulties and possibilities in ecologically friendly electrospinning, such as selecting environmentally friendly materials, reusing solvents, and using environmentally friendly additives. The use of biodegradable synthetic polymers, hybrid/composite nanofibers for improved performance, and natural polymers from renewable resources are only a few of the green electrospinning approaches that are covered. The review emphasises on green practices and sustainable challenges and opportunities. This review gives insight into green electrospinning techniques and the applications are also highlighted in tissue engineering, environmental remediation, energy storage, and environmentally friendly packaging. Further, the scalability, interdisciplinary cooperation, and regulatory issues are only a few of the obstacles and future directions that are discussed. A greener and more sustainable future in materials science is possible thanks to green electrospinning.

1. Introduction

1.1 The Demand for Renewable Nanofibers in Next-Generation Materials

In order to develop next-generation materials, renewable nanofibers have been investigated due to the growing demand for sustainable alternatives. These nanofibers have a number of beneficial properties, such as improved biodegradability, a smaller environmental effect, and the potential for resource regeneration [1-3]. Renewable nanofibers play a crucial role in meeting the urgent demand for eco-friendly solutions since they have applications in a variety of industries, including tissue engineering [4], environmental remediation [5], energy storage [6], and sustainable packaging [7]. We can create the foundation for a more sustainable future by incorporating renewable nanofibers into next-generation materials.

1.2 Electrospinning: An Innovative Approach to Nanofiber Production

By making it possible to produce ultrafine fibres at the nanoscale, electrospinning has completely changed the way that nanofibers are made. With the help of an electric field applied to polymer solutions or melts, special nanofibers with a high surface area-to-volume ratio, customizable shape, and exceptional mechanical strength are produced [8]. Electrospinning is used in a variety of industries, including tissue engineering [4], filtration [9], sensors [10], and energy storage [6], because to its adaptability, scalability, and capacity to include a wide range of materials. Electrospinning has a lot of potential as a cutting-edge method for producing nanofibers in a variety of industries [11].

1.3 Embracing Sustainability in Electrospinning: The Green Paradigm

The green paradigm stresses environmentally friendly electrospinning procedures as a response to the environmental impact of conventional nanofiber production techniques [12]. This calls for the use of environmentally friendly products, replenishable resources, and eco-friendly processes all throughout the process [13]. Important factors to take into account include the use of renewable and biodegradable polymers, solvent recycling, and the incorporation of eco-friendly additives [14,15]. We may decrease waste creation, lower energy use, and create nanofibers that adhere to environmental stewardship standards by implementing sustainable electrospinning procedures [16]. An ethical and sustainable method of producing nanofibers is electrospinning, which embraces the green paradigm.

2. Sustainable Electrospinning: Challenges and Opportunities

2.1 Sustainable Materials for Electrospinning

To achieve ecologically friendly electrospinning operations, it is essential to choose sustainable materials. Natural polymers made from renewable resources, like chitosan, silk fibroin, and cellulose, have a lot of potential as environmentally friendly substitutes [17]. In addition, biodegradable synthetic polymers like polyhydroxyalkanoates (PHAs) [18], Poly caprolactone (PCL) [19] and polylactic acid (PLA) [20] contribute to environmentally friendly electrospinning. These substances have beneficial qualities, such as biocompatibility and biodegradability, which make them appropriate for a variety of uses [21,22]. To achieve greener and more sustainable nanofiber production, it is essential to investigate and use sustainable materials for electrospinning. Fig. 1 depicts a basic set-up of electrospinning.

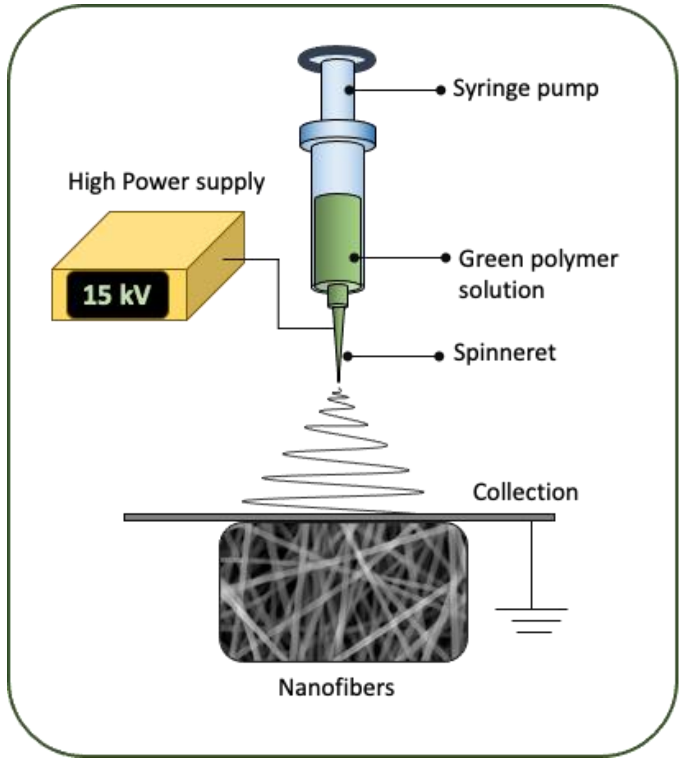

Fig. 1. Basic set-up of Electrospinning

2.2 Solvent Selection and Recycling Strategies

The choice of solvent is essential to the long-term viability of electrospinning processes. The harm to the environment and human health can be reduced by choosing environmentally friendly solvents like water, ethanol, or non-toxic organic solvents. Implementing recycling solutions for solvents can also greatly lower waste production and advance sustainability [23,24]. Solvents can be recovered and reused using methods including distillation, evaporation, and membrane filtration, which minimises the impact on the environment and lowers expenses. Electrospinning procedures can be made more ecologically friendly by concentrating on sustainable solvent selection and recycling [25]. Green solvent electrospinning has become a potentially effective method for making sustainable nanofibers. Water-based electrospinning has several benefits for the environment, including minimal toxicity and simple solvent recovery [26, 27]. Deep eutectic solvents [28] and ionic liquids [29] offer distinctive characteristics and improved processability, making them useful options. These environmentally friendly solvents make it possible to electrospin a variety of materials, including both manufactured and natural polymers.

2.3 Eco-Friendly Additives and Surface Modifications

Incorporating eco-friendly additives and surface modifications in electrospinning processes contributes to sustainability and enhances the properties of nanofibers [30]. Natural additives, such as plant extracts and bioactive compounds, can provide antimicrobial, antioxidant, or other desired functionalities. Surface modifications, including plasma treatment and chemical grafting, can improve biocompatibility, hydrophilicity, and adhesion properties [31]. These eco-friendly approaches minimize the use of harmful chemicals while imparting desirable properties to nanofibers. By exploring and implementing such sustainable additives and surface modifications, electrospun nanofibers can meet specific requirements while aligning with eco-conscious principles [32].

3. Green Electrospinning Techniques for Sustainable Nanofibers

3.1 Natural Polymers: Harnessing Renewable Resources

Natural polymers generated from renewable resources, such as cellulose, alginate, and chitosan, are used in green electrospinning processes [33, 34]. These polymers are excellent choices for a variety of applications since they naturally are biocompatible, biodegradable, and sustainable. These natural polymers can be electrospun to create nanofibers with a controlled shape and improved characteristics. Green electrospinning's use of natural polymers brings up new possibilities for environmentally friendly materials with more functionality [35].

3.2 Biodegradable Synthetic Polymers: Towards Eco-friendly Solutions

A viable strategy for producing sustainable nanofibers is to incorporate biodegradable synthetic polymers into green electrospinning. Commonly utilised biodegradable synthetic polymers include polycaprolactone (PCL) [19], polyhydroxyalkanoates (PHAs) [18], and polylactic acid (PLA) [20]. These polymers are ideal for a variety of applications because of their outstanding biocompatibility, processability, and biodegradability. Researchers can aid in the creation of environmentally friendly approaches to the manufacture of nanofibers by utilising the advantages of biodegradable synthetic polymers in green electrospinning [36].

3.3 Hybrid and Composite Nanofibers: Enhancing Performance and Sustainability

Green electrospinning provides a technique to improve the performance and sustainability of nanofibers through the incorporation of hybrid and composite architectures [37, 38]. Inorganic nanoparticles, natural polymers, biodegradable synthetic polymers [39, 40], and other components can all be combined to create custom nanofibers with the desired qualities. Improved mechanical strength, increased biocompatibility, and multifunctionality are all features of hybrid and composite nanofibers [41, 42]. The creation of such sustainable nanofibers opens doors for developments in filtration, energy storage, tissue engineering, and other areas, as well as improvements in performance.

4. Applications of Sustainable Nanofibers

Although, the applications canvas of nanofibers is big, however, this article covers sustainable nanofibers applications in a selective trending sectors. Fig. 2 shows selective applications of sustainable nanofibers.

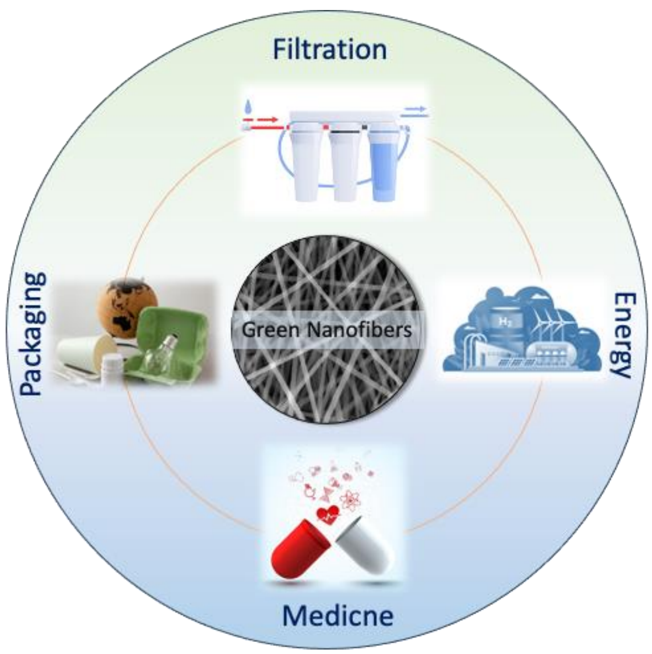

Fig. 2. Selective applications of sustainable nanofibers

4.1 Tissue Engineering and Regenerative Medicine

Sustainable nanofibers have important uses in regenerative medicine [43, 44] and tissue engineering [45,]. Nanofibrous scaffolds offer the best environment for cell adhesion, proliferation, and differentiation because they imitate the extracellular matrix. Sustainable nanofibers promote tissue regeneration in a variety of settings, including brain tissue engineering and skin, bone, cartilage, and other connective tissues [20, 46-48]. High surface area, customizable porosity, and regulated release of bioactive compounds are just a few benefits that these nanofibers have to offer in tissue engineering and other healthcare applications [49]. Researchers can create novel methods for rebuilding harmed or diseased tissues, encouraging healing, and bettering patient outcomes by utilizing sustainable nanofibers.

4.2 Environmental Remediation and Water Purification

Sustainable nanofibers are essential for applications like water purification and environmental remediation [50, 51]. In order to effectively remove contaminants including heavy metals, organic pollutants, and microbes, nanofiber-based filters and membranes have great adsorption capacity, large surface area, and precise pore size distribution [52-54]. In order to improve the adsorption and catalytic capabilities of sustainable nanofibers, certain surface coatings or nanoparticles can be added [55]. Researchers can help develop practical, environmentally friendly solutions for solving environmental issues and guaranteeing clean water resources by deploying sustainable nanofibers [56].

4.3 Energy Storage and Catalysis

Sustainable nanofibers have potential uses in catalysis and energy storage [57, 58]. Lithium-ion batteries, supercapacitors, and fuel cells [59, 60]. can all benefit from the increased surface area, quick ion transport, and improved electrochemical performance of nanofiber-based electrodes and membranes. Sustainable nanofibers can also be functionalized with catalytic nanoparticles or used as catalyst supports, enabling effective catalytic reactions in a variety of processes, including as hydrogen synthesis, pollutant degradation, and carbon dioxide conversion [61, 62]. Researchers can progress the creation of sustainable catalytic systems and energy storage technologies by utilizing sustainable nanofibers.

4.4 Sustainable Packaging to support circular economy

Sustainable packaging made of eco-friendly nanofibers is essential to achieving the circular economy [63-65]. These materials support the circular economy by reducing dependency on non-renewable resources. This ground-breaking packaging technology lowers the environmental impact while delivering great performance by utilizing biodegradable and renewable nanofibers [66]. By incorporating sustainable materials like natural polymers or biopolymers and creating packaging that is simple to recycle or compost, the principles of the circular economy are upheld [67, 68]. Sustainable packaging made of nanofibers helps move away from the linear "take-make-dispose" paradigm and toward a circular economy that recycles and regenerates materials. This strategy promotes waste reduction, resource efficiency, and a more sustainable future for the packaging sector.

5. Future Directions and Challenges

5.1 Scalability and Commercialization of Green Electrospinning

In order for green electrospinning techniques to be widely used, their scalability and commercialization are essential. Focus should be placed on streamlining equipment, increasing equipment capacity, and lowering manufacturing costs while retaining sustainability. Key things to think about the integration of automation, continuous processing, and effective raw material sourcing. The effective commercialization of green nanofibers also depends on creating strong quality control procedures, guaranteeing constant product performance, and answering market demands [69,70]. The recent trends in high production have been in practice such as Kármán vortex solution blow spinning [71], forcespinning™ [72], Needleless Electrospinning [73] and Needleless Electrospinning using annular spinneret [74].

5.2 Multidisciplinary Collaborations for Sustainable Materials Development

Collaborations across disciplines are essential for promoting the development of sustainable materials. Collaborations involving academics, engineers, material scientists, biologists, and business professionals develop creativity, promote knowledge exchange, and make it easier to tackle sustainability problems holistically. Researchers can create novel materials, improve their qualities, and investigate new applications by combining knowledge from several disciplines. Collaborations advance the application of scientific discoveries to real-world problems, encouraging the use of sustainable nanofibers across a range of industries [75-77].

5.3 Regulatory Considerations and Standards for Green Nanofiber Production

For the manufacture of green nanofibers to be both safe and high-quality while having minimal negative effects on the environment, regulatory considerations and criteria must be established. The procurement of materials, production procedures, waste management, and end-of-life considerations should all be covered by regulatory frameworks. For transparency and comparability, standardisation of characterisation techniques, performance assessment, and labelling is also necessary. Consumer confidence will increase, ethical production methods will be encouraged, and the development of sustainable nanofiber technologies will be supported by the creation of thorough norms and standards. The current regulatory practices are same as that for the any chemical or polymer manufacturing industry, their implication depend on type of final product is being produced or the type of application such as polymer therapeutic, cosmetic or food industry [78-81]. Developing acceptable recommendations and standards requires cooperation between researchers, industry stakeholders, and regulatory organisations.

6. Conclusion

In conclusion, the creation of environmentally friendly and renewable alternatives in a variety of applications is paving the way for a future that is greener. The use of biodegradable synthetic polymers, hybrid/composite nanofibers, and natural polymers by researchers shows their dedication to sustainability and careful material selection. Green electrospinning techniques offer a flexible platform for creating nanofibers with a morphology that may be altered and better characteristics.

But there are still issues with commercialization, scalability, and regulatory considerations. It is essential to construct effective supply chains, encourage cross-disciplinary cooperation, and build strong regulatory frameworks. Production process optimization is also important. These initiatives are crucial to ensuring the security, calibre, and environmental impact of sustainably producing nanofibers. Sustainable nanofibers have great potential for use in a variety of applications, such as energy storage, environmental remediation, and tissue engineering.

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