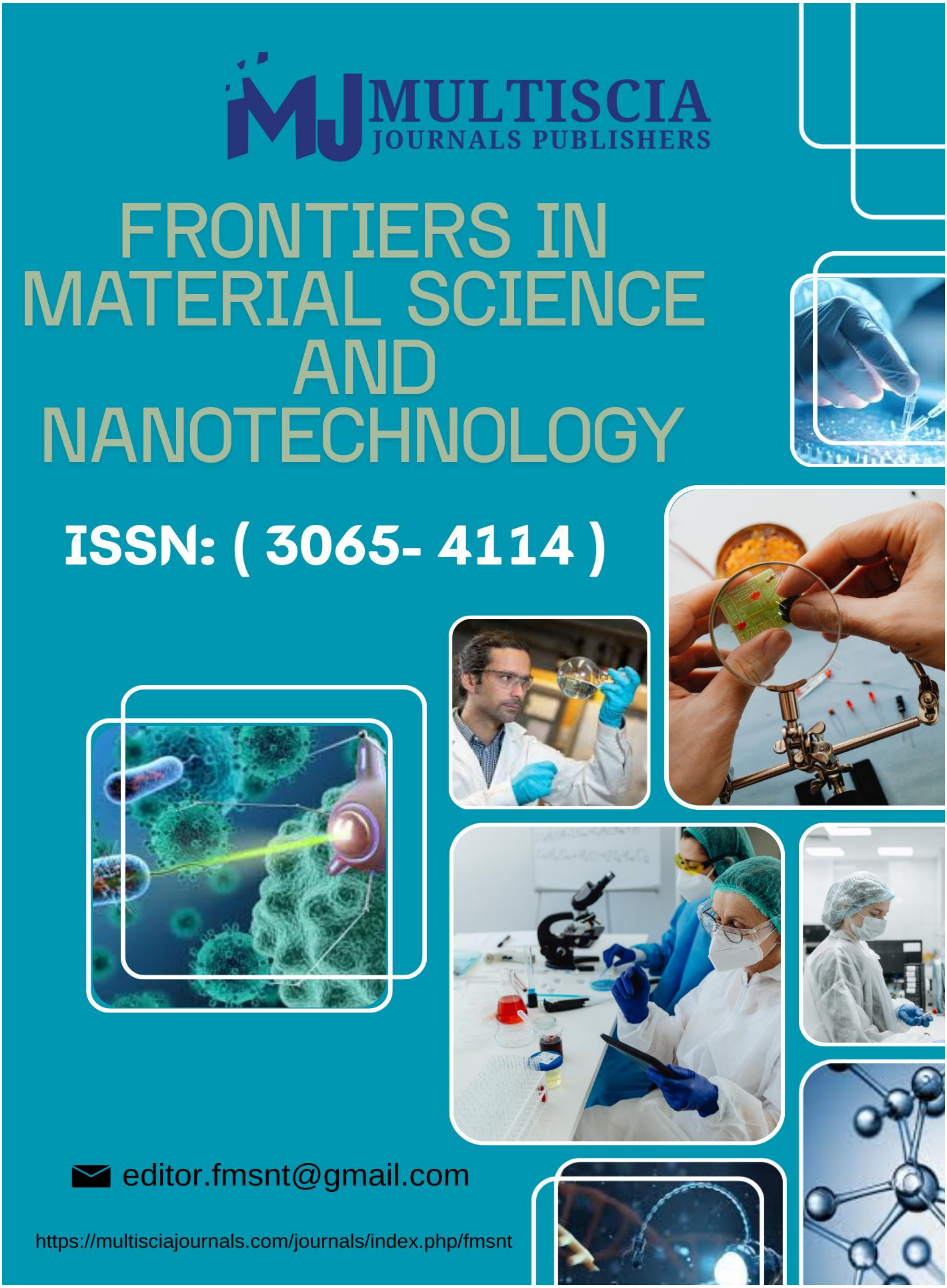

MULTISCIA
JOURNALS PUBLISHERS

FRONTIERS IN MATERIAL SCIENCE AND NANOTECHNOLOGY

ISSN: (3065- 4114)

editor.fmsnt@gmail.com

https://multisciajournals.com/journals/index.php/fmsnt

Frontiers in Material Science and Nanotechnology
Volume1, Issue4, 2025

Potentially Versatile 3D Network Assembly of Polymeric Nano-Fibers and Modified Nano-Fibers

T. Khayetghb*
Department of Material Science and Nanotechnology

Article Info

Received: 30-09-2025 ***Revised:08-12-2025*** ***Accepted:19-12-2025*** ***Published:29-12-2025***

Abstract

One field of study in materials science and nanotechnology is the development and use of materials based on polymeric nanofibers. There is a lot of interest in nano-fibrous materials due to their potential uses in various fields. These include biosensors, antibacterial materials, drug delivery carriers, bioreactors, electronic and semi-conductive materials, reinforced nano-composites, affinity membranes, and stimuli-responsive or "smart" materials. The reason behind this is their remarkable and essential properties, which allow for the creation of a diverse range of nano-fiber based materials, such as beaded, ribbon, porous, and core-shell nano-fibers. These include a very high surface area to volume ratio, a tunable void volume fraction and inter-fiber space, flexibility in surface functionalities, good mechanical performance, and malleability. The method most often thought of for making nano-fibers is electro-spinning, sometimes called electro-static spinning. The electrospinning of nanofibers has been accomplished with the use of a variety of materials, including biopolymers, polymer blends, melts, polymers impregnated with nanoparticles or drugs, and porcelain precursors. Numerous surface modification methods have been used for nano-fibers due to the significant significance that their surface chemical and physical characteristics play in a particular application. The surface of nano-fibers has been physically immobilized with a range of bioactive compounds, such as enzymes, polysaccharides, and anti-cancer medications.

Introduction

Nanoscale fiber materials differ from micro-scale materials in several key respects. Firstly, they have an extremely high surface area to volume ratio—up to 103 times larger for nano-fibers—and a tunable void volume fraction or "porosity." Secondly, they have an inter-fiber space or "pore size" that can range from ten nanometers to several micrometers. Lastly, they are able to construct a wide variety of fiber sizes and shapes, and they are malleable enough to form various tailored membranes. Finally, they have good mechanical performance and are very versatile in their mechanical properties [1]. Electrostatic spinning [1], liquid-liquid phase separation [4], self-assembly [5], vapor-phase polymerization [6], and template synthesis [2] are some of the physical, chemical, thermal, and electrostatic processes that have been used to produce polymer nano-fibers. The simplicity, adaptability, economics (i.e., cost-effectiveness), and scalability of this final method make it the go-to for manufacturing polymeric nano-fibers. Also, it's used to arrange different kinds of nano-fibers (core/sheath, porous, hollow, etc.) into hierarchical structures in a three-dimensional network or into clearly defined arrays. A variety of fiber morphologies, including ribbon, core-shell, porous, and beaded fibers, have been created [1]. Many different types of polymersThis method may be employed with copolymers to create fibers with a range of sizes, from a few micrometers to tens of nanometers, and whose architectures can be controlled by modifying the parameters of the electro-spinning process [7]. For over a hundred years, people have been aware of the electro-spray technique. The method of electro-spraying fluids was patented by Cooley [8] and Morton [9]. Formhals submitted a stack of US patents between WWI and WWII outlining the experimental electro-spinning setup for making polymer fibers by means of electrostatic force [10–13]. Ever then, over fifty patents pertaining to electro-spinning have been submitted.

Electro-spinning

A metallic needle linked to an electrically separated tube is used to deliver a high voltage during electro-spinning. The polymer liquid that has to be spun is passed through this tube at a consistent flow rate [1]. In the case of a metallic needle, for instance, a positive voltage causes the ions of a polymer solution with opposite charges to congregate on the surface of the droplet hanging from the needle's tip. The suspended drop of the polymer solution at the needle tip will deform into a conical shape due to the electric field created by the surface charge. shape. Electrostatic repulsion between surface charges and the Coulombic force from an external electric field between the needle and an electrically grounded collector (a plate, a spinning metal cylinder, or a conducting coagulation bath) are the two main kinds of electrostatic forces that the drop will encounter. At a certain voltage, the electrostatic forces work against the surface tension of the polymer liquid, causing a charged thin jet to erupt from the formed cone's surface and travel towards the collector. With the solvent evaporating and the electrified jet expanding, elongating, and whipping as it passes through the air gap between the needle and collector, a thin polymer fiber may be deposited on a non-woven mat or over a support [1]. Electrostatic forces, air friction, surface tension, polymer viscosity, and gravity are some of the interaction factors that often cause the electro-spinning jet to move erratically and exhibit instability. The production of constructed membranes with particular nanostructures and interconnected aligned nanofibers is possible.

Electro-spinning materials

During last 10 years, electro-spinning has regained attention probably due to the emerging interest in materials science and nanotechnology as well as to the different possible advanced applications of electro-spun nano-fibers [14].

A number of electro-spun polymeric nano-fibers have been fabricated for applications in the diverse fields such as affinity membrane [15], biosensor, optical and chemical sensors [16], stimuli-responsive or “smart” materials [17], bioreactors [18], drug delivery carriers, antibacterial materials, tissue engineering scaffolds, wound dressing [19], clean energy [20], electronic and semi-conductive materials [21], air filtration [22], reinforced nano-composites [23], and membrane distillation [24]. More details on electro-spun nano-fibers and their applications may be found in [14].

Nano-fibers made of synthetic and natural polymers, polymer blends as well as melts, nano-particle- or drug-impregnated polymers, and ceramic precursors have been successfully produced by electro-spinning. Typically, a wide range of polymers like those used in conventional spinning have been used in electro-spinning including polyurethanes, polyamides, polyester, polystyrene, polyvinylidene fluoride, poly (ether imide), styrene–butadiene–styrene triblock copolymer, poly (vinylidene fluoride-co-hexafluoropropylene), etc. Biopolymers like proteins, DNA, collagen, polypeptides or others like electric conducting and photonic polymers and silk fibroin have also been used. For biomedical applications, poly (a-hydroxy acids), especially lactic acids, glycolic acids and their copolymers with 3-caprolactone, are the most commonly used among all biodegradable polymers [25,26].

Modification of electro-spun nano-fibers and nano-fibrous materials

Functionalization is necessary for the effective use of most polymer nano-fibers since they do not naturally contain the necessary specific functional groups. To make nano-fiber based materials work for a certain purpose, scientists have used a variety of surface modification techniques. In most cases, the characteristics of the polymer that forms the nanofibers have a significant impact on the techniques employed to alter their surface. Because of their diminutive size, nano-fibers need regulated reactions and less severe reaction conditions to preserve their shape. When it comes to electro-spun nano-fiber based materials, surface modification is a potent tool for improving performance and increasing the appropriate functionality for certain applications. In most cases, the characteristics of the polymer that forms the nanofibers have a significant impact on the techniques employed to alter their surface. A wide range of physical and chemical methods have been employed to modify surfaces. These include blending, coating, plasma treatment, the wet mechanical method, surface graft polymerization, co-electro-spinning of surface active agents and polymers, molecule immobilization by physical absorption, layer-by-layer assembly, chemical immobilization, and assembly of nano-particles on nano-fiber surfaces.Several bioactive compounds, such as enzymes, polysaccharides, anti-cancer medications, and nanoparticles, have been either directly attached to the surface of nanofibers or trapped inside them. Immobilizing cell-specific bioactive ligands onto the electro-spun nano-fiber surfaces further improved cell adhesion and proliferation by chemically simulating the extracellular matrix's shape and biological function. Since new uses for polymeric materials have arisen, particularly in biotechnology, bioengineering, and, more lately, nanotechnology, surface modification of polymers has remained a hot subject of study, despite its age. The surface of the electro-spun nano-fiber needs to be physically and/or chemically modified before, during, or after the electro-spinning process to enhance its chemical composition, hydrophilicity, roughness, crystallinity, conductivity, lubricity, antibacterial activity, and other desirable properties for a specific application. Because physical surface modification techniques often include the insertion or removal of chemical groups or the activation of chemical reactions on a material's surface, they may alter the chemical composition of the functional groups at the nano-fiber's surface. For instance, when plasma is present, certain chemical reactions can occur, including chain scissions, surface oxidation, selective cross-linking, ion-beam sputtering, and the depletion of small molecular weight fragments. These reactions can also result in the formation of numerous hydroxyl and carbonyl groups.

CONCLUSION

To functionalize a polymer nano-fiber, the simplest and easiest technique is to blend the nano-fibers together. It is a physical method that involves electrospinning a polymer solution after adding ligand molecules to the solution. The polymer and the changed species do not form any kind of chemical connection or attachment. A straightforward approach to polymer nano-fiber modification, it entails combining two or more components [27–29]. Surface adhesion and wetting qualities may be fine-tuned by altering the surface chemical composition by plasma treatment of polymer materials [30,31]. It is crucial to choose a plasma source correctly so that nano-fiber based materials may have various functional groups added to them [32]. An simple and controlled way to introduce graft chains to the surface of nano-fibrous materials without affecting their bulk characteristics is surface graft copolymerization. By switching up the monomers used, this method may alter the nano-fiber surface and impart new characteristics [33]. The hydrophilicity of surfaces and the introduction of multi-functional groups onto nano-fiber surfaces for the covalent immobilization of bioactive molecules are both achieved by surface graft copolymerization. Some methods for starting the surface graft copolymerization process include treating the material with ultraviolet radiation, ozone, gamma rays, electron beams, plasma discharge, or direct chemical alteration [34]. A subfield of materials science and nanotechnology studies the bottom-up methods, such as self-assembly or the application of surface coatings via synthetic chemistry, to various surfaces in order to build very thin layers. A large variety of applications need surfaces with systematically tailored qualities that are largely defect-free, which is the major reason for this interest [35]. The exact control of surface coating thickness ranging from a few nanometers to several micrometers has been achieved by the layer-by-layer construction of polyelectrolyte multilayers [36]. This technique creates a self-assembling multilayer coating by using an electrostatic force to propel the deposition of polyanions and polycations on charged substrates in a layer-by-layer fashion. Various functional polyelectrolytes may be included into multifunctional coatings by the combination of electro-spinning and layer-by-layer electrostatic assembly. Chemical procedures are superior to other surface modification techniques for thick nano-fibrous based materials due to their flexibility [37]. The goal of these techniques is to improve the surface's chemical and physical characteristics by introducing new chemical species to the surface. To surface-graft nano-fibrous-based materials with oxygen-containing functional groups including carbonyl, hydroxyl, and carboxyl groups, wet chemical oxidation procedures are often used [38]. Wetability and adhesion are improved by the functional groups that include oxygen, which boost polarity and hydrogen bonding capabilities. Active surface agents, post-spinning modification, physical adsorption, nano-particle polymer composites, and chemical functionalization are some methods for immobilizing molecules on nano-fiber surfaces. Physical surface adsorption stands out as the most straightforward method among these alternatives. Surface adsorption may often be driven by electrostatic interaction, hydrogen bonding, hydrophobic interaction, or van der Waals contact. A wide variety of functionalized composite nano-fibers, including precursors made of metal alkoxide, were immediately spun from polymer solutions containing nano-particles. Materials with novel characteristics have been created by incorporating metal nano-particles into polymer matrices, where the nano-scale size and form of the disseminated nano-particles give them their distinctive characteristics.

Covalent immobilization of active molecules on a polymer surface improves cell adhesion and cell proliferation [33,39,40]. Unlike physically coated polymer chains, introduced chains are assured of long-term chemical stability.

Acknowledgement

The author gratefully acknowledge the financial support of the I+D+I Project MAT2010-19249 (Spanish Ministry of Science and Innovation).

References

1. Principles and Applications of Membrane Distillation, Khayet and Matsuura (2011). Publisher: Elsevier, therlands.
Nanofiber drawing and nanodevice assembly in poly (trimethylene terephthalate) was published in 2008 by Xing X, Wang Y, and Li B. This article appears in Opt Express, volume 16, pages 10815–10822.Biodegradable poly (epsiloncaprolactone) nanowire and nanofiber arrays aligned by template synthesis; Tao SL, Desai TA (2007). Nano Lett" 7: 1463–1468, 2019. 4. A fibrous extracellular matrix synthesized at the nanoscale by Ma PX and Zhang R (1999). Research in Biomedical Materials, 46, 60–72. The self-assembly and mineralization of peptide-amphiphile nanofibers was published in 2001 by Hartgerink JD, Beniash E, and Stupp SI. This article appears in Science 294: 1684-1688. 6. Rollings DA, Tsoi S, Sit JC, Veinot JG (2007). Surface initiated vapor-phase polymerization of organotrichlorosilanes: a method for preparing polysiloxane nanofibers and their wettability in water. Science 23: 5275–5278. Controlled deposition of electrospun poly (ethylene oxide) fibers was described by Deitzel JM, Kleinmeyer J, Hirvonen JK, and Beck Tan NC in 2001. Citation: Polymer 42: 8163–8170. 8. Device for electrically distributing fluids (Cooley JF, 1902). U.S. patent 692631... The method of distributing fluids was described by Morton WJ in 1902. American patent 705691. The method and tools for making synthetic threads was published by Formhals in 1934. The USPTO. 11. Formhals A. (1939) A spinning method and equipment. New United States patent 2160962. Formhals A. (1940) Man-made thread and its manufacture. The US patent number 2187306. Thirteen. Formhals A. (1943) Making synthetic fibers from liquids that naturally produce them. U.S. patent 2323025 granted. The design of electrospinning and nanofiber assemblies was reviewed by Teo WE and Ramakrishna S in 2006. The citation is from Nanotechnology, volume 17, pages R89–R106.