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Multifunctional Nanofibers Incorporating ZnO NPs, *Tridax procumbens*, and *Azadirachta indica* for Wound Healing: A Review

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ABSTRACT

Polymeric nanofibrous membranes have emerged as a transformative material in wound care, providing enhanced biocompatibility along with faster healing. However, pristine polymeric nanofibers (NFs) and single-drug-impregnated NFs are insufficient to address the needs of chronic wounds. Thus, multi-component NFs are being extensively investigated for improved wound care. This review introduces one such feasible hybridization of materials, namely ZnO nanoparticles, *Tridax procumbens*, and *Azadirachta indica,* towards the realization of a nanofibrous wound-healing membrane. The review begins with details on the bioactivity exhibited by these materials in their pristine form and then describes the benefits obtained by their integration into the NF matrix. Next, the various electrospinning variants that enable the realization of different forms of NFs from multiple constituents, the effects of process parameters, and drug incorporation methods are detailed. Further, the characterization techniques and assays to be conducted for understanding the physicochemical characteristics and bioactivity of the fabricated wound-healing membrane are described, along with the steps required for clinical translation. Finally, a possible extension of the work towards the realization of a smart wound-healing system is presented. Notable NF property enhancements achieved with multi-component NFs include a 2.9 ± 0.5 MPa increase in tensile strength, a two-stage drug release profile, and a 2- to 8-fold decrease in the viscosity of the spinnable solution, resulting in thinner NFs. Given its depth of content, this review could act as a valuable resource for promoting the research and development of facile wound dressings.

Keywords: *Azadirachta indica*; Electrospinning; Multifunctional nanofibers; Nanofibrous membranes; Polymeric nanofibers; *Tridax procumbens*; Wound dressings; Wound healing; Zinc oxide nanoparticles.

1. INTRODUCTION

Electrospun nanofibers (NFs) have an ultrafine, porous, lightweight fibrous structure, a large surface-area-to-volume ratio, and high permeability. These features enable their reliable use in biomedical applications such as biosensors, wound care, tissue regeneration, and drug delivery systems (Ghajarieh *et al.* 2021). NFs are produced using various electrospinning methods tailored to specific applications. The concept of electrospinning dates back to 1600, when William Gilbert described the electrostatic attraction of a liquid (Hiwrale *et al.* 2023). However, the first true electrospun nanofiber was created in 1934, when Anton Formhals developed an experimental process for producing nanoscale fibers from cellulose acetate using electrostatic forces. In this process, a spinnable polymer solution is ejected from a rotating wheel into an electric field, which draws the solution into a thin thread. A movable electrode plate collects these threads. In the initial experiments, Formhals used a voltage of 57 kV and a polymer solution of acetone and monomethyl ether (Islam *et al.* 2019). Traditionally, nanofibers were spun from single materials, resulting in homogeneous fibrous membranes. While such structures are strong, they often fall short for biomedical needs. Natural polymers provide biocompatibility but lack sufficient mechanical strength and tissue regeneration capabilities. Synthetic polymers offer the necessary mechanical properties, and natural extracts (as drugs) add bioactivity, such as antimicrobial effects and tissue regeneration. Consequently, there has been a shift towards combining different polymers and natural extracts to create multi-material NFs (Xing *et al.* 2023). These multifunctional NFs can incorporate nanoparticles to impart conductivity that mimics the extracellular matrix (ECM), along with hybrid polymers for enhanced mechanical stability, as well as drugs and natural extracts to promote cell growth, thereby enabling multiple functions (Hanumantharao and Rao, 2019).

1.1 Advantages of Integrating Nanoparticles and Herbal Drugs in Polymeric Nanofibers

Multi-component NFs used as wound dressings have demonstrated better wound healing and contraction than single-material NFs. For instance, four wound

dressings fabricated using green-synthesized copper NPs, cellulose acetate, gelatin, marine chitosan, carbon dots, acetone, and isopropanol were tested for their wound healing efficacy. Results revealed that multi-component NFs could achieve faster wound contraction, epithelial tissue regrowth, and control of inflammation, resulting in wounds returning to normal in 34 days in the porcine model (Kota *et al.* 2025). The significant benefits of using multiple components include: (i) enhanced mechanical strength of the NF (Yadav *et al.* 2024), (ii) better exudate absorption, moisture retention (Zhou *et al.* 2025), (iii) increased bioavailability of the natural extract and drugs (Ajith *et al.* 2023), (iv) controlled drug release kinetics (Li *et al.* 2021), (v) improved biocompatibility, (vi) reduced inflammations (Ejiohuo *et al.* 2024) (vii) reduced scarring (Ejiohuo *et al.* 2024), and (viii) accelerated wound healing (Xie *et al.* 2013).

1.2 Significance of ZnO NP, *Tridax Procumbens*, *Azadirachta indica*

ZnO nanoparticles are given GRAS status (Generally recognized as safe) by the US Food and Drug Administration (FDA) (Kumar *et al.* 2023). ZnO NPs possess numerous pharmaceutical applications, including antimicrobial and anticancer activities, UV protection (as used in cosmetics), and wound-healing properties. However, ZnO exhibits size-dependent cytotoxicity. Specifically, ZnO NPs below 100 nm in size are prone to releasing more Zn^{2+} ions, which may increase oxidative stress and lead to cell death (Yin *et al*. 2015). Thus, ZnO NPs larger than 100 nm are considered biocompatible (Saadony *et al.* 2024). The inclusion of ZnO NPs in nanofibers was demonstrated to increase their mechanical strength (Rezaei *et al*. 2023; Nageh *et al.* 2022). *Tridax procumbens* L. is traditionally known and experimentally proven to accelerate wound closure (Verma *et al.* 2023). In addition, they possess antimicrobial, antioxidant, and wound-healing efficacies, which contribute to enhanced wound healing. *Azadirachta indica* (commonly known as neem) is known for its medicinal benefits and is predominantly used in traditional medicine to treat numerous ailments. Further, it is used for treating skin diseases, wounds, ulcers, diabetic wounds, cancer, intestinal worms, urinary disorders, tumors, cough, fever, and many more. Primarily, *A. indica* leaf pastes were used for absorbing exudate from wounds and are well-known to treat skin wounds (Maan *et al.* 2017). It promotes tissue regeneration by collagen production and fibroblast support (Ashiq *et al.* 2025). Traditionally, *A. indica* oil and its leaf pastes have been used as topical applications for wound healing (Sahni and Dubey, 2017). However, with recent nanotechnology integration, its extracts and oils have been incorporated into hydrogels, composites, polymers, and nanofibers to realize improved wound-dressing materials (Wylie and Merrell, 2022). In summary, ZnO NPs are safe nanoparticles to use with biomedical applications and could provide the required mechanical strength to the NF matrix. *T. procumbens* could accelerate wound contraction, and *A. indica* could provide the required medicine for promoting healing. These potentials inherent in ZnO, *T. procumbens*, and *A. indica* have motivated the investigation of their efficacy as a multi-component NF membrane for wound-healing applications. Thus, this review aims to explore literature findings that support the wound-healing efficacy of these three constituents, along with the feasible methods of integrating them into a multi-component NF. The component combination, as well as the idea of realizing them as an NF membrane for wound healing applications, is novel to the best of our knowledge.

With this brief introduction, the rest of this article is organized as follows: Section 2 details the wound-healing efficacy of ZnO NPs, their potential in NFs, and the challenges associated with integrating ZnO NPs into NFs. Section 3 describes the phytochemicals in *T. procumbens* and their potential when integrated with NFs, while phytochemicals and NF integration of *A. indica* are detailed in Section 4. Section 5 presents various types of NF fabrication techniques and the effects of process parameters on NF properties.

2. ZnO NANOPARTICLES AND THEIR WOUND HEALING POTENTIAL

2.1 ZnO NPs Antibacterial Mechanism

ZnO NPs inhibit bacterial growth in three different ways: (i) by directly interacting with and disrupting bacterial cells; (ii) by generating reactive oxygen species (ROS), which induce oxidative stress, disrupt cell membranes, and damage DNA, ultimately leading to bacterial death; and (iii) by releasing Zn^{2+} ions, which disrupt bacterial cell membranes (Qu *et al.* 2025). However, when integrating with polymeric, organic, and inorganic materials, the properties of the resulting material depend on the size and morphology of ZnO NPs included. For instance, pyramidal ZnO NPs increase the mechanical strength of the resulting NFs, while the star-shaped ZnO NPs decrease it. Similarly, smaller diameter ZnO NPs result in thick fibers, and larger particles result in finer NFs (Rezaei *et al.* 2023). However, major challenges associated with the use of ZnO in biomedical applications include: (i) concerns regarding its long-term toxicity, (ii) the scalability of green synthesis methods, and (iii) the need for optimized synthesis methods (Dey *et al.* 2025).

2.2 ZnO Integration into Polymer Matrices and Nanofiber Formation

Integrating ZnO NPs with different materials or introducing morphological changes enables tailoring their characteristics (Dejene, 2024). A summary of the different ZnO variants and their properties and bioactivities is presented in Table 1. It is found that

including ZnO NPs with PVA and electrospinning them resulted in NFs with improved wound-healing efficacy (Dey *et al.* 2025). Similarly, a polycaprolactone–chitosan solution containing curcumin and ZnO NPs (PCL–CS–Cur–ZnO), when electrospun, resulted in NFs with diameters ranging from 100 to 212 nm. These NFs demonstrated higher tensile strength and anti-bacterial activity than native PCL–CS, resulting from ZnO and curcumin, respectively (Mosallanezhad *et al.* 2022). In addition, core-sheath structures of polyacrylonitrile/hyper-branched polyester (PAN/HBPE) loaded with ZnO NPs are electrospun to NFs. This combination resulted in improving the air permeability of the NF membrane as well as improving its antibacterial activity and biocompatibility in comparison to native PAN/HBPE NFs (Sun *et al.* 2023). Further, ZnO NPs in cellulose acetate solution were electrospun to NFs, and it was found that ZnO NP incorporation reduced solution viscosity, which resulted in finer, thinner fibers with stable ZnO dispersion (Voorhis *et al.* 2024). Incorporation of ZnO NPs in PVDF matrix resulted in adsorption and antiviral mechanisms (Nageh *et al.* 2022). Further, ZnO NP-incorporated polyvinyl alcohol/sodium alginate (PVA/SA) nanofibers demonstrated excellent antibacterial and antifungal activities (Kenawy *et al.* 2025). Similarly, electrospinning polylactic acid–gelatin–ZnO NP-loaded solution resulted in NF membranes with excellent mechanical properties and drug release kinetics (Ali and Habeeb, 2025). In addition to electrospinning, ZnO NPs were surface-coated on polymeric NFs to improve their bioactivity (Kayaci *et al.* 2013). The literature reveals that the incorporation of ZnO NPs in NF membranes resulted in improving the mechanical strength as well as improving their wound healing efficacy. However, the size and shape of ZnO NPs could impact the properties of the NF membrane. Specifically, star-shaped ZnO NPs decreased the mechanical strength of NFs compared to rod-shaped NPs (Rezaei *et al.* 2023). Similarly, smaller ZnO NPs resulted in thick NFs compared to larger ZnO NPs (Voorhis *et al.* 2024), and core-shell NFs enabled good adsorption (Sun *et al.* 2023).

2.3 Challenges in Loading ZnO NPs to NFs

A potential challenge in the use of ZnO NPs includes its toxicity (NP size-dependent toxicity), potential introduction of oxidative stress and inflammation, and photodegradation (Gulab *et al.* 2024). Oxidative stress and inflammation can be reduced by using ZnO NPs of the proper size. Literature reveals that ZnO NPs below 100 nm diameter are prone to release more Zn^{2+} ions, which result in increased oxidative stress and inflammation, resulting in cell death (Rezaei *et al.* 2023). Further, photodegradation effects can be reduced by proper functionalization. Surface functionalization could improve the biocompatibility of ZnO NPs, the addition of stabilizing agents reduces particle agglomeration when spun, and doping with other materials reduces their photodegradation and improves their antimicrobial activity (Lebaka *et al.* 2025). In addition to the properties of ZnO NPs, concerns arise regarding the uniformity and efficacy of NF fabrication, which depend entirely on the nature of the solution being spun and the process parameters. Thus, this requires: (i) careful optimization of electrospinning process parameters, (ii) appropriate selection of the polymer matrix, and (iii) choosing a biocompatible ZnO NP morphology (Rezaei *et al.* 2023; Voorhis *et al.* 2024, and Maduna and Patnaik, 2024). These studies highlight that although the incorporation of ZnO into NF matrices can improve mechanical properties, selecting an appropriate ZnO NP morphology is critical to minimizing toxicity and therefore requires careful consideration.

Table 1. ZnO variants: properties and bioactivity

Reference	Material	Property	Biological Activity
Rezaei *et al.* 2023	Pyramidal rod ZnO (80-90 nm)	Increased mechanical strength of PVA/CS NFs	Better wound healing than star-like ZnO
Rezaei *et al.* 2023	Star-like ZnO (800-900 nm)	Decreased mechanical strength	Least wound healing
Rezaei *et al.* 2023	ZnO PVA/CS NFs	Enhances heat resistance	Improved wound healing compared to native ZnO
Mosallanezhad *et al.* 2022	PCL–CS–Cur–ZnO NFs	Improved tensile strength	Improved antibacterial activity
Sun *et al.* 2023	PAN/HBPE/ZnO NP NFs	Enhanced air permeability	Exhibited the required biocompatibility
Voorhis *et al.* 2024	CA-PEO/ZnO NP	Reduced solution viscosity, thin fibers, stable ZnO	-
Nageh *et al.* 2022	PVDF/ZnO NP	-	Exhibited adsorption and antiviral mechanism
Kenawy *et al.* 2025	SA/PVA/ZnO composite NFs	-	Improved antibacterial and antiviral actions
Ali and Habeeb, 2025	PLA/GA/ZnO with naproxen and meloxicam	Improved degree of crystallization and tensile strength.	Potential drug delivery mechanism

3. TRIDAX PROCUMBENS

3.1 Phytochemicals and Healing Mechanism

T. procumbens (TP) is a rich source of phytochemicals, which include alkaloids (N-containing organic compounds), flavonoids (polyphenols), and terpenoids. Flavonoids ensure antioxidant, hepatoprotective, anti-cancer, antibacterial, and wound

healing properties. Terpenoids are responsible for reducing cholesterol, boosting immunity, and providing antiparasitic, anti-inflammatory, anti-cancer, antifungal, antiviral, antimutagenic, antioxidant, and anti-HBV properties (Ingole *et al.* 2022).

Experimental studies revealed that ethanoic extracts from *T. procumbens* could inhibit *Escherichia coli, Proteus mirabilis, Staphylococcus aureus, and Bacillus subtilis* bacterial strains and could scavenge free radicals in the DPPH assay. These results support their antibacterial and antioxidant activity (Andriana *et al.* 2019). *T. procumbens* leaf pastes and extracts were demonstrated to expedite wound contraction and the epithelization period. Further, it was noted that hydroxyproline content, protein, and DNA concentration were higher in TP-treated animal groups, and there was minimal to no difference in healing diabetic and non-diabetic groups (Shrivastav *et al.* 2020). Another study reported that the wound-healing mechanism of TP primarily involves stimulating collagen synthesis and modulating inflammation during healing. Wound histopathology indicated fibroblast proliferation and neovascularization. These results reveal that TP works in the proliferation and remodelling stages of wound healing (Yaduvanshi *et al.* 2011). Fresh TP leaf juice is traditionally used to stop bleeding and bring about wound closure in cut wounds (Devi *et al.* 2014). These results favour the use of TP along with anti-inflammatory drugs for faster wound healing in post-surgical wounds. Cellulose films synthesized from carboxymethylcellulose (CMC) loaded with TP were demonstrated to enhance wound healing. Specifically, histopathology results revealed maximum fibroblast and collagen fibers in the TP-treated mouse model (Chinnappan *et al.* 2023). However, triterpenoid derivatives from TP have demonstrated potential cytotoxicity against cancer cell lines; no toxicity was registered for oral administration of TP extract (25, 50, 100 mg/kg for 28 days) in animal models. These results reveal the necessity of understanding the cytotoxicity of TP (Ingole *et al.* 2022). The phytochemical constituents and bioactivity of *T. procumbens* are presented in Fig. 1.

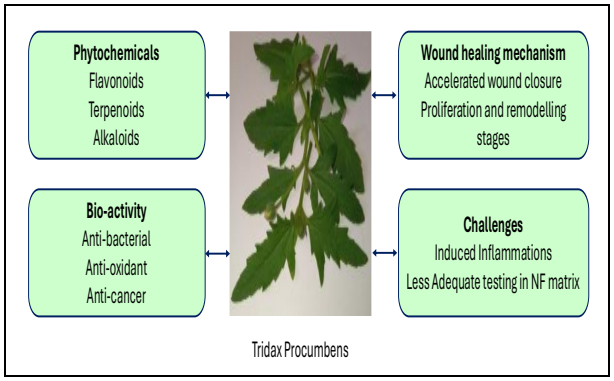


Fig. 1: Phytochemicals and bioactivity of *T. procumbens*

3.2 Integration into Nanofibers

Immobilization of TP extract on polycaprolactone (PCL) electrospun nanofibers exhibited good antibacterial efficacy. This enables their use for wound healing with good infection control (Suryamathi *et al.* 2019). Similarly, a bi-layered nanofibrous membrane was spun from polycaprolactone/polyvinyl alcohol–chitosan, and TP (800 µg/mL) was infused into it by spraying. This nanofibrous mat exhibited good bacterial inhibition against *E. coli* and *S. aureus*. Further, it demonstrated accelerated wound closure in the L929 cell line (Cheriyan *et al.* 2025). In another experiment, biodegradable polymer PVA is blended with methanolic TP extract in an 80:20 ratio, and the solution is electrospun to obtain a nanofibrous mat for wound healing. This PVA/TP blend was demonstrated to inhibit *E. coli* and *S. aureus* bacteria effectively (Ganesan and Pradeepa, 2017). A summary of various nanofibers fabricated with TP inclusion is presented in Table 2. Comparing these studies reveals that there is literature proof for the traditional use of TP juice to stop bleeding and bring about rapid wound closure (Devi *et al.* 2014). The use of TP-sprayed NF was demonstrated to accelerate wound closure in L929 fibroblast (Cheriyan *et al.* 2025). However, in most experiments, extracts from TP have demonstrated antioxidant and antibacterial activities. These studies highlight that, in spite of being used for fast wound closure, the potential of TP as a wound-healing drug still remains underexplored and holds numerous research opportunities.

Table 2. *T. procumbens* in a nanofiber matrix for wound healing

Reference	Nanofiber Composition	TP Inclusion Method	Biological Activity	Wound Healing Action
Suryamathi *et al.* 2019	PCL–TP	Immobilization	Improved antibacterial action	-
Cheriyan *et al.* 2025	PCL/PVA–CS/TP	Spraying and heating	Inhibition of *E. coli* and *S. aureus*	Accelerated wound closure in the L929 cell line
Ganesan and Pradeepa, 2017	PVA–TP blend	The blended solution is spun	Inhibition of *E. coli* and *S. aureus*	-

4. *Azadirachta indica*

Phytochemicals and wound healing: The primary bioactive compounds in *A. indica* are triterpene (Nimbin) and flavonoids. Nimbin exhibits anti-inflammatory, antioxidant, antipyretic, antihistamine, antifungal, and antiseptic properties (Islas *et al.* 2020). *A. indica* inhibits bacterial growth by disrupting the bacterial cell wall and causing bacterial cell death. Further, extracts from *A. indica* were found to: (i) supplement natural antioxidant agents, (ii) exhibit anticancer activity by modulating antitumour agents like

p53, VEGF, and bcl2, and (iii) promote wound healing by neovascularization (Alzohairy, 2016).

Specifically, neem possesses good antioxidant activity and could scavenge free radicals in the wound site, enabling enhanced proliferation of fibroblasts and keratinocytes. This directly improves collagen synthesis and re-epithelialization, which are important for wound healing (Nasrine *et al.* 2023 and Acharya, 2025). It clearly reveals that these extracts were supplementing the naturally existing system and thus, are offering safe bioactivity. However, increased concentrations of *A. indica* extract were found to bring in vomiting, hepatic toxicity, and metabolic acidosis (Alzohairy, 2016). Further, extracts from *A. indica* fruit were demonstrated to be a rich source of Vitamin E, and their hexane extracts exhibited no acute toxicity (Baby *et al.* 2022). Owing to its safe and potential antimicrobial activity, *A. indica* extracts were widely investigated for use with cosmetics and skin wound relief (Boukeloua *et al.* 2023). Further, Nimbin and deacetyl-nimbin were demonstrated to exhibit anti-inflammatory potential with antimicrobial action (Sudhakaran *et al.* 2022). The phytochemicals and bioactivity of *A. indica* are shown in Fig. 2.

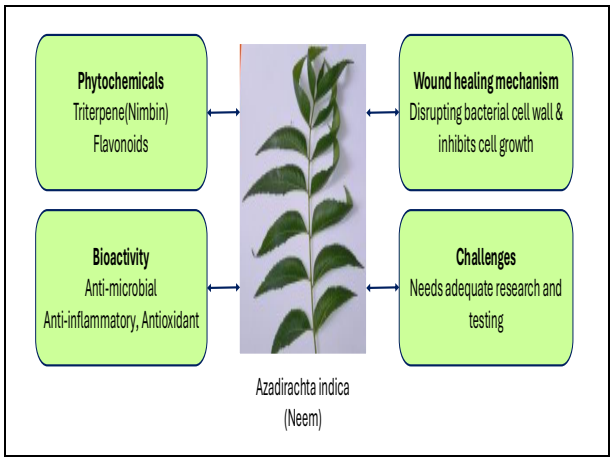


Fig. 2: Phytochemicals and bioactivity of *A. indica*

4.1 *A. indica* Integration into Nanofiber

Inherent to its potential antimicrobial action and minimal to nil toxicity, the incorporation of *A. indica* into electrospun NF has been adequately investigated. For instance, aqueous extract of *A. indica* was blended with chitosan, alginate, and polyethylene oxide polymer mixture, and the solution was electrospun to a nanofibrous mat (CS–A–PEO–*A. indica*). This blend was spun into nanofibers with a 120 nm diameter and was demonstrated to possess antifungal and antioxidant activity. In addition, the NF mat exhibited a biphasic drug release kinetics (Hameed *et al.* 2022). Similarly, *A. indica* gum polysaccharides (NGP) incorporated into polyvinyl alcohol crosslinked with glutaraldehyde vapors were spun into nanofibrous mats. These NF membranes were demonstrated to accelerate wound healing in a mouse model (Rajora and Bal, 2023). In addition, SiC–TiO_2–graphene and *A. indica* extract in a PVA matrix were electrospun to fabricate a nanofibrous mat. This SiC–TiO_2–graphene–*A. indica*–PVA inhibited bacterial growth with no cytotoxicity (Chowdhury *et al.* 2022). In another experiment, PVA–*A. indica*–chitosan blend is electrospun to form NFs with a maximum diameter of 298 nm and demonstrated to exhibit enhanced bacterial inhibition. The fibers spun had 18.78 N tensile strength and 4.98 mm elongation (Ali *et al.* 2019). Considering the glutaraldehyde cross-linked, PVA/CS/tannic acid-based nanofibrous membrane, they exhibited a tensile strength in the range of 3 – 18 MPa (He *et al.* 2024). Comparing the above two results reveals a reduction in tensile strength in the case of PVA–*A. indica*–chitosan nanofibers. This is because of the incorporation of natural extracts in the polymeric blend (Ajith *et al.* 2023). In another experiment, PVA, graphene, and *A. indica* extract were electrospun into nanofibers of diameter 276.9 nm. These NF mats could inhibit both Gram-positive and Gram-negative bacteria (Haque *et al.* 2023). Similarly, *A. indica* oil, polyesteramide (PEA), and polycaprolactone (PCL) were electrospun to an NF mat of a diameter ranging between 200 and 450 nm. These mats were immobilized with transfluthrin (Tf) and demonstrated to have sustained drug-release kinetics (Konchada *et al.* 2020). A summary of various wound-healing materials incorporating *A. indica* into polymer matrices is presented in Table 3. These studies highlight the antibacterial and anti-inflammatory efficacy of *A. indica* extracts and their reliable use for wound care applications in the form of NF mats. *A. indica* was considered a safe natural agent for healing wounds.

Table 3. *A. indica* integration with nanofibers

Reference	Nanofiber Composition	TP Inclusion	Biological Activity	Significant Characteristic
Hameed *et al.* 2022	CS–A–PEO–*A. indica*	*A. indica* blend	Antifungal, antioxidant activity	Biphasic drug release
Rajora *et al.* 2023	NGP–PVA–glutaraldehyde	Blend and spun	Accelerated wound healing resulted in dense collagen and fibroblast formation	Improved tensile strength and morphology of NF
Chowdhury *et al.* 2022	SiC–TiO_2–graphene, *A. indica* extract, and PVA	Blend and spun	Antibacterial activity	-
Ali *et al.* 2019	PVA–*A. indica*–CS	Blend and spun	Antibacterial activity	Tensile strength = 18.78 N, Elongation = 4.98 mm
Haque *et al.* 2023	PVA–Graphene–*A. indica*	Blend and spun	Antibacterial activity	Fiber diameter of 276.9 nm
Konchada *et al.* 2020	*A. indica* oil–PEA–PCL with transfluthrin	Blend and spun	Mosquito repellent	Fiber diameter 200 – 450 nm

5. FABRICATION OF NANOFIBERS

Nanofibers can be fabricated using several methods, including electrospinning, directed assembly, induced phase separation, template-assisted synthesis,

fiber drawing, and centrifugal spinning. Although self-assembly techniques allow the direct synthesis of multi-component NFs, they are less productive, highly complex, and costly. Phase separation methods offer defined-size NF fabrications with minimal equipment, but can be used only with specific polymers and cannot produce long fibers, whereas template synthesis offers a wide range of NF sizes, though template removal is difficult. Drawing methods could only produce NFs with a diameter of less than 100 nm, while centrifugal force spinning offers a low-cost, high-throughput production method but is limited by the difficulty in collecting NFs. However, electrospinning has the ability to produce NFs from the few nm to µm range, with high aspect ratio, mechanical strength, and economic benefits. But electrospinning is often affected by the instability of the jet and limitations in pore size. Among these methods, electrospinning is the most widely used top-down method of NF fabrication (Anusiya and Jaiganesh, 2022; Alghoraibi and Alomari, 2018).

5.1. Electrospinning and Its Variants

Electrospinning employs an electrostatic potential for stretching a viscous polymer solution into fibers of nanoscale dimensions. This method can be used with synthetic polymers, natural polymers, polymer blends, NP-loaded polymers, metals, and ceramics (Alghoraibi and Alomari, 2018). Electrospinning enables tailoring fiber structure and surface properties by tuning various process parameters. There are numerous variants in electrospinning, each capable of producing a specific pattern of NFs with unique process-dependent properties (Bhattarai *et al.* 2018; Reddy *et al.* 2021). A schematic representation of a basic electrospinning setup is given in Fig. 3.

5.1.1 Coaxial Electrospinning

Coaxial electrospinning enables the fabrication of hollow/core-shell type fibrous membranes as opposed to the single-nozzle traditional electrospinning method. Such a fabrication is facilitated by the use of coaxial nozzles, with a change in the spinneret structure. This method enables the realization of a core-shell type fiber, where including even non-spinnable precursors to the fiber is possible. This method enables the realization of more uniformly distributed NF architectures (Khan *et al.* 2024). This method is more reliable for the fabrication of composite nanofibers (Rathore and Schiffman, 2021).

5.1.2 Bubble Electrospinning (Gas Foaming)

Bubble electrospinning employs air or nitrogen to form bubble-induced (multiple) cones, as opposed to the single Taylor cone in traditional electrospinning. This facilitates increased fiber production with comparatively smaller fiber diameters. These methods are adequately used for fabricating composite scaffolds, which are beneficial in tissue engineering applications (Erben *et al.* 2020; Yang *et al.* 2009).

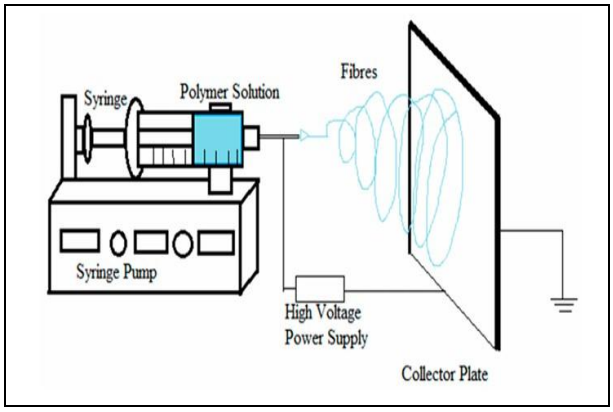


Fig. 3: Basic electrospinning setup (reproduced from Bhattarai *et al.* 2018)

5.1.3 Gas-assisted Electrospinning

Gas-assisted electrospinning employs high-velocity gas for accelerated fabrication of thin fibers. This method is normally used to force and elongate fibers from a single polymer cone, which enables faster fabrication with up to 20-fold fiber thinning (Xu *et al.* 2023; Zhmayev *et al.* 2010).

5.1.4 Multi-jet Electrospinning

This is a common umbrella term used to represent an electrospinning technique that is capable of producing nanofibers at a rapid rate by inducing multiple polymer jets at the same time. This fabrication approach is achieved by modifying the electrospinning system. These modifications include using multiple spinnerets with single jets, splitting a single jet into multiple jets (e.g., via gas foaming), and employing multiple spinnerets with multiple jets. These methods enable faster fabrication; however, careful handling is required to maximize their benefits (Zheng *et al.* 2020; SalehHudin *et al.* 2017).

5.2. Factors that Influence NF Properties

In addition to the type of electrospinning, process parameters play a major role in determining the nanofiber properties. These process-dependent factors are generally of two categories: (i) related to the electrospinning method and (ii) related to the solution properties. The various process-related parameters that influence NF properties are: (i) strength of applied voltage, (ii) flow rate, (iii) capillary collector distance, (iv) orifice diameter, and (v) gas temperature, velocity, and pressure, when gas-assisted electrospinning is considered (Refate *et al.* 2023). In addition, considering the solution, parameters such as solution concentration, viscosity, molecular weight, surface tension, conductivity, surface charge density, and solvent

volatility have an impact on the spun NF (Barata *et al.* 2025). These parameters should be carefully adjusted for spinning out a uniform and homogeneous NF membrane.

5.3. Drug Incorporation Methods

Drugs can be incorporated into nanofibers using several methods: (i) blending, which involves dissolving or dispersing the drug and other constituents in a polymeric solvent, followed by electrospinning, resulting in the drug being embedded within the nanofibers, (ii) drug-loaded nanocarriers, where nanocarriers are added to the polymeric solution and attach to the surface of the nanofibers, (iii) core–shell nanofibers, in which the drug-loaded polymer acts as the core and is spun with another polymer forming the shell, enabling controlled drug release, and (iv) post-treatment methods, in which drugs are incorporated onto spun nanofibers using techniques such as surface immobilization/adsorption, spraying, or coating (Torres *et al.* 2018 and Gaydhane *et al.* 2023). Electrospinning a drug-included polymeric blend enables the entrapping of drugs and nanoparticles in the pores of the nanofiber matrix. Post-treatment drug incorporation, that is, adsorption of the drug onto the NF matrix through dip-drying or solvent casting, enables the dispersion of nanoparticles or natural drug molecules within the nanofiber matrix through electrostatic interactions. Both these methods enable sustained drug release and enable bioavailability of natural drugs; however, they differ in the force binding the NPs to the NF surface. However, incorporation of drug/NPs in the core of coaxial NFs enables the encapsulation of drugs, facilitating controlled as well as sustained drug delivery. Encapsulated drugs get released based on some condition/stimuli, which imparts control to drug delivery (Shetty *et al.* 2022). Based on the requirements of a wound dressing and solvent compatibility, a specific method is chosen for adding drugs to the NF matrix.

6. SYNERGISTIC EFFECTS OF MATERIALS: MULTI-COMPONENT NANOFIBERS

Multi-component NFs are composed of two or more distinct materials, such as polymers, drugs, NPs, and metals, to harvest the synergistic benefits of their ingredients. Such a multi-component NF showcases multi-faceted properties, such as improved mechanical strength, wound-healing efficacy, antimicrobial functions, and sustained drug release. For instance, a bi-layered nanofibrous mat was spun out using polyvinyl alcohol/chitosan/collagen/licorice in order to harvest the synergistic effects of the biopolymers used in it. Such an experiment examined the functional bonds, morphological features, antibacterial activity, and moisture retention behavior of the NF membrane to verify its characteristics. FTIR revealed the presence of peaks corresponding to its constituents, and SEM images revealed NF diameter ranging between 188 and 219 nm. Moisture management studies showed that the nanofibers exhibited slow adsorption and drying capabilities, while disk diffusion assays confirmed their antibacterial activity against both Gram-positive and Gram-negative bacteria. These findings demonstrate the synergistic effects arising from the NF constituents (Shahid *et al.* 2022). Similarly, a blend of grass pea protein isolate, sumac extract, and polyvinyl alcohol was electrospun into a nanofibrous membrane, exhibiting strong antimicrobial action and antioxidant potential (Rezaei *et al.* 2024). There are numerous studies on fabricating drug-loaded nanofibrous mats in order to harvest the synergistic effect of drugs as well as the polymers in them (Sethuram and Thomas, 2023). Integrating multiple components in a nanofibrous matrix enables multi-faceted functions that facilitate their use as potential tissue and bone regeneration scaffolds. However, these scaffolds incorporate biodegradable materials, allowing safe removal once their intended functions are fulfilled (Serim *et al*. 2024). The integration of biopolymers, biologically active agents, and nanoparticles imparts synergistic properties to the fabricated nanofiber (Prabhakaran *et al.* 2011; Hanumantharao and Rao, 2019). These hybrid blends of specific materials have shown promising results in the development of scaffolds for bone, ocular, liver, neural, cartilage, ligament, tendon, skin, and vascular tissue regeneration (Owida *et al.* 2022). Advancements in electrospinning techniques remain the cornerstone for these developments (Rahmati *et al.* 2021). Although the examples cited in this section differ from the components of interest (ZnO NPs, *A. indica*, and *T. procumbens*), they demonstrate that multi-component nanofibers can exhibit synergistic properties derived from their constituents. Such nanofibers are in demand for tissue regeneration applications. Furthermore, these findings signify that the components selected for multi-component NF fabrication should align with the desired properties required from the nanofibers.

7. CHARACTERIZATION TECHNIQUES AND BIOACTIVITY TESTING

For the fabrication of a wound-healing nanofibrous mat, the next step is to evaluate the membrane. This involves (i) confirming the integration of its constituents, (ii) characterizing the membrane properties, and (iii) assessing its bioactivity. Various characterization techniques (Kaliva and Vamvakaki, 2020; Mourdikoudis *et al.* 2018) and bioactivity assays (Ahmad, 2022) were conducted for the validation of the efficacy of the wound-healing material. Table 4 lists the structural and mechanical characterization techniques and biological activity tests conducted for understanding and verifying the NF membrane's properties and wound healing efficacy. Specifically, SEM results help in understanding the membrane morphology (Akhtar and Zuhair, 2025), and XRD helps in finding the crystalline nature of the material (Akhavan and Mirbagheri, 2024; Riasvand *et al.* 2019). FTIR enables understanding the functional groups present in the sample (Wang *et al.* 2019

and Nandiyanto *et al.* 2023), while UV-Vis spectroscopy provides insight into electronic transitions and particle size (Arif *et al.* 2024 and Quevedo *et al.* 2021). All these techniques facilitate understanding the structural properties of the sample. While thermogravimetry analysis (TGA) helps in finding the thermal stability and degradation mechanism of the material (Thayyullathil *et al.* 2025 and Rami *et al.* 2021), tensile testing helps in finding the tensile strength of the material (Kaliva and Vamvakaki, 2020). The swelling test evaluates their moisture retention and stability (Lee *et al*. 2016). These three tests provide insight into the mechanical properties of the sample. However, the biological activity of the NF membrane could be verified by a series of bioactivity tests. They include testing for antimicrobial activity by disc diffusion test or agar-well diffusion test (Bayot and Bragg, 2025); antioxidant activity is often tested by DPPH assay (Shahidi and Zhong, 2015). Cell viability is tested by MTT assay (Gavanji *et al.* 2023), and wound healing potentials are tested *in vitro* by scratch tests (Bolla *et al*. 2019). Drug release rates are quantified by dissolution studies (Gómez *et al.* 2024). However, in practice, these *in vitro* tests are often complemented by *in vivo* animal tests (Ahmad, 2022).

8. TRANSLATIONAL POTENTIAL AND RESEARCH TRENDS

To facilitate the smooth transfer of technology, specifically, the clinical use of a wound-healing mat from the laboratory to the clinic, it is essential to ensure that all regulations are met and the material complies with relevant standards. Key considerations for proper technology transfer are outlined below.

8.1 Preclinical Studies for Effective Technology Transfer

Ensuring biocompatibility and safety are the primary requirements for effective technology transfer from lab to clinic. This can be ensured by adequate laboratory testing and conducting preclinical studies to understand the outcomes in clinical setups (Nguyen *et al.* 2023). Further, multi-component wound-healing materials could promote wound healing across multiple stages of the process; their functions are complex, and this necessitates adequate testing for their clinical translation (Liu *et al.* 2023). Recent studies have demonstrated the use of simulated wound fluids to test wound-healing materials, providing more reliable evidence to support clinical trials (Nygren *et al.* 2025). These examples underscore the importance of thorough testing and preclinical evaluation for effective technology transfer.

8.2 Industrial Scale-up and Commercialization

Electrospinning for large-scale production was initially demonstrated with multi-spinneret machines (Kolbasov *et al.* 2016). However, fiber diameter uniformity was difficult to achieve with these machines. Despite technological advancements and manufacturing processes that enable high throughput, producing stable, uniform-diameter NFs at low cost remains challenging. This is because of the technical difficulties, such as clogging of needles by polymer solutions and mutual interference of the electric fields applied. To overcome these difficulties, even needleless electrospinning techniques have emerged. For instance, a free-liquid-surface electrospinning was demonstrated to achieve a production capacity of 13.7 g/h with minimal fiber diameter variation (Xiong *et al.* 2021).

Table 4. Characterization techniques and tests

Reference	Equipment/Test	Properties Found
Akhtar and Zuhair, 2025	SEM	Morphology of the material, thickness, shape
Akhavan and Mirbagheri (2024); Riasvand *et al.* (2019)	XRD	Crystal structure, crystalline grain size, and composition of materials
Wang *et al.* (2019); Nandiyanto *et al.* (2023)	FTIR	Material Composition
Arif *et al.* (2024); Quevedo *et al.* (2021)	UV-Vis	Optical properties, particle size, agglomeration state
Thayyullathil *et al.* (2025); Rami *et al.* (2021)	TGA	Thermal stability of the material
Kaliva and Vamvakaki (2020)	Tensile testing	Mechanical strength and properties
Lee *et al.* 2016	Swelling and expansion tests	Wound exudate absorption capability and moisture retention
Bayot and Bragg, 2025	Disc diffusion and agar well diffusion methods	Antibacterial, antifungal activity
Shahidi and Zhong, 2015	DPPH assay	Antioxidant activity testing
Gavanji *et al.* 2023	MTT assay (*in vitro* cell culture)	Cell viability testing
Bolla *et al.* 2019	Scratch testing (*in vitro* cell culture)	Wound healing measurement
Gómez *et al.* 2024	*In vitro* dissolution study	Drug release quantification
Ahmad, 2022	*In vivo* testing in animal models	To study wound healing

8.3 Future Research Trends

Multifunctional wound dressing incorporating biopolymers, drugs, and nanoparticles aims to promote wound healing across multiple stages of wound healing in order to facilitate accelerated healing of chronic

wounds (Raju *et al*. 2022). Further, the use of smart stimuli-response materials and self-healing materials could promote wound dressings to sense and react to wound conditions. Further, such self-degradable materials could provide transient supporting functions and degrade after the wound heals (Dong and Guo, 2021). Such self-regenerating materials are the potential candidates for future wound-dressing materials and thus carry significance (Ghomi *et al.* 2019). However, integrating such wound dressing with biocompatible, flexible electronics could facilitate wound monitoring and precise, targeted drug delivery (Jiang *et al.* 2023). Thus, future wound dressings will offer a holistic approach, encompassing the promotion of wound healing, real-time monitoring of wound status, and closed-loop, feedback-based customization of drug delivery in wound care.

9. CONCLUSION

This review presented the biological activity exhibited by three materials, namely, ZnO NPs, *Tridax procumbens* extract, and *Azadirachta indica* extract, along with their nanofiber integrations. In addition, various nanofabrication methods and their advantages and limitations are discussed. This synthesis reveals that, the primary challenges in integrating nanoparticles and natural drugs into nanofibrous membranes include: (i) selecting biocompatible nanoparticles; in the case of ZnO NPs, particle size and shape greatly affect the safety and stability of the membrane; (ii) natural drugs often suffer from poor bioavailability; however, their incorporation into nanofibers can improve bioavailability; (iii) incorporation of natural drugs into polymeric blends may reduce the mechanical strength of nanofibers; and (iv) selecting appropriate fabrication processes, materials, and process parameters to achieve the desired functions and properties. These multi-component NFs should be thoroughly evaluated to validate their performance, including structural and mechanical characterization as well as bioactivity testing. Despite these benefits, large-scale manufacturing of NFs remains challenging due to technical issues such as polymer solution clogging in the spinneret and electric field interference, which lead to non-uniform fiber diameters. However, multi-component NFs are in high demand for use as wound-healing materials and tissue regeneration scaffolds. In the future, multi-component nanofibers could be integrated with flexible electronics to enable real-time monitoring capabilities.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Acharya, S. K., Neem Leaf Extract in Wound Healing: Mechanisms and Efficacy, *Int. J. Sci. Innov. Eng.*, 2(5), 822–830 (2025). https://doi.org/10.70849/IJSCI

Ahmad, N., In Vitro and In Vivo Characterization Methods for Evaluation of Modern Wound Dressings, *Pharma.*, 15(1), 42 (2022). https://doi.org/10.3390/pharmaceutics15010042

Ajith, G., Tamilarasi, G. P., Sabarees, G., Gouthaman, S., Manikandan, K., Velmurugan, V., Alagarsamy, V. and Solomon, V. R., Recent Developments in Electrospun Nanofibers as Delivery of Phytoconstituents for Wound Healing, *Drugs Drug Candidates,* 2(1), 148-171 (2023). https://doi.org/10.3390/ddc2010010

Akhavan, -M. S. and Mirbagheri, M. S., Perspective Chapter: Characterization Methods for Nanofibers, Nanotechnology and Nanomaterials, *IntechOpen*, (2024). https://doi.org/10.5772/intechopen.1006179

Akhtar, S. and Zuhair, F., Advancing Nanomedicine Through Electron Microscopy: Insights Into Nanoparticle Cellular Interactions and Biomedical Applications, *Int. J. Nanomed.*, 20, 2847-2878 (2025). https://doi.org/10.2147/IJN.S500978

Alghoraibi, I. and Alomari, S., Different Methods for Nanofiber Design and Fabrication, In: Barhoum, A., Bechelany, M., Makhlouf, A. (eds) *Handbook of Nanofibers. Springer, Cham*., 1-46 (2018). https://doi.org/10.1007/978-3-319-42789-8_11-2

Ali, A., Shahid, Md. A., Hossain, Md. D. and Islam, Md. N., Antibacterial bi-layered polyvinyl alcohol (PVA)-chitosan blend nanofibrous mat loaded with *Azadirachta indica* (neem) extract, *Int. J. Biol. Macromol.*, 138, 13-20 (2019). https://doi.org/10.1016/j.ijbiomac.2019.07.015

Ali, G. I. and Habeeb, S. A., Preparation and characterization of the PLA: GA: ZnO nanofibers-based drug delivery system, *Results Chem.*, 16, 102351 (2025). https://doi.org/10.1016/j.rechem.2025.102351

Alzohairy, M. A., Therapeutics Role of *Azadirachta indica* (Neem) and Their Active Constituents in Diseases Prevention and Treatment, *Evid Based Complement Altern. Med.*, 1(2016), 7382506 (2016). https://doi.org/10.1155/2016/7382506

Andriana, Y., Xuan, T. D., Quy, T. N., Minh, T. N., Van, T. M. and Viet, T. D., Antihyperuricemia, Antioxidant, and Antibacterial Activities of *Tridax procumbens* L, *Foods,* 8(1), 21 (2019). https://doi.org/10.3390/foods8010021

Anusiya, G. and Jaiganesh, R., A review on fabrication methods of nanofibers and a special focus on application of cellulose nanofibers, *Carbohydr. Polym. Technol. Appl.*, 4, 100262 (2022). https://doi.org/10.1016/j.carpta.2022.100262

Arif, M., Raza, H. and Akhter, T., UV-Vis spectroscopy in the characterization and applications of smart microgels and metal nanoparticle-decorated smart microgels: a critical review, *RSC Adv.*, 14, 38120-38134 (2024). https://doi.org/10.1039/D4RA07643E

Ashiq, A., Das, C. S., Biswas, S., Akter, R., Masum, Md. A. and Bedoura, S., Accelerating wound healing: Unveiling a synergistic neem-chitosan composite for rapid tissue regeneration, *Next Res.*, 2(3), 100541 (2025). https://doi.org/10.1016/j.nexres.2025.100541

Baby, A. R., Freire, T. B., Marques, G. d. A., Rijo, P., Lima, F. V., Carvalho, J. C. M. d., Rojas, J., Magalhães, W. V., Velasco, M. V. R and Morocho, -J. A. L., *Azadirachta indica* (Neem) as a Potential Natural Active for Dermocosmetic and Topical Products: A Narrative Review, *Cosmet.*, 9(3), 58 (2022). https://doi.org/10.3390/cosmetics9030058

Barata, T. R. A., Paul, R. and Belino, N. J., Effect of solution concentration, process parameters and a second electric field on electrospun polyamide-11 fibers, *J. Ind. Text.*, 55, (2025). https://doi.org/10.1177/15280837241299694

Bayot, M. L. and Bragg, B. N., Antimicrobial Susceptibility Testing, *In: StatPearls* [oldInternet]. Treasure Island (FL): *StatPearls Publishing*; 2025. https://www.ncbi.nlm.nih.gov/books/NBK539714/

Bhattarai, R. S., Bachu, R. D., Boddu, S. H. S. and Bhaduri, S., Biomedical Applications of Electrospun Nanofibers: Drug and Nanoparticle Delivery, *Pharm.*, 11(1), 5 (2018). https://doi.org/10.3390/pharmaceutics11010005

Bolla, S. R., Subaie, -A. A. M., Jindan, -A. R. Y., Balakrishna, J. P., Ravi, P. K., Veeraraghavan, V. P., Pillai, A. A., Gollapalli, S. S. R., Joseph, J. P. and Surapaneni, K. M., In vitro wound healing potency of methanolic leaf extract of Aristolochia saccata is possibly mediated by its stimulatory effect on collagen-1 expression, *Heliyon*, 5(5), e01648 (2019). https://doi.org/10.1016/j.heliyon.2019.e01648

Boukeloua, A., Kouadria, M., Bendif, H., Plavan, G., Alsalamah, S. A., Alghonaim, M. I., Boufahja, F. and Abd, -E. O. H., Physicochemical Analysis and Wound Healing Activity of *Azadirachta indica* (A. Juss) Fruits, *Processes,* 11(6), 1692 (2023). https://doi.org/10.3390/pr11061692

Cheriyan, S., Shin, H., Razack, S. A., Kang, M., Boopathi, T. S., Kang, H. W. and Mani, K., In-vitro and in-vivo studies of *Tridax procumbens* leaf extract incorporated bilayer polycaprolactone/polyvinyl alcohol-chitosan electrospun nanofiber for wound dressing application, *Int. J. Biol. Macromol.*, 299, 139920 (2025). https://doi.org/10.1016/j.ijbiomac.2025.139920

Chinnappan, B. A., Krishnaswamy, M., Bal, T. and Rajora, A. D., In vitro-in vivo wound healing efficacy of *Tridax Procumbens* extract loaded Carboxymethylcellulose film, *Int. J. Biol. Macromol.*, 253(Part 1), 126695 (2023). https://doi.org/10.1016/j.ijbiomac.2023.126695

Chowdhury, M. A., Hossain, N., Shahid, M. A., Alam, M. J., Hossain, S. M., Uddin, M. I. and Rana, M. M., Development of SiC–TiO_2-Graphene neem extracted antimicrobial nano membrane for enhancement of multiphysical properties and future prospect in dental implant applications, *Heliyon*, 8(9), e10603 (2022). https://doi.org/10.1016/j.heliyon.2022.e10603

Dejene, B. K., Exploring the Potential of ZnO Nanoparticle-treated Fibers in Advancing Natural Fiber Reinforced Composites: A Review, *J. Nat. Fibers*, 21(1), 2311304 (2024). https://doi.org/10.1080/15440478.2024.2311304

Devi, R. D., Sandhya, P., Subhashri, S., Hari, V. B. N., *Tridax Procumbens*: A Herbal Nano Formulation for Cancer Therapy, *Asian J. Chem.,* 26(12), 3719-3723 (2014). https://doi.org/10.14233/ajchem.2014.17061

Dey, S., Mohanty, D. L., Divya, N., Bakshi, V., Mohanty, A., Rath, D., Das, S., Mondal, A., Roy, S. and Sabui, R., A critical review on zinc oxide nanoparticles: Synthesis, properties and biomedical applications, *Intell. Pharmacy*, 3(1), 53-70 (2025). https://doi.org/10.1002/cbin.11769

Dong, R. and Guo, B., Smart wound dressings for wound healing, *Nano Today*, 41, 101290 (2021). https://doi.org/10.1016/j.nantod.2021.101290

Ejiohuo, O., Folami, S. O., Edi, D. and Isaac, J., Polyphenol encapsulated nanofibers in wound healing and drug delivery, *Eur. J. Med. Chem. Rep.*, 12, 100184 (2024). https://doi.org/10.1016/j.ejmcr.2024.100184

Erben, J., Kalous, T and Chvojka, J., AC Bubble Electrospinning Technology for Preparation of Nanofibrous Mats, *ACS Omega*, 5(14), 8268-8271 (2020). https://doi.org/10.1021/acsomega.0c00575

Ganesan, P. and Pradeepa, P., Development and characterization of nanofibrous mat from PVA/*Tridax Procumbens* (TP) leaves extracts, *Wound Med.*, 19, 15-22 (2017). https://doi.org/10.1016/j.wndm.2017.09.004

Gavanji, S., Bakhtari, A., Famurewa, A. C. and Othman, E. M., Cytotoxic Activity of Herbal Medicines as Assessed in Vitro: A Review, *Chem. Biodivers.*, 20(2), e202201098 (2023). https://doi.org/10.1002/cbdv.202201098

Gaydhane, M. K., Sharma, C. S. and Majumdar, S., Electrospun nanofibres in drug delivery: advances in controlled release strategies, *RSC Adv.,* 13, 7312-7328 (2023). https://doi.org/10.1039/D2RA06023J

Ghajarieh, A., Habibi, S. and Talebian, A., Biomedical Applications of Nanofibers, *Russ. J. Appl. Chem.*, 94 (7), 847–872 (2021). https://doi.org/10.1134/S1070427221070016

Ghomi, E. R., Khalili, S., Khorasani, S. N., Neisiany, E. R. and Ramakrishna, S., Wound dressings: Current advances and future directions, *J. Appl. Polym. Sci.*, 136, 47738 (2019). https://doi.org/10.1002/app.47738

Gómez, -L. L, Martín, -S. C., Aparicio, -B. J. and Torres, -S. A. I., Assessment of In Vitro Release Testing Methods for Colloidal Drug Carriers: The Lack of Standardized Protocols, *Pharm.*, 16(1), 103 (2024). https://doi.org/10.3390/pharmaceutics16010103

Gulab, H., Fatima, N., Tariq, U., Gohar, O., Irshad, M., Khan, M. Z., Saleem, M., Ghaffar, A., Hussain, M., Jan, A. K., Humayun, M., Motola, M. and Hanif, M. B., Advancements in zinc oxide nanomaterials: Synthesis, properties, and diverse applications, *Nano-Struct. Nano-Objects*, 39, 101271 (2024). https://doi.org/10.1016/j.nanoso.2024.101271

Hameed, A., Rehman, T. U., Rehan, Z. A., Noreen, R., Iqbal, S., Batool, S., Qayyum, M. A., Ahmed, T. and Farooq, T., Development of polymeric nanofibers blended with extract of neem (*Azadirachta indica*), for potential biomedical applications, *Front. Mater.*, 9, 1042304 (2022). https://doi.org/10.3389/fmats.2022.1042304

Hanumantharao, S. N. and Rao, S., Multi-Functional Electrospun Nanofibers from Polymer Blends for Scaffold Tissue Engineering, *Fibers*, 7(7), 66 (2019). https://doi.org/10.3390/fib7070066

Haque, S. R., Chowdhury, M. A., Rana, M. M. and Hossain, N., Fabrication of PVA/graphene nanofibrous membrane infused with neem extraction for packaging and biomedical applications, *SN Appl. Sci.,* 5, 177, (2023). https://doi.org/10.1007/s42452-023-05393-w

He, Y., Zhong, T., Liu, Y., Wan, M., Sun, L., Zhao, Y. and Wang, Z., Development of a multifunctional active food packaging membrane based on electrospun polyvinyl alcohol/chitosan for preservation of fruits, Int. J. Biol. Macromol., 277(Part 4), 134636 (2024). https://doi.org/10.1016/j.ijbiomac.2024.134636

Hiwrale, A., Bharati, S., Pingale, P. and Rajput, A., Nanofibers: A current era in drug delivery system, *Heliyon*, 9(9), e18917 (2023). https://doi.org/10.1016/j.heliyon.2023.e18917

Ingole, V. V., Mhaske, P. C. and Katade, S. R., Phytochemistry and pharmacological aspects of *Tridax procumbens* (L.): A systematic and comprehensive review, *Phytomed. Plus*, 2(1), 100199 (2022). https://doi.org/10.1016/j.phyplu.2021.100199

Islam, M. S., Ang, B. C., Andriyana, A. and Afifi, A. M., A review on fabrication of nanofibers via electrospinning and their applications, *SN Appl. Sci.,* 1, 1248 (2019). https://doi.org/10.1007/s42452-019-1288-4

Islas, J. F., Acosta, E., Buentello, G. Z., Delgado, -G. J. L., Moreno, -T. M. G., Escalante, B. and Moreno, -C. J. E., An overview of Neem (*Azadirachta indica*) and its potential impact on health, *J. Funct. Foods*, 74, 104171, (2020). https://doi.org/10.1016/j.jff.2020.104171

Jiang, Y., Trotsyuk, A. A., Niu, S. Henn, D., Chen, K., Shih, C. -C., Larson, M. R., Mermin, B. A. M., Mittal, S., Lai, -C. J., Saberi, A., Beard, E., Jing, S., Zhong, D., Steele, S. R., Sun, K., Jain, T., Zhao, E., Neimeth, C. R., Viana, W. G., Tang, J., Sivaraj, D., Padmanabhan, J., Rodrigues, M., Perrault, D. P., Chattopadhyay, A., Maan, Z. N., Leeolou, M. C., Bonham, A. C., Kwon, S. H., Kussie, H. C., Fischer, K. S., Gurusankar, G., Liang, K., Zhang, K., Nag, R., Snyder, M. P., Januszyk, M., Gurtner, G. C. and Bao, Z., Wireless, closed-loop, smart bandage with integrated sensors and stimulators for advanced wound care and accelerated healing, *Nat. Biotechnol., 41*, 652–662 (2023). https://doi.org/10.1038/s41587-022-01528-3

Kaliva, M. and Vamvakaki, M., Chapter 17 - Nanomaterials characterization, *Polym. Sci. Nanotechnol.,* 401-433 (2020). https://doi.org/10.1016/B978-0-12-816806-6.00017-0

Kayaci, F., Ozgit, -A. C., Biyikli, N. and Uyar, T., Surface-decorated ZnO nanoparticles and ZnO nanocoating on electrospun polymeric nanofibers by atomic layer deposition for flexible photocatalytic nanofibrous membranes, *RSC Adv.*, 3, 6817-6820 (2013). https://doi.org/10.1039/C3RA40359A

Kenawy, E. R., Kamoun, E. A., Shehata, A., Moslamy, -E. S. H. and Rahman, A. A. -H. A., Biosynthesized ZnO NPs loaded-electrospun PVA/sodium alginate/glycine nanofibers: synthesis, spinning optimization and antimicrobial activity evaluation, *Sci. Rep.*, 15, 1882 (2025). https://doi.org/10.1038/s41598-024-81939-1

Khan, J., Khan, A., Khan, M. Q. and Khan, H., Applications of co-axial electrospinning in the biomedical field, *Next Mater.*, 3, 100138 (2024). https://doi.org/10.1016/j.nxmate.2024.100138

Kolbasov, A., Sinha, -R. S., Joijode, A., Hassan, M. A., Brown, D., Maze, B., Pourdeyhimi, B. and Yarin, A. L., Industrial-Scale Solution Blowing of Soy Protein Nanofibers, *Ind. Eng. Chem. Res.*, 55(1), 323-333 (2016). https://doi.org/10.1021/acs.iecr.5b04277

Konchada, S., Killi, N., Sayyad, S., Gathalkar, G. B. and Gundloori, R. V. N., Blends of neem oil based polyesteramide as nanofiber mats to control Culicidae, *RSC Adv.*, 10, 42827-42837 (2020). https://doi.org/10.1039/D0RA08297J

Kota, S., Anantha, R., Sajja, R., Dumpala, P., Multicomponent nanofibrous electrospun dressings, evaluated for the healing of full-thickness excision wounds in a porcine model, *3 Biotech*, 15, 335 (2025). https://doi.org/10.1007/s13205-025-04460-w

Kumar, A., Verma, L. M., Sharma, S. and Singh, N., Zinc oxide nanoparticles (ZnO NPs) stabilized by phytocellulose derived biopolymer and their bipartite interaction studies with agriculturally important microbes/Raphanus sativus (L.) seeds, *Ceram. Int.*, 49(24), 39771-39787 (2023). https://doi.org/10.1016/j.ceramint.2023.07.179

Lebaka, V. R., Ravi, P., Reddy, M. C., Thummala, C. and Mandal, T. K., Zinc Oxide Nanoparticles in Modern Science and Technology: Multifunctional Roles in Healthcare, Environmental Remediation, and Industry, *Nanomater. (Basel)*, 15(10), 754 (2025). https://doi.org/10.3390/nano15100754

Lee, S. M., Park, I. K., Kim, Y. S., Kim, H. J., Moon, H., Mueller, S. and Jeong, Y. I., Physical, morphological, and wound healing properties of a polyurethane foam-film dressing, *Biomater Res*., 20, 15 (2016). https://doi.org/10.1186/s40824-016-0063-5

Li, Z., Mei, S., Dong, Y., She, F., Li, P., Li, Y. and Kong, L., Multi-Functional Core-Shell Nanofibers for Wound Healing, *Nanomater. (Basel)*, 11(6), 1546 (2021). https://doi.org/10.3390/nano11061546

Liu, W., Zu, L., Wang, S., Li, J., Fei, X., Geng, M., Zhu, C. and Shi, H., Tailored biomedical materials for wound healing, *Burns Trauma*, 11, tkad040 (2023). https://doi.org/10.1093/burnst/tkad040

Maan, P., Yadav, K. S. and Yadav, N. P., Wound Healing Activity of *Azadirachta indica* A. Juss Stem Bark in Mice, *Pharmacogn Mag.,* 13(Suppl 2), S316-S320 (2017). https://doi.org/10.4103/0973-1296.210163

Maduna, L. and Patnaik, A., Challenges Associated with the Production of Nanofibers, *Processes,* 12(10), 2100 (2024). https://doi.org/10.3390/pr12102100

Mosallanezhad, P., Nazockdast, H., Ahmadi, Z. and Rostami, A., Fabrication and characterization of polycaprolactone/chitosan nanofibers containing antibacterial agents of curcumin and ZnO nanoparticles for use as wound dressing, *Front Bioeng. Biotechnol*., 10, 1027351 (2022). https://doi.org/10.3389/fbioe.2022.1027351

Mourdikoudis, S., Pallares, R. M. and Thanh, N. T. K., Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties, *Nanoscale*, 10, 12871-12934 (2018). https://doi.org/10.1039/C8NR02278J

Nageh, H., Emam, M. H., Ali, F., Fattah, N. F. A., Taha, M., Amin, R., Kamoun, E. A., Loutfy, S. A. and Kasry, A., Zinc Oxide Nanoparticle-Loaded Electrospun Polyvinylidene Fluoride Nanofibers as a Potential Face Protector against Respiratory Viral Infections, *ACS Omega*, 7 (17), 14887-14896 (2022). https://doi.org/10.1021/acsomega.2c00458

Nandiyanto, A. B. D., Ragadhita, R. and Fiandini, M., Interpretation of Fourier Transform Infrared Spectra (FTIR): A Practical Approach in the Polymer/Plastic Thermal Decomposition, *Indones. J. Sci Technol.,* 8, 113-126 (2023). https://doi.org/10.17509/ijost.v8i1.53297

Nasrine, A., Narayana, S., Ahmed, M. G., Sultana, R., Noushida, N., Salian, R. T., Almuqbil, M., Almadani, M. E., Alshehri, A., Alghamdi, A., Alshehri, S. and Asdaq, S. M. B., Neem (*Azadirachta indica*) and silk fibroin associated hydrogel: Boon for wound healing treatment regimen, *Saudi Pharm J.*, 31(10), 101749 (2023). https://doi.org/10.1016/j.jsps.2023.101749

Nguyen, H. M, Ngoc, L. T. T., Nguyen, A. T., Thienm L. H. N. and Pham, T. T., Biomedical materials for wound dressing: recent advances and applications, *RSC Adv.*, 13(8), 5509-5528 (2023). https://doi.org/10.1039/D2RA07673J

Nygren, E., Malone, M. and Gefen, A., Laboratory Evaluations of Wound Dressings: Key Advances to Reflect Clinical Reality, *Int. Wound J.,* 22(Suppl 1), e70333 (2025). https://doi.org/10.1111/iwj.70333

Owida, H. A., Nabulsi, -A. J. I., Alnaimat, F., Ayyad, -A. M., Turab, N. M., Sharah, A. A. and Shakur, M., Recent Applications of Electrospun Nanofibrous Scaffold in Tissue Engineering, *Appl. Bionics Biomech.*, 2022(1), 1953861 (2022). https://doi.org/10.1155/2022/1953861

Prabhakaran, M. P., Ghasemi, -M. L. and Ramakrishna, S., Electrospun composite nanofibers for tissue regeneration, *J. Nanosci. Nanotechnol.*, 11(4), 3039-3057 (2011). https://doi.org/10.1166/jnn.2011.3753

Qu, B., Xiao, Z. and Luo, Y., Sustainable nanotechnology for food preservation: Synthesis, mechanisms, and applications of zinc oxide nanoparticles, *J. Agric. Food Res.*, 19, 101743 (2025). https://doi.org/10.1016/j.jafr.2025.101743

Quevedo, A. C., Guggenheim, E., Briffa, S. M., Adams, J., Lofts, S., Kwak, M., Lee, T.G., Johnston, C., Wagner, S., Holbrook, T.R., Hachenberger, Y.U., Tentschert, J., Davidson, N., Valsami-Jones, E., "UV-Vis Spectroscopic Characterization of Nanomaterials in Aqueous Media, *J. Vis. Exp.,* (176), e61764 (2021). https://doi.org/10.3791/61764

Rahmati, M., Mills, D. K., Urbanska, A. M., Saeb, M. R., Venugopal, J. R., Ramakrishna, S. and Mozafari, M., Electrospinning for tissue engineering applications, *Prog. Mater. Sci.*, 117, 100721 (2021). https://doi.org/10.1016/j.pmatsci.2020.100721.

Rajora, D. A. and Bal, T., Evaluating neem gum-polyvinyl alcohol (NGP-PVA) blend nanofiber mat as a novel platform for wound healing in murine model, *Int. J. Biol. Macromol.*, 226, 760-771 (2023). https://doi.org/10.1016/j.ijbiomac.2022.12.014

Raju, R. N., Silina, E., Stupin, V., Manturova, N., Chidambaram, S. B. and Achar, R. R., Multifunctional and Smart Wound Dressings-A Review on Recent Research Advancements in Skin Regenerative Medicine, *Pharm.,* 14(8), 1574 (2022). https://doi.org/10.3390/pharmaceutics14081574

Rami, J. M., Patel, C. D., Patel, C. M. and Patel, M. V., Thermogravimetric analysis (TGA) of some synthesized metal oxide nanoparticles, *Mater. Today: Proc.*, 43(Part 1), 655-659 (2021). https://doi.org/10.1016/j.matpr.2020.12.554

Rathore, P. and Schiffman, J. D., Beyond the Single-Nozzle: Coaxial Electrospinning Enables Innovative Nanofiber Chemistries, Geometries, and Applications, *ACS Appl. Mater. Interfaces,* 13(1), 48-66 (2021). https://doi.org/10.1021/acsami.0c17706

Reddy, V. S., Tian, Y., Zhang, C., Ye, Z., Roy, K., Chinnappan, A., Ramakrishna, S., Liu, W. and Ghosh, R., A Review on Electrospun Nanofibers Based Advanced Applications: From Health Care to Energy Devices, *Polym.,* 13(21), 3746 (2021). https://doi.org/10.3390/polym13213746

Refate, A., Mohamed, Y., Mohamed, M., Sobhy, M., Samhy, K., Khaled, O., Eidaroos, K., Batikh, H., El-Kashif, E., El-Khatib, S. and Mehanny, S., Influence of electrospinning parameters on biopolymers nanofibers, with emphasis on cellulose & chitosan, *Heliyon,* 9(6), e17051 (2023). https://doi.org/10.1016/j.heliyon.2023.e17051

Rezaei, A., Katoueizadeh, E. and Zebarjad, S. M., Investigating of the influence of zinc oxide nanoparticles morphology on the properties of electrospun polyvinyl alcohol/chitosan (PVA/CS) nanofibers, *J. Drug Delivery Sci. Technol.*, 86, 104712 (2023). https://doi.org/10.1016/j.jddst.2023.104712

Rezaei, M., Sedaghat, N., Hedayati, S. and Mohammad, -T. G., Fabrication and characterization of novel electrospun nanofibers based on grass pea (Lathyrus sativus L.) protein isolate loaded with sumac (Rhus coriaria L.) extract, *Curr. Res. Food Sci.*, 9, 100891 (2024). https://doi.org/10.1016/j.crfs.2024.100891

Riasvand, L., Chenari, M. H. and Khalili, S., Electrospun Mn:CeO_2/PVP Nanofiber Fabrication: Whole Powder Pattern Modeling of X-ray Diffraction Data, Morphology Study and Optical Properties, *J. Electron. Mater.*, 48, 7730–7737 (2019). https://doi.org/10.1007/s11664-019-07597-6

Saadony, -El. M. T., Fang, G., Yan, S., Alkafaas, S. S., Nasharty, M. A. El., Khedr, S. A., Hussien, A. M., Ghosh, S., Dladla, M., Elkafas, S. S., Ibrahim, E. H., Salem, H. M., Mosa, W. F. A., Ahmed, A. E., Mohammed, D. M., Korma, S. A., Tarabily, M. K. -El., Saad, A. M., Tarabily, -El. K. A. and AbuQamar, S. F., Green Synthesis of Zinc Oxide Nanoparticles: Preparation, Characterization, and Biomedical Applications - A Review, *Int. J. Nanomed.*, 19, 12889–12937, (2024). https://doi.org/10.2147/IJN.S487188

Sahni, R. N. and Dubey, V. S., Pharmaco-therapeutic study of neem (*Azadirachta indica* a. juss.) In the management wound healing, *Ayushdhara*, 4(2), (2017). https://ayushdhara.in/index.php/ayushdhara/article/view/265

SalehHudin, H. S., Mohamad, E. N., Mahadi, W. N. L. and Afifi, M. A., Multiple-jet electrospinning methods for nanofiber processing: A review, *Mater. Manuf. Processes*, 33(5), 479–498 (2017). https://doi.org/10.1080/10426914.2017.1388523

Serim, T. M., Amasya, G., Eren, -B. T., Şengel, -T. C. T. and Özdemir, A. N., Electrospun nanofibers: building blocks for the repair of bone tissue, *Beilstein J. Nanotechnol.* 15, 941–953 (2024). https://doi.org/10.3762/bjnano.15.77

Sethuram, L. and Thomas, J., Therapeutic applications of electrospun nanofibers impregnated with various biological macromolecules for effective wound healing strategy – A review, *Biomed. Pharmacother.*, 157, 113996 (2023). https://doi.org/10.1016/j.biopha.2022.113996

Shahid, Md. A., Hasan, Md. M., Alam, M. R., Mohebullah, M. and Chowdhury, M. A., Antibacterial multicomponent electrospun nanofibrous mat through the synergistic effect of biopolymers, *J. Appl. Biomater. Funct. Mater.,* 20, x-x (2022). https://doi.org/10.1177/22808000221136

Shahidi, F. and Zhong, Y., Measurement of antioxidant activity, *J. Funct. Foods*, 18(Part B), 757-781, (2015). https://doi.org/10.1016/j.jff.2015.01.047

Shetty, K., Bhandari, A. and Yadav, K. S., Nanoparticles incorporated in nanofibers using electrospinning: A novel nano-in-nano delivery system, *J. Controlled Release*, 350, 421-434 (2022). https://doi.org/10.1016/j.jconrel.2022.08.035

Shrivastav, A., Mishra, A. K., Abid, M., Ahmad, A., Fabuzinadah, M. and Khan, N. A., Extracts of *Tridax procumbens* linn leaves causes wound healing in diabetic and Non-diabetic laboratory animals, *Wound Med.*, 29, 100185 (2020). https://doi.org/10.1016/j.wndm.2020.100185

Sudhakaran, G., Prathap, P., Guru, A., Rajesh, R., Sathish, S., Madhavan, T., Arasu, M. V., Al-Dhabi, N. A., Choi, K. C., Gopinath, P. and Arockiaraj, J., Anti-inflammatory role demonstrated both in vitro and in vivo models using nonsteroidal tetranortriterpenoid, Nimbin (N1) and its analogs (N2 and N3) that alleviate the domestication of alternative medicine, *Cell Biol. Int.*, 46(5), 771-791 (2022). https://doi.org/10.1002/cbin.11769

Sun, M., Hou, T., Zhou, J., Zhou, L., Zhang, Z., Li, X. and Yang, B., Nanofibers with an Adjustable Core-Sheath Structure Constructed from Hyperbranched Polyester for Efficient Loading of ZnO Nanoparticles, *ACS Appl. Nano Mater.*, 6 (11), 9707-9717 (2023). https://doi.org/10.1021/acsanm.3c01386

Suryamathi, M., Ruba, C., Viswanathamurthi, P., Balasubramanian, V. and Perumal, P., *Tridax Procumbens* Extract Loaded Electrospun PCL Nanofibers: A Novel Wound Dressing Material, *Macromol. Res.,* 27, 55–60 (2019). https://doi.org/10.1007/s13233-019-7022-7

Thayyullathil, T., Francis, T., Stephy, A. and Padmanabhan, A., Thermal degradation kinetics studies of polyvinylidene fluoride/ZSM-5 hybrid nanofiber by thermogravimetric analysis, *Therm. Adv.*, 3, 100035 (2025). https://doi.org/10.1016/j.thradv.2025.100035

Torres, -M. E. J., Bravo, C. J. M., Medina, S. A., González, P. G. L., Gómez, V. L. J., A Summary of Electrospun Nanofibers as Drug Delivery System: Drugs Loaded and Biopolymers Used as Matrices, *Curr. Drug Deliv.,* 15(10), 1360-1374 (2018). https://doi.org/10.2174/1567201815666180723114326

Verma, A., Kumar, D., Nema, A., Sheikh, T., Shukla, M., Ranjan, R. and Jain, P., Studies on the efficacy of fresh *Tridax procumbens* leaves on wound healing in calves, *Pharma Innovation,* 12(6), 1303-1305 (2023). https://doi.org/10.13140/RG.2.2.12394.53441

Voorhis, C., González-Benito, J. and Kramar, A., Nano in Nano—Incorporation of ZnO Nanoparticles into Cellulose Acetate–Poly(Ethylene Oxide) Composite Nanofibers Using Solution Blow Spinning, *Polym.,* 16(3), 341 (2024). https://doi.org/10.3390/polym16030341

Wang, H., Li, S., Wu, T., Wang, X., Cheng, X. and Li, D., A Comparative Study on the Characterization of Nanofibers with Cellulose I, I/II, and II Polymorphs from Wood, *Polym. (Basel).*, 11(1), 153 (2019). https://doi.org/10.3390/polym11010153

Wylie, M. R. and Merrell, D. S., The Antimicrobial Potential of the Neem Tree *Azadirachta indica*, *Front. Pharmacol.*, 13, 891535 (2022). https://doi.org/10.3389/fphar.2022.891535

Xie, Z., Paras, C. B., Weng, H., Punnakitikashem, P., Su, L. C., Vu, K., Tang, L., Yang, J. and Nguyen, K. T., Dual growth factor releasing multi-functional nanofibers for wound healing, *Acta Biomaterialia*, 9(12), 9351-9 (2013). https://doi.org/10.1016/j.actbio.2013.07.030

Xing, J., Zhang, M., Liu, X., Wang, C., Xu, N. and Xing, D., Multi-material electrospinning: from methods to biomedical applications, *Mater. Today Bio*, 21, 100710 (2023). https://doi.org/10.1016/j.mtbio.2023.100710

Xiong, J., Liu, Y., Li, A., Wei, L., Wang, L., Qin, X. and Yu, J., Mass production of high-quality nanofibers via constructing pre-Taylor cones with high curvature on needleless electrospinning, *Mater. Des.*, 197, 109247 (2021). https://doi.org/10.1016/j.matdes.2020.109247

Xu, G., Chen, M., Gao, Y., Chen, Y., Luo, Z., Wang, H., Fan, J., Luo, J., Ou, W., Zeng, J., Zhu, Z. and Chen, R., Gas-assisted electrospinning of high-performance ceramic fibers: Optimal design modelling and experimental results of the gas channel of the nozzl, *Front. Mater.*, 10, 1113168 (2023). https://doi.org/10.3389/fmats.2023.1113168

Yadav, P. D., Londhe, P. V., Chavan, S. S., Mohite, D. D., Firame, G. B., Kadam, S. S., Patil, M. J. and Ansari, M. I., Electrospun composite nanofibers for wound healing: synthesis, characterization, and clinical potential of biopolymer-based materials, *Discover Mater.*, 4, 99 (2024). https://doi.org/10.1007/s43939-024-00173-8

Yaduvanshi, B., Mathur, R., Mathur, S. R. and Velpandian, T., Evaluation of wound healing potential of topical formulation of leaf juice of *tridax procumbens* L. In mice, *Ind. J. Pharm. Sci.*, 73(3), 303-6 (2011). https://doi.org/10.4103/0250-474X.93523

Yang, R., He, J., Xu, L. and Yu, J., Bubble-electrospinning for fabricating nanofibers, *Polym.*, 50(24), 5846-5850 (2009). https://doi.org/10.1016/j.polymer.2009.10.021

Yin, H., Casey, P. S., McCall, M. J. and Fenech, M., Size-dependent cytotoxicity and genotoxicity of ZnO particles to human lymphoblastoid (WIL2-NS) cells, *Environ. Mol. Mutagenesis*, 56(9), 767-776 (2015). https://doi.org/10.1002/em.21962

Zheng, G., Jiang, J., Wang, X., Li, W., Liu, J., Fu, G. and Lin, L., Nanofiber membranes by multi-jet electrospinning arranged as arc-array with sheath gas for electrodialysis applications, *Mater. Des.*, 189, 108504 (2020). https://doi.org/10.1016/j.matdes.2020.108504

Zhmayev, E., Cho, D. and Joo, Y. L., Nanofibers from gas-assisted polymer melt electrospinning, *Polym.*, 51(18), 4140-4144 (2010). https://doi.org/10.1016/j.polymer.2010.06.058

Zhou, R., Ma, Y., Yang, M., Cheng, Y., Ma, X., Li, B., Zhang, Y., Cui, X., Liu, M., Long, Y. and Li, C., Wound dressings using electrospun nanofibers: mechanisms, applications, and future directions, *Eur. Polym. J.*, 231, 113900 (2025). https://doi.org/10.1016/j.eurpolymj.2025.113900