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Mini Review

Biodegradable nanofiber scaffolds as dual-action platforms for drug delivery and enhanced tissue healing

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A B S T R A C T

Biodegradable nanofiber scaffolds are a newly emerging platform that provide the advantages of controlled drug delivery with improved tissue repair. They can replicate an extracellular matrix by introducing a porous, breathable and moist environment for the subsequent proper growth and migration of cells. The relatively large surface area provides an ideal medium for loading and sustained release of the bioactive agents (e.g., growth factors and antimicrobials), and can help promote hemostasis, reduce inflammation, stimulate angiogenesis and limit infection. Each of these processes contributes to the development of new tissues, however, in complex injuries (e.g. bone defects) this dual purpose can accelerate the rate of regeneration. Recently, researchers have reported that a temporally specific, sequential drug delivery by a biodegradable nanofiber scaffold could provide more effective healing opportunities compared to delivering one agent at a time. While we may still have challenges in getting or matching the drug loading with the temporal delivery, biodegradable nanofiber scaffolds will continue to be a promising and emerging platform for tissue regeneration and drug delivery. This mini-review discusses the different aspects related to biodegradable nanofiber scaffolds: designs and strategies for fabrication, methods of drug incorporation and drug release mechanisms, their biomedical applications, limitations and future pathways for enhancing therapeutic effects using biodegradable nanofiber scaffolds.

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1. Introduction

Biodegradable nanofiber scaffolds are a novel innovation in biomedical engineering, functioning as a vehicle for drug delivery and for stimulation of tissue repair [1]. The nanofiber modular design of the nanofiber scaffold accurately simulates the extracellular matrix (ECM), creating a porous, breathable, and moisture-retentive environment conducive to cell adhesion, growth, and appropriately programmed differentiation [2-4]. This structural simulation provides the scaffold with the ability to support tissue regeneration, and serve as an effective carrier for therapeutic agents; making these scaffolds

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excellent candidates for multifaceted wound management, and tissue engineering applications [5, 6].

Biodegradable polymers incorporated in nanofiber scaffolds help repair tissues by degrading at a controlled rate that is consistent with the healing process, which leads to less chronic inflammation and foreign body response [7, 8]. New advances show the scaffold possess multi-functional properties as scaffolds and drug storage carriers [6, 7]. For example, cellulose-based electrospun nanofibers show favorable biocompatibility, may be incorporated with nanoparticles for antimicrobial activities, which will by far, improve wound healing [9-11]. Nanofibers composed of silk fibroin and collagen were shown to release therapeutic agents in a sustained manner while enhancing tissue regeneration by lessening the effects of infection and inflammation [8, 12]. Even though scaffolds are promising, challenges still exist in balancing drug loading without damaging the integrity of the scaffold, and in precisely controlling the spatial and temporal drug release rate [13]. Current studies are focusing on stimulus-responsive delivery systems based on nanofibers that can respond to environmental cues (e.g. pH or temperature) to induce drug release [14]. These developments are intended to maximize the therapeutic utility and flexibility of nanofiber scaffolds in various clinical contexts, including, but not limited to, chronic wound care and oncologic therapy [13].

This mini review provides a comprehensive overview of biodegradable nanofiber scaffolds serving as dual-use platforms. It emphasizes their design, fabrication methods, and biomedical applications. The review considers how the scaffolds integrate drug delivery alongside tissue regeneration, discusses recent advances in the field, and considers potential future applications for improving scaffold performance for both regenerative medicine and drug delivery.

2. Materials of Biodegradable Nanofibers

Biodegradable nanofibers are made of natural and synthetic biopolymers (including composite versions) that environmentally degrade. They are alternative supplies that are sustainable for applications in biomedical devices, filtration, and packaging [15]. The different types of materials used to produce biodegradable nanofibers are shown in Fig. 1.

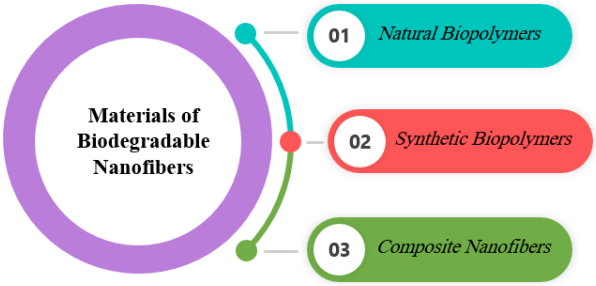

Fig. 1. Materials of Biodegradable Nanofibers.

2.1. Natural Biopolymers

Commonly used natural biopolymers involve: cellulose, chitosan, starch, alginate, silk fibroin, and gelatin[16]. These materials are sourced from renewable resources and have a lot of value for their biodegradability, biocompatibility, and sustainability [17, 18]. Cellulose, which forms the basis of the plant cell wall, is very popular because it is abundant and strong [19, 20]. Chitosan, which is derived from shellfish shells, is known for its antibacterial effects [21, 22]. Starch, and alginate are both used frequently as they can biodegrade and are eco-friendly [23]. Silk fibroin and gelatin, which derive from animals, are attractive due to their excellent biocompatibility and mechanical properties [24].

2.2. Synthetic Biopolymers

Synthetic biodegradable polymers, including polylactic acid (PLA) and polycaprolactone (PCL), are essential to producing formidable biodegradable nanofibers [25]. PLA is produced from renewable resources like corn and sugarcane and is used in a variety of applications in the biomedical fields and also in filtration membranes due to its outstanding biodegradability and compatibility with human cells [26]. PLA can also be formed into nanofibers with porous nanofiber structures that enhance filtration performance [27]. PCL, a synthetic polymer, is another biodegradable polymer and is used due to its biodegradability and flexible characteristics.

2.3. Composite Nanofibers

Composite biodegradable nanofibers are advanced materials formed by blending biodegradable polymers with nanoscale fillers or biofibers, typically using electrospinning [28]. These nanofibers typically contain polymers such as polyhydroxyalkanoate (PHA) or its derivatives, together with a natural nanoscale filler, such as treated fish-scale powder (TFSP), that contains hydroxyapatite similarly found in bone tissue, thereby improving the mechanical strength, bioactivity and compatibility with biological systems [29]. The use of fillers provides improved tensile strength and hydrophilicity, yielding a better environment for cell growth and therefore, are highly versatile for applications in biomedicine, including, tissue engineering and filtration membranes. Furthermore, biofiber-reinforced nanocomposites are lightweight, stiff, biodegradable, and mechanically improved, broadening their applications across medical, environmental, and sustainability sectors [30]. The combination of natural nanofibers and biodegradable polymers enables customization of performance, including improved strength and controlled degradation, while being environmentally friendly [31]. Table 1 presents the properties and uses of various types of biodegradable nanofibers.

3. Dual-Functionality: Drug Delivery and Tissue Regeneration

Biodegradable nanofiber scaffolds have become a revolutionary tool in regenerative medicine, providing dual functions by combining drug delivery with tissue regeneration [36, 37]. Their distinctive structure and material qualities allow for controlled release of therapeutic agents while creating a biomimetic environment that promotes cell adhesion, growth, and differentiation.

3.1. Mechanisms of drug incorporation and release

The effectiveness of drug loading and the precision of release profiles in biodegradable nanofiber scaffolds are based on the combination of drug incorporation method, polymer properties and scaffold design. This makes them flexible platforms for controlled drug delivery [6, 38, 39].

3.1.1. Drug Incorporation Mechanisms

Drugs can be incorporated into biodegradable nanofiber scaffolds using a number of different methods, including physical adsorption and chemical conjugation, and each method will impact loading efficiency and release behavior [6, 40]. A very useful method is physical adsorption; drugs are physically adsorbed to the scaffold because of non-covalent forces of attraction such as van der Waals interactions and electrostatic forces [41, 42]. Physical adsorption has advantageous because it is very easy, does not alter the physical or chemical integrity of the drug, or any function that its activity may possess, however, surface adsorption will usually release faster as these drugs are only on the surface of the scaffold and loading capacity is limited on the surface of the scaffold and the solubility of the drug is dependent on surface area [6]. Blending is a common technique, involving mixing the drug with the polymer solution prior to fiber formation, typically through electrospinning [38]. This method disperses the drug evenly within the fiber matrix, leading to greater loading capacity and a more sustained release profile [43]. Additionally, core/shell and multilayer nanofiber structures can fine-tune drug incorporation [44].

In core/shell fibers, the drug resides in the core and is shielded by a polymer shell that acts as a diffusion barrier, allowing for extended and controlled drug release [38, 45].

Table 1. Characteristics of Different Types of Biodegradable Nanofibers.

Material Type	Examples	Source	Properties/Applications	References
Natural Biopolymers	Cellulose, Chitosan, Chitin, Collagen, Gelatin, Silk fibroin, Pectin, Alginate, Hyaluronic acid	Derived from plants, shellfish, animals	Biocompatible, biodegradable, bioactive, used in tissue engineering, wound healing, drug delivery, packaging	[32, 33]
Synthetic Biopolymers	PLA, Poly lactic-co-glycolic acid (PLGA), Polyethylene oxide (PEO), PCL, Polybutyrolactam (PBY)	Bioplastic or synthetic bio-based	Tunable biodegradability, mechanical stability, used in drug delivery, tissue engineering, flexible electronics	[34]
Composite Nanofibers	Collagen-PCL, Gelatin-PCL, Chitosan-PEO, PLGA-collagen, Cellulose-chitosan-PEO	Combination of natural and synthetic polymers	Improved spinnability, controlled degradation rate, enhanced mechanical properties	[29, 35]

Surface modification involves chemically or physically changing the nanofiber surface to enhance drug attachment or add functional groups that interact with the drug [46]. Also, the physical state of the drug, whether crystalline or amorphous, influences release behavior, as crystalline drugs on the fiber surface can lead to an initial burst release [46, 47].

3.1.2. Drug Release Mechanisms

Drug release mechanisms are varied and can include processes such as dissolution, diffusion, osmosis, partitioning, swelling, erosion, and targeting. These mechanisms depend on the specific application and may occur simultaneously or at different stages during the delivery process. The main process is diffusion, where drug molecules move from inside the fibers to the outside, driven by concentration differences [48].

The release of drugs from biodegradable nanofiber scaffolds involves multiple mechanisms, often working together [38]. Polymer degradation is an essential process, particularly for biodegradable scaffolds [49, 50]. As the polymer matrix breaks down via hydrolysis or enzymatic action, the encapsulated drug is released gradually. The rate of degradation depends on factors such as the polymer's composition, molecular weight, and environmental conditions like pH and temperature [39, 51]. The hydrophobic nature of the polymer matrix can greatly slow water infiltration, which in turn delays drug diffusion and results in a more controlled, sustained release [38].

In certain cases, drug release occurs in multiple phases. It starts with a rapid burst of drug molecules on or near the fiber surface, then shifts to a slower, diffusion-driven stage as the drug moves from deeper inside the fibers. Finally, as the scaffold degrades, drugs embedded within the matrix are released when the polymer network breaks down [52].

The nanofiber scaffold's structure, including fiber diameter and porosity, affects the drug release profile [53, 54]. Thinner fibers or more porous scaffolds facilitate quicker drug diffusion, whereas thicker fibers and denser matrices tend to slow it down. Adding barrier layers or nanoparticles to the scaffold can further control the release rate, allowing for customized delivery suited to specific therapeutic requirements [55, 56].

Le et al. [38] examined Berberine-loaded PLA nanofiber scaffolds as a drug delivery system, linking their chemical properties to release behavior and antibacterial activity. The BBR/PLA scaffold's release fit best with the Ritger–Peppas model, indicating Fickian diffusion, while BBR NPs/PLA aligned with both Higuchi and Ritger–Peppas models, showing a combined diffusion and degradation mechanism. In BBR/PLA, release involved water dissolving surface BBR and slow diffusion from the core. For BBR NPs/PLA, rapid surface dissolution was followed by gradual internal diffusion via pore formation. Overall, BBR release is mainly influenced by drug distribution, wettability, and nanofiber pore structure, with PLA degradation being a slow process. Fig. 2 shows in vitro release patterns of BBR from BBR/PLA (blue line) and BBR NPs/PLA (pink line) nanofiber scaffolds [38].

3.2. Tissue healing support: physical cues and bioactive loading

Biodegradable nanofiber scaffolds facilitate tissue healing by offering physical cues that mimic the native ECM environment, alongside bioactive loading that delivers therapeutic agents or cells [57]. These combined approaches actively modulate the healing microenvironment, promoting cell survival, ECM remodeling, angiogenesis, and immunomodulation. As a result, they contribute to faster wound closure and better skin regeneration [58, 59]. Physical cues encompass the scaffold's structural and mechanical characteristics that affect cell behavior and tissue growth. Electrospun nanofiber scaffolds composed of blends of natural and synthetic polymers such as PCL, gelatin, chitosan, collagen, and silk fibroin imitate the ECM architecture, creating a supportive microenvironment for cell attachment, growth, and differentiation. Their nanofibrous structure helps retain moisture and facilitate gas exchange, both essential for healing [8, 57].

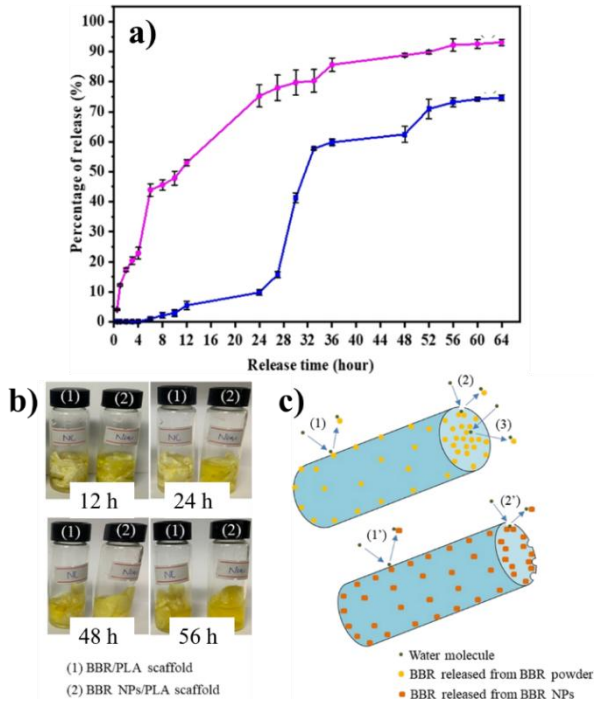

Fig. 2. a) In vitro release patterns of BBR from BBR/PLA (blue line) and BBR NPs/PLA (pink line) nanofiber scaffolds, b) photographic images depicting the BBR release outcomes at 12, 24, 48, and 56 hours, and c) suggested mechanism underlying BBR release from the BBR/PLA and BBR NPs/PLA nanofiber scaffolds [38].

Modifying scaffold stiffness, porosity, fiber orientation, and surface topology can enhance cell migration, promote blood vessel formation, and support ECM remodeling faster tissue regeneration [60]. In particular, scaffolds with modified stiffness enhance cell migration, whereas specific topological features may attract immune cells and result in new angiogenesis[61]. Bioactive loading is the active incorporation of therapeutic agents into scaffolds (i.e. growth factor, ECM proteins, such as fibrinogen and collagen I, nanoparticles, or stem cells) in order to facilitate a healing process. This technique takes into consideration prolonged, localized release of the bioactive molecule, which can elicit cell responses, decrease inflammation, and aid tissue regeneration [62]. For example, coaxial nanofiber scaffolds that sequentially release fibrinogen and collagen I, mimicking dynamic ECM composition during wound healing, have been used to promote immunomodulation and shift macrophage polarization to a regenerative macrophage phenotype, thereby promoting healing of chronic wounds [59]. Scaffolds with incorporated skin-derived precursor cells or mesenchymal stromal cells support formation of ECM, increased cell proliferation, and integration into the wound area [58].

4. Current Limitations and Future Perspectives

The existing constraints of biodegradable nanofiber scaffolds as dual-purpose platforms for drug delivery and tissue repair. These limitations lie primarily in their degradation rate, drug loading capacity and release profiles. Managing biodegradability aligns with tissue regeneration; for example, a scaffold that degrades too quickly may not provide enough structural stability and time for adequate tissue formation due to accumulation of byproducts that may cause toxicity or inflammation.

In contrast, a scaffold that degrades slowly may become encapsulated in scar tissue or experience immune rejection, preventing integration into surrounding tissue [63, 64]. The degradation rate is influenced by several factors including the composition of the material, but also the architecture of the scaffold, surface modifications, and the physiological environment, making it difficult to precisely control [63].

There is an obvious challenge to controlling drug loading and spatiotemporal release such that the activity of the drug is not inhibited [6]. Although nanofibers provide an important high surface area and porous structure that resembles the extracellular matrix to allow efficient drug loading and sustained drug release, they still have the challenge to keep the drug stable during the fabricating of the scaffold and the releasing of the drug [65]. Furthermore, customizing for release profiles of various tissue healing stages is still required into advanced stimulus-responsive systems that are still developing [6].

Future directions call for the development of manufacturing technologies like electrospinning, 3D printing, and molecular self-assembly, to generate advanced scaffolds with multi-functionality and improved mechanical stability, biodegradability, and drug-delivery capabilities [66]. Advances would involve the design of composite nanofibers based on biocompatible polymers incorporating bioactive substances, including growth factors and anti-inflammatory molecules to facilitate integrated healing. Also, scaffold-loaded and stimulus-response nanofiber scaffolds, to deliver drugs in response to stimulations including changes in pH or temperature, may offer more specific treatment opportunities. Also, a better understanding of the scaffold-tissue interactions, and patient-specific variables, may lead to personalized scaffolds for better binding and efficacy [5]. Successful completion of these aims is necessary to achieve the full potential of biodegradable nanofiber scaffolds as dual-function platforms for drug delivery and tissue regeneration [1].

5. Conclusion

Biodegradable nanofiber scaffolds are a promising dual-functionality technology that allows for targeted drug delivery and enhanced tissue repair. These scaffolds provide structural conditions that mirror the extracellular matrix to provide an ideal cell attachment, growth, and differentiation environment. Additionally, scaffolds that allow for localized controlled drug release will address the clinically significant challenges of effectiveness and side effects of treatment regimens. New advances in both material science and nanotechnology have begun to provide scaffolds that are customizable, biomimetic, biocompatible, and safely biodegradable in the body - eliminating the surgical intervention for material removal and reducing the risk of long-term complications.

As research advances to enhance scaffold composition, drug loading strategies, and the kinetics of drug release, these multifunctional scaffolds could be game changers in regenerative medicine and wound care, providing better clinical outcomes and promoting improved patient quality of life. Future research into regulatory pathways, in vivo performance, and large-scale production will be critical to translating these innovative scaffolds from research use to the clinic, where they can benefit patients across healthcare.

Author Contributions

Ebadullah Asadi: Conceptualization, Writing – original draft, Writing – review & editing. **Noushin Ezati:** Writing – original draft, Writing – review & editing. All authors read and approved the final version of manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data is available.

Ethical issues

The authors confirm full adherence to all ethical guidelines, including the prevention of plagiarism, data fabrication, and double publication.

6. References

[1] Chen S, John JV, McCarthy A, Xie J. New forms of electrospun nanofiber materials for biomedical applications. Journal of materials chemistry B. 2020;8(17):3733-46. DOI: https://doi.org/10.1039/d0tb00271b.

[2] Ji E, Song YH, Lee JK, Kim Y, Lee E, Joo KI, et al. Bioadhesive levan-based coaxial nanofibrous membranes with enhanced cell adhesion and mesenchymal stem cell differentiation. Carbohydrate Polymers. 2025:123337. DOI: https://doi.org/10.1016/j.carbpol.2025.123337.

[3] Hu Z, Lin H, Wang Z, Yi Y, Zou S, Liu H, et al. 3D Printing Hierarchical Porous Nanofibrous Scaffold for Bone Regeneration. Small. 2025;21(2):2405406. DOI: https://doi.org/10.1002/smll.202405406.

[4] Singh R, Dolatabadi ZR, Tripathi N, Mukhtar S, Sheriff DS, Morais FG, et al. Recent progress on filtration technologies for the fabrication of effective COVID masks: A review. Journal of Composites and Compounds. 2021;3(9):218-29. DOI: https://doi.org/10.52547/jcc.3.4.3.

[5] Gupta KC, Haider A, Choi Y-r, Kang I-k. Nanofibrous scaffolds in biomedical applications. Biomaterials research. 2014;18(1):5. DOI: https://doi.org/10.1186/2055-7124-18-5.

[6] Jiang Z, Zheng Z, Yu S, Gao Y, Ma J, Huang L, et al. Nanofiber scaffolds as drug delivery systems promoting wound healing. Pharmaceutics. 2023;15(7):1829. DOI: https://doi.org/10.3390/pharmaceutics15071829.

[7] Sharma D, Srivastava S, Kumar S, Sharma PK, Hassani R, Dailah HG, et al. Biodegradable electrospun scaffolds as an emerging tool for skin wound regeneration: a comprehensive review. Pharmaceuticals. 2023;16(2):325. DOI: https://doi.org/10.3390/ph16020325.

[8] Arumugam M, Murugesan B, kumar Chinnalagu D, Mahalingam S. Dual therapeutic approach: biodegradable nanofiber scaffolds of silk fibroin and collagen combined with silver and gold nanoparticles for enhanced bacterial infections treatment and accelerated wound healing. Journal of Drug Delivery Science and Technology. 2024;95:105620. DOI: https://doi.org/10.1016/j.jddst.2024.105620.

[9] GhavamiNejad A, Rajan Unnithan A, Ramachandra Kurup Sasikala A, Samarikhalaj M, Thomas RG, Jeong YY, et al. Mussel-inspired electrospun nanofibers functionalized with size-controlled silver nanoparticles for wound dressing application. ACS applied materials & interfaces. 2015;7(22):12176-83. DOI: https://doi.org/10.1021/acsami.5b02542.

[10] Fahimirad S, Khaki M, Ghaznavi-Rad E, Abtahi H. Investigation of a novel bilayered PCL/PVA electrospun nanofiber incorporated Chitosan-LL37 and Chitosan-VEGF nanoparticles as an advanced antibacterial cell growth-promoting wound dressing. International Journal of Pharmaceutics. 2024;661:124341. DOI: https://doi.org/10.1016/j.ijpharm.2024.124341.

[11] Pagliaro M, Ciriminna R, Yusuf M, Eskandarinezhad S, Wani IA, Ghahremani M, et al. Application of nanocellulose composites in the environmental engineering as a catalyst, flocculants, and energy storages: A review. Journal of Composites and Compounds. 2021;3(7):114-28. DOI: https://doi.org/10.52547/jcc.3.2.5.

[12] Yang C, Li S, Huang X, Chen X, Shan H, Chen X, et al. Silk fibroin hydrogels could Be therapeutic biomaterials for neurological diseases. Oxidative Medicine and Cellular Longevity. 2022;2022(1):2076680. DOI: https://doi.org/10.1155/2022/2076680.

[13] Chen T, Jiang Y, Huang J-P, Wang J, Wang Z-K, Ding P-H. Essential elements for spatiotemporal delivery of growth factors within bio-scaffolds: a comprehensive strategy for enhanced tissue regeneration. Journal of Controlled Release. 2024;368:97-114. DOI: https://doi.org/10.1016/j.jconrel.2024.02.006.

[14] Chen K, Li Y, Li Y, Tan Y, Liu Y, Pan W, et al. Stimuli-responsive electrospun nanofibers for drug delivery, cancer therapy, wound dressing, and tissue engineering. Journal of Nanobiotechnology. 2023;21(1):237. DOI: https://doi.org/10.1186/s12951-023-01987-z.

[15] Chaudhary V, Punia Bangar S, Thakur N, Trif M. Recent advancements in smart biogenic packaging: Reshaping the future of the food packaging industry. Polymers. 2022;14(4):829. DOI: https://doi.org/10.3390/polym14040829.

[16] Izadi M, Bazli L. Eco-friendly composites: developing sustainable solutions for modern engineering. Journal of Composites and Compounds. 2025;7(22). DOI: https://doi.org/10.61186/jcc.7.1.4.

[17] Sreena R, Nathanael AJ. Biodegradable biopolymeric nanoparticles for biomedical applications-challenges and future outlook. Materials. 2023;16(6):2364. DOI: https://doi.org/10.3390/ma16062364.

[18] Cui C, Fu Q, Meng L, Hao S, Dai R, Yang J. Recent progress in natural biopolymers conductive hydrogels for flexible wearable sensors and energy devices: materials, structures, and performance. ACS applied bio materials. 2020;4(1):85-121. DOI: https://doi.org/10.1021/acsabm.0c00807.

[19] Chen D, Melton LD, McGillivray DJ, Ryan TM, Harris PJ. Changes in the orientations of cellulose microfibrils during the development of collenchyma cell walls of celery (Apium graveolens L.). Planta. 2019;250(6):1819-32. DOI: https://doi.org/10.1007/s00425-019-03262-8.

[20] Dampanaboina L, Yuan N, Mendu V. Estimation of crystalline cellulose content of plant biomass using the updegraff method. Journal of Visualized Experiments (JoVE). 2021(171):e62031. DOI: https://doi.org/10.3791/62031.

[21] Bano I, Ghauri MA, Arshad M, Yasin T, Younus M. Bioactivity of variant molecular weight chitosan against drug-resistant bacteria isolated from human wounds. Microbial Drug Resistance. 2017;23(8):958-65. DOI: https://doi.org/10.1089/mdr.2016.0211.

[22] Salehi M, Mirhaj M, Hoveizavi NB, Tavakoli M, Mahheidari N. Advancements in Wound Dressings: The Role of Chitin/Chitosan-based Biocomposites. Journal of Composites and Compounds. 2025;7(23). DOI: https://doi.org/10.61186/jcc.7.2.2.

[23] Lin Q, Li H, Ji N, Dai L, Xiong L, Sun Q. Self-healing, stretchable, and freezing-resistant hydroxypropyl starch-based double-network hydrogels. Carbohydrate polymers. 2021;251:116982. DOI: https://doi.org/10.1016/j.carbpol.2020.116982.

[24] Zhuang Y, Zhang Q, Feng J, Wang N, Xu W, Yang H. The effect of native silk fibroin powder on the physical properties and biocompatibility of biomedical polyurethane membrane. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine. 2017;231(4):337-46. DOI: https://doi.org/10.1177/0954411917697357.

[25] Shamsuri AA, Md. Jamil SNA, Abdan K. A brief review on the influence of ionic liquids on the mechanical, thermal, and chemical properties of biodegradable polymer composites. Polymers. 2021;13(16):2597. DOI: https://doi.org/10.3390/polym13162597.

[26] Singhvi MS, Zinjarde SS, Gokhale DV. Polylactic acid: synthesis and biomedical applications. Journal of applied microbiology. 2019;127(6):1612-26. DOI: https://doi.org/10.1111/jam.14290.

[27] Ji X, Bian Y, Zhang C, Zhong Z, Wang Y. Making Accessible and Attractive Porosities in Block Copolymer Nanofibers for Highly Permeable and Durable Air Filtration. Small. 2025;21(6):2410692. DOI: https://doi.org/10.1002/smll.202410692.

[28] Wei L, McDonald AG. A review on grafting of biofibers for biocomposites. Materials. 2016;9(4):303. DOI: https://doi.org/10.3390/ma9040303.

[29] Wu C-S, Wu D-Y, Wang S-S. Biodegradable composite nanofiber containing fish-scale extracts. ACS Applied Bio Materials. 2020;4(1):462-9. DOI: https://doi.org/10.1021/acsabm.0c00955.

[30] Movahedi M, Karbasi S. Electrospun halloysite nanotube loaded polyhydroxybutyrate-starch fibers for cartilage tissue engineering. International Journal of Biological Macromolecules. 2022;214:301-11. DOI: https://doi.org/10.1016/j.ijbiomac.2022.06.072.

[31] Sun J, Shen J, Chen S, Cooper MA, Fu H, Wu D, et al. Nanofiller reinforced biodegradable PLA/PHA composites: Current status and future trends. Polymers. 2018;10(5):505. DOI: https://doi.org/10.3390/polym10050505.

[32] Li Z, Mei S, Dong Y, She F, Li Y, Li P, et al. Functional nanofibrous biomaterials of tailored structures for drug delivery—a critical review. Pharmaceutics. 2020;12(6):522. DOI: https://doi.org/10.3390/pharmaceutics12060522.

[33] Zhou J, Li X, Zhang Z, Hou T, Xu J, Wang Y, et al. Bio-based and bio-degradable nanofiber materials: A sustainable platform for energy, environmental, and biomedical applications. Chemical Engineering Journal. 2024:152105. DOI: https://doi.org/10.1016/j.cej.2024.152105.

[34] Zhao J, Zhang R, Zhang Y, Piao H, Ren Z, Zhang H, et al. Biobased Polybutyrolactam Nanofiber with Excellent Biodegradability and Cell Growth for Sustainable Healthcare Textiles. Biomacromolecules. 2024;25(9):5745-57. DOI: https://doi.org/10.1021/acs.biomac.4c00249.

[35] Arun R, Shruthy R, Preetha R, Sreejit V. Biodegradable nano composite reinforced with cellulose nano fiber from coconut industry waste for replacing synthetic plastic food packaging. Chemosphere. 2022;291:132786. DOI: https://doi.org/10.1016/j.chemosphere.2021.132786.

[36] Chen S, Li R, Li X, Xie J. Electrospinning: An enabling nanotechnology platform for drug delivery and regenerative medicine. Advanced drug delivery reviews. 2018;132:188-213. DOI: https://doi.org/10.1016/j.addr.2018.05.001.

[37] Gupta A, Bozcheloei ZA, Ghofrani A, Nejad SK, Chakraborty P, Ambekar RS, et al. Electroactive composite for wound dressing. Journal of Composites and Compounds. 2022;4(10):13-23. DOI: https://doi.org/10.52547/jcc.4.1.3.

[38] Nguyen HT, Nguyen LT, Tran HQ, Nguyen TTT. Berberine-loaded polylactic acid nanofiber scaffold as a drug delivery system: The relationship between chemical characteristics, drug-release behavior, and antibacterial efficiency. Beilstein Journal of Nanotechnology. 2024;15(1):71-82. DOI: https://doi.org/10.3762/bjnano.15.7.

[39] Kalayil N, Budar AA, Dave RK. Nanofibers for Drug Delivery: Design and Fabrication Strategies. BIO Integration. 2024;5(1):978. DOI: https://doi.org/10.15212/bioi-2024-0023.

[40] Son YJ, Kim WJ, Yoo HS. Therapeutic applications of electrospun nanofibers for drug delivery systems. Archives of pharmacal research. 2014;37(1):69-78. DOI: https://doi.org/10.1007/s12272-013-0284-2.

[41] Sato N, Aoyama Y, Yamanaka J, Toyotama A, Okuzono T. Particle adsorption on hydrogel surfaces in aqueous media due to van der Waals attraction. Scientific reports. 2017;7(1):6099. DOI: https://doi.org/10.1038/s41598-017-06257-1.

[42] Mukhopadhyay TK, Datta A. Delicate Balance of Non-Covalent Forces Govern the Biocompatibility of Graphitic Carbon Nitride towards Genetic Materials. ChemPhysChem. 2020;21(16):1836-46. DOI: https://doi.org/10.1002/cphc.202000385.

[43] Petlin D, Amarah A, Tverdokhlebov S, Anissimov Y. A fiber distribution model for predicting drug release rates. Journal of Controlled Release. 2017;258:218-25. DOI: https://doi.org/10.1016/j.jconrel.2017.05.021.

[44] Yang J, Xu L. Electrospun nanofiber membranes with various structures for wound dressing. Materials. 2023;16(17):6021. DOI: https://doi.org/10.3390/ma16176021.

[45] Chen J, Zhang G, Zhao Y, Zhou M, Zhong A, Sun J. Promotion of skin regeneration through co-axial electrospun fibers loaded with basic fibroblast growth factor. Advanced composites and hybrid materials. 2022;5(2):1111-25. DOI: https://doi.org/10.1007/s42114-022-00439-w.

[46] ZAMANI T. Release mechanisms for profen-loaded nanofibers: Challenges and opportunities. Journal of advanced Biomedical and Pharmaceutical Sciences. 2021;4(4):195-213. DOI: https://dx.doi.org/10.21608/jabps.2021.72197.1126.

[47] Joiner JB, Prasher A, Young IC, Kim J, Shrivastava R, Maturavongsadit P, et al. Effects of drug physicochemical properties on in-situ forming implant polymer degradation and drug release kinetics. Pharmaceutics. 2022;14(6):1188. DOI: https://doi.org/10.3390/pharmaceutics14061188.

[48] Bruschi M. Main mechanisms to control the drug release. Strategies to modify the drug release from pharmaceutical systems. 2015:37-62. DOI: https://doi.org/10.1016/B978-0-08-100092-2.00004-7.

[49] Malek-Khatabi A, Tabandeh Z, Nouri A, Mozayan E, Sartorius R, Rahimi S, et al. Long-term vaccine delivery and immunological responses using biodegradable polymer-based carriers. ACS Applied Bio Materials. 2022;5(11):5015-40. DOI: https://doi.org/10.1021/acsabm.2c00638.

[50] Hsu S-h, Hung K-C, Chen C-W. Biodegradable polymer scaffolds. Journal of Materials Chemistry B. 2016;4(47):7493-505. DOI: https://doi.org/10.1039/c6tb02176j.

[51] Rodriguez-Rivera GJ, Green M, Shah V, Leyendecker K, Cosgriff-Hernandez E. A user's guide to degradation testing of polyethylene glycol-based hydrogels: From in vitro to in vivo studies. Journal of Biomedical Materials Research Part A. 2024;112(8):1200-12. DOI: https://doi.org/10.1002/jbm.a.37609.

[52] Sadri M, Mohammadi A, Hosseini H. Drug release rate and kinetic investigation of composite polymeric nanofibers. Nanomedicine Research Journal. 2016;1(2):112-21. DOI: https://doi.org/10.7508/nmrj.2016.02.008.

[53] Lanno G-M, Ramos C, Preem L, Putrins M, Laidmae I, Tenson T, et al. Antibacterial porous electrospun fibers as skin scaffolds for wound healing applications. ACS omega. 2020;5(46):30011-22. DOI: https://doi.org/10.1021/acsomega.0c04402.

[54] Wang H, Bao Y, Yang X, Lan X, Guo J, Pan Y, et al. Study on filtration performance of PVDF/PUL composite air filtration membrane based on far-field electrospinning. Polymers. 2022;14(16):3294. DOI: https://doi.org/10.3390/polym14163294.

[55] Shetty K, Bhandari A, Yadav KS. Nanoparticles incorporated in nanofibers using electrospinning: A novel nano-in-nano delivery system. Journal of controlled release. 2022;350:421-34. DOI: https://doi.org/10.1016/j.jconrel.2022.08.035.

[56] Kumar S, Singh AP, Senapati S, Maiti P. Controlling drug delivery using nanosheet-embedded electrospun fibers for efficient tumor treatment. ACS Applied Bio Materials. 2019;2(2):884-94. DOI: https://doi.org/10.1021/acsabm.8b00735.

[57] Partovi A, Khedrinia M, Arjmand S, Ranaei Siadat SO. Electrospun nanofibrous wound dressings with enhanced efficiency through carbon quantum dots and citrate incorporation. Scientific Reports. 2024;14(1):19256. DOI: https://doi.org/10.1038/s41598-024-70295-9.

[58] Anjum F, Agabalyan NA, Sparks HD, Rosin NL, Kallos MS, Biernaskie J. Biocomposite nanofiber matrices to support ECM remodeling by human dermal progenitors and enhanced wound closure. Scientific reports. 2017;7(1):10291. DOI: https://doi.org/10.1038/s41598-017-10735-x.

[59] Sun L, Li J, Gao W, Shi M, Tang F, Fu X, et al. Coaxial nanofibrous scaffolds mimicking the extracellular matrix transition in the wound healing process promoting skin regeneration through enhancing immunomodulation. Journal of Materials Chemistry B. 2021;9(5):1395-405. DOI: https://doi.org/10.1039/D0TB01933J.

[60] Ma B, Xie J, Jiang J, Shuler FD, Bartlett DE. Rational design of nanofiber scaffolds for orthopedic tissue repair and regeneration. Nanomedicine. 2013;8(9):1459-81. DOI: https://doi.org/10.2217/nnm.13.132.

[61] Qin J, Chen F, Wu P, Sun G. Recent advances in bioengineered scaffolds for cutaneous wound healing. Frontiers in Bioengineering and Biotechnology. 2022;10:841583. DOI: https://doi.org/10.3389/fbioe.2022.841583.

[62] Afsharian YP, Rahimnejad M. Bioactive electrospun scaffolds for wound healing applications: A comprehensive review. Polymer Testing. 2021;93:106952. DOI: https://doi.org/10.1016/j.polymertesting.2020.106952.

[63] Echeverria Molina MI, Malollari KG, Komvopoulos K. Design challenges in polymeric scaffolds for tissue engineering. Frontiers in Bioengineering and Biotechnology. 2021;9:617141. DOI: https://doi.org/10.3389/fbioe.2021.617141.

[64] Malekmohammadi S, Jamshidi R, Sadowska JM, Meng C, Abeykoon C, Akbari M, et al. Stimuli-responsive codelivery system-embedded polymeric nanofibers with synergistic effects of growth factors and low-intensity pulsed ultrasound to enhance osteogenesis properties. ACS Applied Bio Materials. 2024;7(7):4293-306. DOI: https://doi.org/10.1021/acsabm.4c00111.

[65] Huesca-Urióstegui K, García-Valderrama EJ, Gutierrez-Uribe JA, Antunes-Ricardo M, Guajardo-Flores D. Nanofiber systems as herbal bioactive compounds carriers: current applications in healthcare. Pharmaceutics. 2022;14(1):191. DOI: https://doi.org/10.3390/pharmaceutics14010191.

[66] Gholap AD, Rojekar S, Kapare HS, Vishwakarma N, Raikwar S, Garkal A, et al. Chitosan scaffolds: Expanding horizons in biomedical applications. Carbohydrate Polymers. 2024;323:121394. DOI: https://doi.org/10.1016/j.carbpol.2023.121394.