



AEROGELS AND XEROGELS IN DRUG DELIVERY: ADVANCES, OPPORTUNITIES, AND FUTURE DIRECTIONS

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Abstract. One of the leading strategies for delivering bioactive molecules involves the design and development of drug delivery systems that can precisely control drug release, have low side effects, and ensure high patient compliance. Topical drug delivery has gained attention owing to its advantages such as ease of self-application, targeted drug delivery, and reduced total dose. The extensive surface area of the skin presents a promising opportunity for drug delivery. Therefore, topical drug delivery systems must penetrate the specific skin layers where the active pharmaceutical ingredient exerts its pharmacological effects. Extra drug carriers, can be employed in drug release studies primarily to enhance drug delivery efficiency, control release kinetics, and protect the drug from degradation. Aerogels are ultra-light porous nanomaterials with a complex three-dimensional structures. Silica aerogels remain the most widely used due to their characteristics such as high porosity, large specific surface area and low density. These unique features make them highly beneficial in drug delivery. However, the fabrication of aerogels requires supercritical drying technique, which is highly expensive, low in scalability and energy-intensive. Xerogels are porous materials that can be synthesized via ambient pressure drying of any wet gel precursor, which is a cheaper and easier method. They have lower porosity and surface area than aerogels due to the drying difference; however, they have better mechanical stability and higher density than aerogels. In addition, the ease of fabrication, large surface area, and high porosity of electrospun nanofibrous webs make them particularly attractive for use as drug delivery systems. In recent years, there has been a growing research interest in the development of composite systems capable of achieving controlled drug release. This review highlights the applications of xerogels and aerogels in nanofibrous drug delivery systems, discusses their respective advantages and limitations, and identifies potential gaps for future studies.

Keywords: drug delivery systems, carrier, xerogel, aerogel, electrospinning

1. INTRODUCTION

Nanocarriers, including nanospheres, liposomes, solid-lipid, magnetic and metal-based nanoparticles, micelles, dendrimers, and polymeric nanofibrous webs, have recently gained attention as advanced platforms for drug delivery [1,2].

Previous studies have demonstrated that various physicochemical characteristics of the nanocarriers such as composition, particle size, morphology, and surface chemistry, together with their interactions with the encapsulated drug, aggregation tendencies, and dissolution behavior, play a significant role in determining the drug release kinetics.

On the other hand, since these nanocarriers can adsorb large amounts of drug molecules on their surfaces, they may exhibit a rapid release profile, thus requiring the use of an additional carrier or ligand. Researchers have particularly focused on the application of nanotechnology in topical and transdermal drug delivery systems using nanoparticles and nanofibers [3].

2. NANOFIBROUS WEBS IN DRUG DELIVERY

Electrospinning is a method that allows the production of nano or microscale fibers with a high surface area and is based on the principle of ejecting a polymer solution through one or multiple needle tips under an electrical charge. When the electrodes of the power supply are connected, an electric field is generated between the collector and needle. This field induces the formation of a Taylor cone at the tip of the needle, subsequently leading to the elongation and ejection of a polymer jet. As the solvent evaporates during the jet's flight, polymeric fibers are deposited on the collector. This method allows the fabrication of self-assembled, interconnected, open-porous web structures [4]. A strategy for achieving controlled release of bioactive compounds involves designing drug delivery systems that reduce adverse effects while precisely modulating release kinetics. One method to improve the release characteristics of such systems is the pre-loading of drugs into a carrier prior to their integration into the delivery platform such as nanofibrous webs. This study highlights the utilization of xerogels and aerogels within nanofibrous drug delivery systems, examines their specific benefits and constraints, and outlines gaps for future studies.

In addition to its ease of processing and suitability for designing diverse morphological structures, the electrospinning technique is highly adaptable for incorporating various functional agents such as drugs, nanoparticles, antibacterial, or antioxidant compounds into the polymer solution to impart specific properties to the resulting fibers. Electrospun nanofibrous mats offer several advantageous characteristics for drug delivery applications. They can be fabricated from bio-based, biodegradable, and biocompatible polymers such as polycaprolactone (PCL), polyglycolide (PGA), polylactide (PLA), poly(lactic-co-glycolic acid) (PLGA), and polyvinyl alcohol (PVA), collagen, gelatin, chitosan [5]. Moreover, nanofibrous structures possess a large surface area that enables the efficient loading and delivery of both hydrophobic and hydrophilic drugs [6]. In addition, variables such as the polymer-to-drug ratio, porosity and fiber morphology can be tailored to modulate the drug release profile [7, 8], thereby facilitating controlled and sustained drug release from nanofibrous webs.

Drugs can be incorporated into nanofibers through various approaches [9, 10] (Figure 1).

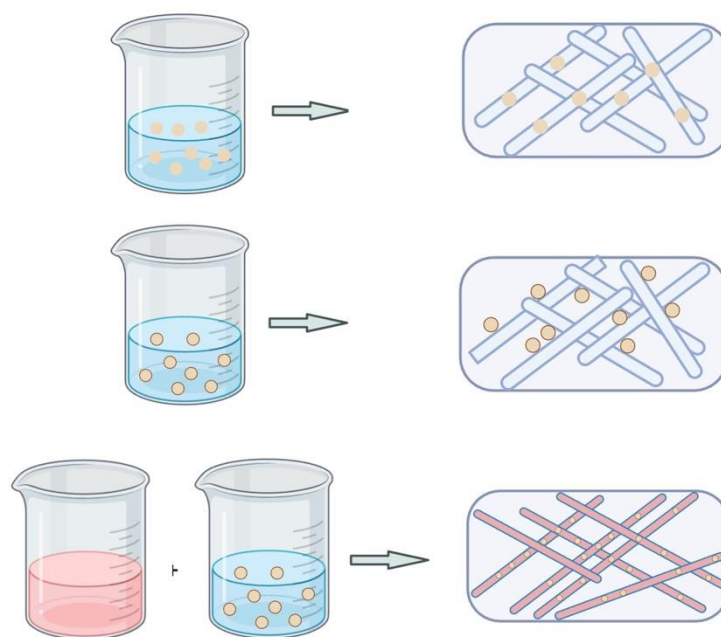


Figure 1. Production of drug-loaded electrospun nanofiber webs

The drug can be dissolved or dispersed directly within the polymer solution; however, this method often results in a burst release because of drug accumulation near the fiber surface. Achieving a proper balance between the hydrophobic /hydrophilic characteristics of the polymer and the drug is therefore critical; otherwise, surface drug accumulation and rapid release may occur. Core-shell electrospinning provides an effective strategy to overcome this limitation. In this approach, the core carries the drug-loaded polymer intended for prolonged release, while the shell layer may or may not contain the drug. The shell polymer serves as a protective barrier that isolates the therapeutic agent in the core from direct interaction with the biological environment, thereby minimizing the risk of premature degradation. This structural configuration

renders the technique especially advantageous for encapsulating sensitive biomolecules, including proteins, growth factors, and antibiotics. In the emulsion electrospinning method, a polymer–drug emulsion is initially formulated and introduced into a syringe; however, the shear stresses generated at the interface of the two immiscible phases during the spinning process may lead to the denaturation or degradation of delicate biomolecules such as nucleic acids. In the encapsulation method, drugs are first loaded into nanoparticles, which are then dispersed within the polymer solution before electrospinning. In the adsorption method, nanofiber webs are immersed in a drug-containing solution, and the drug adheres to the fiber surface via electrostatic attractions, hydrophobic interactions, and van der Waals forces. [11]. Although this approach is simple and cost-effective, the weak binding between the drug and the fibers makes the system highly sensitive to environmental changes such as temperature or pH, often resulting in a rapid release. To achieve slower release, the drug can be covalently attached to the polymer surface; however, the use of chemical cross-linkers in this process may compromise the bioactivity of the therapeutic agent.

Another strategy to mitigate the initial burst release involves applying a coating layer to the nanofibers. The coating acts as a diffusion barrier, effectively controlling the initial drug release rate. For example, Hai et al. [12] coated berberine hydrochloride-loaded ethyl cellulose nanofibers with an oil layer, reducing the initial burst release from 65% to 40% within the first four hours. Similarly, Singh et al. [13] employed the core–shell electrospinning method to achieve sequential drug release. They fabricated nanofibers with a shell from poly(N-isopropylacrylamide)/lidocaine, and a core from PLA/ levofloxacin/ gold nanorods. In aqueous conditions, the drug was released first from the shell, while the release of the core drug was controlled by near-infrared (NIR) irradiation through the gold nanorods. Meenatchi et al. [14] also incorporated an anti-inflammatory drug into hydroxypropyl- β -cyclodextrin nanofibrous webs.

One of the most widely used polymers using in nanofiber-based wound dressing and drug delivery is PVA, a water-soluble, biocompatible and biodegradable polymer [15–18]. In the study by Fathollahipour et al. [15], PVA/chitosan nanofibrous webs comprising gelatin nanoparticles were fabricated as a drug delivery system. In another research [16], collagen/PVA nanofibers were produced and subsequently crosslinked using UV radiation or glutaraldehyde to enhance the structural integrity and reduce burst release. Cui et al. [19] reported that crosslinked PVA/chitosan nanofibers exhibited a lower drug release rate and a reduced burst effect compared to their non-crosslinked counterparts. Rahmani et al. [20] developed buprenorphine-loaded poly(vinyl pyrrolidone) (Bup/PVP) and buprenorphine-loaded PVA/PVP nanofibrous webs for transdermal drug delivery. El Fawal et al. [21] prepared a PVA-based nanofibrous drug carrier system for fluorescein isothiocyanate by employing a phospholipid nanocarrier. Shakiba et al. [22] loaded curcumin onto carboxymethylated carbon nanotubes, incorporated them into a polyamide 6 (PA6)/PVA polymer solution, and produced nanofibrous drug delivery systems via electrospinning. Darabi et al. [23] fabricated starch/PVA nanofibers with silver nanowire hybrid nanoparticles/ciprofloxacin-loaded graphene oxide, achieving a controlled release profile with a reduced initial burst. Elsherbini et al. [24] developed composite nanofibers by combining tadalafil-loaded zein/sodium caseinate nanoparticles with pectin/PVA, successfully extending the drug release period up to 14 days.

2.1. Factors influencing drug release from nanofibrous systems and transdermal absorption

In local skin diseases, topical therapy is preferred over systemic treatment. The primary reasons for this preference are as follows: since the drug is applied directly to the affected skin area, a lower dose may be required compared to the systemic dose of the active substance; systemic side effects of the active compound are avoided; the therapeutic efficacy is enhanced; patient compliance is generally high; and treatment can be discontinued when necessary. However, the stratum corneum, the skin's outermost layer, presents the primary obstacle to transdermal delivery due to its hydrophobic nature. With a thickness of 20–25 μm and a porosity ranging from approximately 250 to 500 μm , it effectively limits the percutaneous absorption of active compounds. Nevertheless, the effectiveness of topical drug therapy increases with the ability of the active compound to reach the targeted region within the skin. Consequently, effective topical drug delivery relies on the ability of the active compound to traverse the stratum corneum and access the underlying skin layers [25, 26].

The factors influencing the transdermal permeation of drugs can be classified into three main categories: (i) physicochemical properties of the active substance, (ii) skin-related factors, and (iii) properties of the drug delivery system [27, 28].

*Physicochemical factors related to the active substance are summarized below:

- a) Lipophilic character of the active substance: The logarithmic value of the oil/water partition coefficient ($\log P$) is a key parameter affecting transdermal permeation. Drugs with moderate lipophilicity ($\log P$ between 1-3) generally exhibit optimal passive diffusion across the skin, whereas compounds with lower or higher lipophilicity show limited permeation through the stratum corneum into deeper layers.
- b) Molecular weight: Drugs with a molecular weight below 500 g/mol display more efficient skin permeation.
- c) Melting point, aqueous solubility, and diffusion coefficient: As the diffusion coefficient of the active substance increases, its transdermal permeation also improves. To achieve a high diffusion coefficient, the drug should possess a low melting point ($< 200\text{ }^{\circ}\text{C}$) and good aqueous solubility ($> 1\text{ mg/mL}$).
- d) Concentration and ionization state: The non-ionized forms of drugs exhibit higher passive diffusion through the skin. Additionally, a higher concentration of the dissolved active compound in the formulation enhances transdermal permeation due to increased thermodynamic activity.

*Skin-related factors include the health condition of the skin, its hydration level, the presence or absence of occlusion, skin temperature, anatomical site, species, and age.

*Factors associated with the drug delivery system involve the composition and physicochemical characteristics of the carrier, as well as its interaction with the active compound. These parameters influence the drug release profile and consequently its permeation through the skin. Furthermore, the interaction between the delivery system and the skin can also affect penetration. The structural nature of the system (lipid-based or polymeric) and the particle size are additional critical parameters determining the extent of skin penetration [27, 28, 29].

In nanofibrous web-based drug delivery systems, the overall release profile is largely governed by the interplay between the drug's physicochemical features, the structural attributes of the polymeric matrix, the characteristics of the release medium, and their possible interactions. Key physicochemical factors of the drug include solubility, chemical stability, molecular weight, charge, pK_a , and potential chemical interactions with the polymer. Meanwhile, the structural parameters of polymeric nanofibers such as fiber morphology, diameter, porosity, surface area, entanglement, and alignment significantly influence release kinetics. Additionally, environmental and physiological conditions, including temperature, pH, ionic strength, and enzymatic activity in the surrounding medium, can markedly affect drug release behavior. Hence, a comprehensive understanding of the interrelationship among these variables is critical for the rational design of efficient and predictable drug delivery platforms.

Drug release from nanofibers predominantly follows a diffusion-controlled mechanism. Biodegradable polymers generally follow Fickian diffusion behavior, whereas non-biodegradable or complex polymeric systems exhibit non-Fickian (anomalous) release mechanisms [8]. In wound dressing applications, drug release generally follows a transdermal delivery pathway. In this route, the permeability of the uppermost layer of the epidermis, the stratum corneum is utilized. Since this layer is semi-permeable and contains lipids and sebum, it preferentially allows the diffusion of hydrophobic drugs. Transdermal delivery systems are particularly employed for wound healing and skin regeneration applications. Beyond facilitating drug release, nanofibers can also stabilize damaged cells and guide cellular differentiation. By maintaining an optimal moisture balance in the wound area, nanofibrous dressings help minimize scar formation. For instance, Tavira et al. [30] embedded doxorubicin-loaded silica/silver nanoparticles into polycaprolactone/gelatin nanofibers, aiming to use the resulting composite nanofibers for healing wounds resulting from skin cancer, where a sustained drug release behavior was observed.

3. AEROGELS AND XEROGEL IN DRUG DELIVERY

Aerogels are highly porous, ultra-lightweight nanomaterials characterized by a three-dimensional network architecture. Numerous types of aerogels have been synthesized, including those based on silica, metal oxides, and carbon. Silica aerogels, in particular, are favored due to their unique combination of low density, high porosity, extensive surface area, and minimal thermal conductivity [31]. These unique characteristics make aerogels suitable for a wide range of applications, including acoustic and thermal insulation [32], capacitors [33], solar energy collectors [34], sensors [35], and drug delivery systems [36]. Xerogels are

porous materials synthesized by evaporative drying of a precursor. Although xerogels exhibit lower porosity and surface area than aerogels, they are more cost-effective [37, 38], easier to produce, and possess better mechanical stability as well as higher density than aerogels [39]. The main distinction between aerogels and xerogels (Figure 2) lies in their production processes: while aerogels are obtained by removing the liquid phase from a gel under supercritical conditions, xerogels are produced through conventional drying techniques such as oven drying or ambient air drying [40].

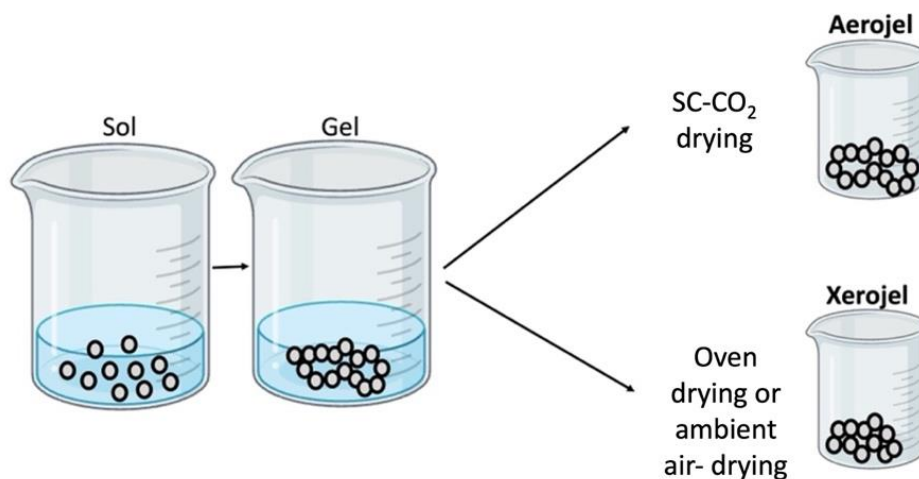


Figure 2. Aerogel and xerogel production methods

In a previous study [41], an alginate-based xerogel was functionalized with grafted poly(methacrylic acid) for insulin delivery, which enhanced its physical stability and promoted favorable swelling characteristics. The system achieved the release of over 70% of the encapsulated insulin within two days. Rafati et al. [42] prepared a xerogel composed of silica and polyethylene glycol via the sol-gel technique, enabling controlled release of the antibiotic enrofloxacin. Additionally, silk fibroin-based xerogels have been developed and assessed for their capability to sustain estradiol hormone release [43]. Controlled drug release was achieved for up to 129 days, demonstrating the potential of xerogels for the sustained delivery of hydrophobic drugs. However, studies on silica-based xerogel-containing nanofibers for drug loading and release are still very limited in the literature. Zhou et al. [44] fabricated PCL–chitosan–silica xerogel composite nanofibers for the delivery of tetracycline hydrochloride. Drug release was conducted in phosphate buffer solution, and the drug loading capacity was determined. The incorporation of silica into xerogels has been shown to markedly improve their thermal stability, *in vitro* bioactivity, and ability to achieve controlled drug release. In our previous study [45], PVA-based nanofibrous webs containing drug-loaded silica xerogels were successfully fabricated through electrospinning, demonstrating their potential for controlled topical drug delivery. In the study, xerogels, synthesized through sol-gel polymerization and loaded with mometasone furoate monohydrate and melatonin, were embedded into PVA matrices. *In vitro* release studies revealed that xerogel incorporation effectively slowed melatonin release compared to xerogel-free formulations, demonstrating the potential of PVA/xerogel nanofibrous webs as promising wound dressing materials for sustained drug delivery.

4. FUTURE WORK

Future studies on drug-loaded aerogel/xerogel-based nanofibrous systems could focus on optimizing the physicochemical properties of the polymeric carrier to achieve more precise control over drug loading and release kinetics. Investigations into the interfacial interactions between xerogel/aerogel particles and polymer chains could elucidate their influence on fiber morphology, stability, and mechanical performance. Incorporating stimuli-responsive components (e.g., pH-, temperature-, or light-sensitive agents) within these composite systems may enable on-demand and site-specific drug release. Furthermore, extending the concept to multidrug-loaded or sequential-release platforms could enhance therapeutic efficacy in complex wound healing or chronic disease management. Special attention should be directed toward clarifying how both the composite formulation and the physicochemical properties of the active agents, particularly the lipophilicity-hydrophilicity balance, which critically influences transdermal permeation, affect the drug

release behavior and kinetics. Moreover, comprehensive in vivo evaluations, including biocompatibility, cytotoxicity, and pharmacokinetic analyses, are crucial to confirm the safety and therapeutic potential of these nanofibrous systems for clinical applications. In addition, the adoption of environmentally friendly sol-gel synthesis routes and the use of biodegradable or naturally sourced polymers could enhance the sustainability and scalability of the fabrication process.

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REFERENCES

- [1] Mitchell MJ, Billingsley MM, Haley RM, Wechsler ME, Peppas NA, Langer R. Nanotechnology in drug delivery. *Nat Rev Drug Discov.* 2021;20(1):101.
- [2] Hiwrale A, Bharati S, Pingale P, Rajput A. Nanofibers: A current era in drug delivery system. *Heliyon.* 2023;9:e18917.
- [3] Goyal R, Macri LK, Kaplan HM, Kohn J. Nanoparticles and nanofibers for topical drug delivery. *J Control Release.* 2016;240:77–92.
- [4] Huang L, Manickam SS, McCutcheon JR. Increasing strength of electrospun nanofiber membranes for water filtration using solvent vapor. *J Membr Sci.* 2013;436:213–20.
- [5] Jain R, Shetty S, Yadav KS. Unfolding the electrospinning potential of biopolymers for preparation of nanofibers. *J Drug Deliv Sci Technol.* 2020;57:101604.
- [6] Verreck G, Chun I, Rosenblatt J, Peeters J, Van Dijk A, Mensch J, et al. Incorporation of drugs in an amorphous state into electrospun nanofibers composed of a water-insoluble, nonbiodegradable polymer. *J Control Release.* 2003;92(3):349–60.
- [7] Macri LK, Sheihet L, Singer AJ, Kohn J, Clark RA. Ultrafast and fast bioerodible electrospun fiber mats for topical delivery of a hydrophilic peptide. *J Control Release.* 2012;161(3):813–20.
- [8] He FL, Deng X, Zhou YQ, Zhang TD, Liu YL, Ye YJ, et al. Controlled release of antibiotics from poly-ε-caprolactone/polyethylene glycol wound dressing fabricated by direct-writing melt electrospinning. *Polym Adv Technol.* 2019;30(5):425–34.
- [9] Gaydhane MK, Sharma CS, Majumdar S. Electrospun nanofibers in drug delivery: Advances in controlled release strategies. *RSC Adv.* 2023;13(12):7312–33.
- [10] Bhattarai RS, Bachu RD, Boddu SHS, Bhaduri S. Biomedical applications of electrospun nanofibers: Drug and nanoparticle delivery. *Pharmaceutics.* 2019;11(5):248.
- [11] Smith S, Goode K, Delaney M, Struzyk A, Tansey N, Frey M. A comprehensive review of the covalent immobilization of biomolecules onto electrospun nanofibers. *Nanomaterials (Basel).* 2020;10(1):1.
- [12] Hai T, Wan X, Yu DG, Wang K, Yang Y, Liu ZP. Electrospun lipid-coated medicated nanocomposites for an improved drug sustained-release profile. *Mater Des.* 2019;162:70–9.
- [13] Singh B, Kim J, Shukla N, Lee J, Kim K, Park MH. Smart delivery platform using core-shell nanofibers for sequential drug release in wound healing. *ACS Appl Bio Mater.* 2023;6(3):2314–24.
- [14] Meenatchi V, Sood A, Bhaskar R, Han SS. Electrospun hydroxypropyl-β-cyclodextrin nanofibers loaded with anti-inflammatory drugs for potential therapeutic wound dressings. *J Mol Liq.* 2024;393:123558.
- [15] Fathollahipour S, Abouei Mehrizi A, Ghaee A, Koosha M. Electrospinning of PVA/chitosan nanocomposite nanofibers containing gelatin nanoparticles as a dual drug delivery system. *J Biomed Mater Res A.* 2015;103(12):3852–62.
- [16] Zhang X, Tang K, Zheng X. Electrospinning and crosslinking of COL/PVA nanofiber-microspheres containing salicylic acid for drug delivery. *J Bionic Eng.* 2016;13(1):143–9.
- [17] Vashisth P, Pruthi V. Synthesis and characterization of crosslinked gellan/PVA nanofibers for tissue engineering applications. *Mater Sci Eng C.* 2016;67:304–12.
- [18] Moydeen AM, Syed Ali Padusha M, Aboelfetoh EF, Al-Deyab SS, El-Newehy MH. Fabrication of electrospun poly(vinyl alcohol)/dextran nanofibers via emulsion process as a drug delivery system: Kinetics and in vitro release study. *Int J Biol Macromol.* 2018;116:1250–9.
- [19] Cui Z, Zheng Z, Lin L, Si J, Wang Q, Peng X, et al. Electrospinning and crosslinking of polyvinyl alcohol/chitosan composite nanofiber for transdermal drug delivery. *Adv Polym Technol.* 2018;37:1917–28.
- [20] Rahmani F, Ziyadi H, Baghali M, Luo H, Ramakrishna S. Electrospun PVP/PVA nanofiber mat as a novel potential transdermal drug-delivery system for buprenorphine: A solution needed for pain management. *Appl Sci (Basel).* 2021;11(6):2779.
- [21] El Fawal G, Hong H, Song X, Wu J, Sun M, Zhang L, et al. Polyvinyl alcohol/hydroxyethylcellulose containing ethosomes as a scaffold for transdermal drug delivery applications. *Appl Biochem Biotechnol.* 2020;191(4):1624–37.
- [22] Shakiba M, Jahangiri P, Rahmani E, Hosseini SM, Bigham A, Foroozandeh A, et al. Drug-loaded carbon nanotube incorporated in nanofibers: A multifunctional nanocomposite for smart chronic wound healing. *ACS Appl Polym Mater.* 2023;5(11):5662–72.
- [23] Darabi NH, Kalaei M, Mazinani S, Khajavi R. GO/AgNW aided sustained release of ciprofloxacin loaded in starch/PVA nanocomposite mats for wound dressings application. *Int J Biol Macromol.* 2024;266:130977.
- [24] Elsherbini AM, Shalaby TI, Abdelmonsif DA, Rashed SA, Haroun M, Sabra SA. Tadalafil-loaded zein nanoparticles incorporated into pectin/PVA nanofibers as a diabetic wound dressing with enhanced angiogenic and healing properties. *J Drug Deliv Sci Technol.* 2023;89:105019.

- [25] Güngör S, Erdal MS, Aksu B. New formulation strategies in topical antifungal therapy. *J Cosmet Dermatol Sci Appl*. 2013;3(1):10–7.
- [26] Trommer H, Neubert RH. Overcoming the stratum corneum: The modulation of skin penetration. *Skin Pharmacol Physiol*. 2006;19(2):106–21.
- [27] Brown MB, Martin GP, Jones SA, Akomeah FK. Dermal and transdermal drug delivery systems: Current and future prospects. *Drug Deliv*. 2006;13(3):175–87.
- [28] Naik A, Kalia YN, Guy RH. Transdermal drug delivery: Overcoming the skin's barrier function. *Pharm Sci Technol Today*. 2000;3(9):318–26.
- [29] Zhang Z, Tsai PC, Ramezanli T, Michniak-Kohn BB. Polymeric nanoparticles-based topical delivery systems for the treatment of dermatological diseases. *Wiley Interdiscip Rev Nanomed Nanobiotechnol*. 2013;5(3):205–18.
- [30] Tavira M, Mousavi-Khattat M, Shakeran Z, Zarrabi A. PCL/gelatin nanofibers embedded with doxorubicin-loaded mesoporous silica nanoparticles/silver nanoparticles as an antibacterial and anti-melanoma cancer agent. *Int J Pharm*. 2023;642:123162.
- [31] Gizli N, Sert Çok S, Koç F. Aerogel, xerogel, and cryogel: Synthesis, surface chemistry, and properties-practical environmental applications and the future developments. In: Giannakoudakis D, Meili L, Anastopoulos I, editors. *Adv Mater Sustain Environ Remediat*. Amsterdam: Elsevier; 2022. p. 195–229.
- [32] Cuce E, Cuce PM, Wood CJ, Riffat SB. Toward aerogel-based thermal superinsulation in buildings: A comprehensive review. *Renew Sustain Energy Rev*. 2014;34:273–99.
- [33] Long JW, Swider-Lyons KE, Stroud RM, Rolison DR. Design of pore and matter architectures in manganese oxide charge-storage materials. *Electrochem Solid-State Lett*. 2000;3(10):453.
- [34] Reim M, Beck A, Körner W, Petricevic R, Glora M, Weth M, et al. Highly insulating aerogel glazing for solar energy usage. *Sol Energy*. 2002;72(1):21–9.
- [35] Amonette JE, Matyáš J. Functionalized silica aerogels for gas-phase purification, sensing, and catalysis: A review. *Microporous Mesoporous Mater*. 2017;250:100–19.
- [36] García-González CA, Sosnik A, Kalmár J, De Marco I, Erkey C, Concheiro A, et al. Aerogels in drug delivery: From design to application. *J Control Release*. 2021;332:40–63.
- [37] Liu H, Chu P, Li H, et al. Novel three-dimensional halloysite nanotubes/silica composite aerogels with enhanced mechanical strength and low thermal conductivity prepared at ambient pressure. *J Sol-Gel Sci Technol*. 2016;80:651–9.
- [38] Kaya G, Deveci H. Synergistic effects of silica aerogels/xerogels on properties of polymer composites: A review. *J Ind Eng Chem*. 2020;89:13–27.
- [39] Torres-Rodríguez J, Gutierrez-Cano V, Menelaou M, Kaštyl J, Cihlár J, Tkachenko S, et al. Rare-earth zirconate $\text{Ln}_2\text{Zr}_2\text{O}_7$ (Ln: La, Nd, Gd, and Dy) powders, xerogels, and aerogels: Preparation, structure, and properties. *Inorg Chem*. 2019;58(21):14467–77.
- [40] Tüysüz H, Schüth F. Ordered mesoporous materials as catalysts. In: Gates BC, Jentoft FC, editors. *Adv Catal*. Vol. 55. Cambridge (MA): Academic Press; 2012. p. 127–239.
- [41] Rajalekshmy G, Rekha M. Synthesis and evaluation of an alginate-methacrylate xerogel for insulin delivery towards wound healing applications. *Ther Deliv*. 2021;12:215–34.
- [42] Rafati A, Ebadi A, Bavafa S, Nowroozi A. Kinetic study, structural analysis and computational investigation of novel xerogel based on drug-PEG/SiO₂ for controlled release of enrofloxacin. *J Mol Liq*. 2018;266:733–42.
- [43] Križman K, Novak S, Kristl J, Majdič G, Drnovšek N. Long-acting silk fibroin xerogel delivery systems for controlled release of estradiol. *J Drug Deliv Sci Technol*. 2021;65:102701.
- [44] Zhou HJ, Teng SH, Zhou YB, Qian HS. Green strategy to develop novel drug-containing poly(ϵ -caprolactone)-chitosan-silica xerogel hybrid fibers for biomedical applications. *J Nanomater*. 2020;2020:6659287.
- [45] Palak H, Gürbüz Yurtsever A, Kalaoğlu Altan Öİ, Erdal MS, Karagüzel Kayaoğlu B. Fabrication of polyvinyl alcohol nanofibrous webs containing mometasone furoate monohydrate and melatonin loaded silica xerogels for topical drug delivery: in vitro release study. *Journal of Textiles and Engineer*. 2025;32(138):95–104.