

Journal Homepage: www.geobioj.com

Georgian Biomaterials Journal



Mini-Review

Plant-derived biomaterials as sustainable platforms for controlled release dressings in drug-resistant wounds

Mahsa Borzouyan Dastjerdi ^{a*} , Mehrasa Nikandish ^b ^a College of Engineering, Science, and Environment, School of Engineering, The University of Newcastle, Newcastle, Australia.^b Faculty of Life Science and Medicine King's College London, London, UK.

ABSTRACT

The rising incidence of drug-resistant wound infections poses a major problem for modern healthcare, demanding innovative and sustainable solutions in wound care. Plant-based biomaterials have become promising alternatives for creating advanced wound dressings because of their natural biocompatibility, biodegradability, and rich supply of bioactive compounds with antimicrobial, antioxidant, and anti-inflammatory effects. These natural materials, like cellulose, lignin, and various plant extracts, can be engineered into hydrogels, films, and nanofiber scaffolds that resemble the extracellular matrix and keep a moist environment that promotes tissue regeneration. Additionally, embedding controlled release systems into plant-based dressings allows for the continuous and localized delivery of therapeutic agents, specifically targeting drug-resistant bacteria while reducing systemic side effects. This strategy not only improves wound healing outcomes but also addresses the urgent demand for eco-friendly, multifunctional dressings capable of overcoming the limitations of traditional antibiotics. This review showcases recent progress in plant-based biomaterials as sustainable platforms for controlled release dressings, and applications in Wound Healing.

©2025 UGPH

Peer review under responsibility of UGPH.

ARTICLE INFORMATION

Article History:

Received 1 April 2025

Received in revised form 7 June 2025

Accepted 23 June 2025

Keywords:

Plant-derived biomaterials

Controlled release

Drug delivery

Wound healing

Table of Contents:

1. Introduction.....	1
2. Plant-Derived Biomaterials.....	2
3. Mechanisms of Controlled Release.....	2
4. Applications in Wound Healing.....	3
5. Future Perspectives and Challenges.....	3
6. Conclusion.....	3
7. References.....	3

1. Introduction

Plant-derived biomaterials are increasingly being identified as a viable, environmentally sound alternative for advanced wound dressings, in particular, difficult-to-treat drug-resistant wounds [1, 2]. The increase in chronic wounds complicated by antimicrobial resistance presents a real challenge for health care providers. Therefore, it is necessary to find new approaches in addressing and resolving issues of infection control, which ensure that products are biocompatible, and environmentally friendly [3-5]. There are several advantages of using natural polymers derived from plants, including biodegradability, body compatibility and controlled drug delivery systems, which prolong their usefulness and make them excellent candidates for the development of next generation wound care products [6]. The switch

to eco-friendly wound dressings is in line with goals for health and the environment, focusing on using renewable resources and green chemistry to make materials [7-9]. Plant-based biomaterials, such as cellulose, alginate, and other polysaccharides, are processed using methods that are good for the environment, like enzymatic crosslinking with an eco-friendly solvent [10]. These eco-friendly methods have less of an effect on the environment while keeping or improving the effectiveness of the treatment. Adopting sustainable practices will not only reduce the carbon footprint of wound care but will also promote a cost-saving manufacturing method that can be used in large-scale production [7]. Plant-based biomaterials can be made to have many functions that are important for healing wounds, in addition to being environmentally friendly [11]. These functions include keeping the wound moist, helping gases exchange, soaking up fluids, and protecting the wound mechanically [12].

* Corresponding Author: Mahsa Borzouyan Dastjerdi, Email Address: Mahsa.BorzouyanDastjerdi@uon.edu.auDOI: <https://doi.org/10.62343/geobioj.2025.5>This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>)

They can also be made to release their contents slowly. Systems that send antimicrobial agents, growth factors, or other bioactive substances straight to the wound, which helps fight drug resistance and the growth of biofilms [13, 14]. These dressings help wounds heal faster by delivering drugs directly to the area and reducing side effects throughout the body [15]. Recent advances in biomaterial science have made it possible to combine plant-based polymers with nanotechnology and bioactive molecules. This has increased their ability to fight germs and help tissues heal [16, 17]. For example, composites that mix plant cellulose with natural antibacterial agents or nanoparticles have a lot of potential for getting rid of resistant bacterial strains and speeding up the healing of wounds [3, 6]. These changes show how natural biomaterials and advanced drug delivery systems can work together, which could lead to smarter, more effective wound dressings [18]. The current status of biomaterials derived from plants as environmentally friendly platforms for controlled release dressings is covered in this review. Their composition, manufacturing methods, antimicrobial strategies, and clinical importance in the treatment of drug-resistant wounds are all covered. Providing a comprehensive understanding of how plant-based materials can revolutionize wound care with sustainable, biocompatible, and efficacious therapeutic options is the goal of this review of recent developments and potential future directions.

2. Plant-Derived Biomaterials

Plant-derived biomaterials are natural substances obtained from plants, including cellulose, lignin, pectin, alginate, and nanocellulose [19, 20]. They are increasingly valued for their biocompatibility, biodegradability, renewability, and environmentally friendly properties [21, 22]. These features make them well-suited for various uses in biomedical engineering, tissue regeneration, wound care, drug delivery, food technology, cosmetics, environmental health, and energy fields [23]. The advantages of Plant-derived biomaterials are shown in Fig. 1. Also, Table 1 provide a concise overview of the main types, their biomedical relevance, and properties of Plant-Derived Biomaterials.

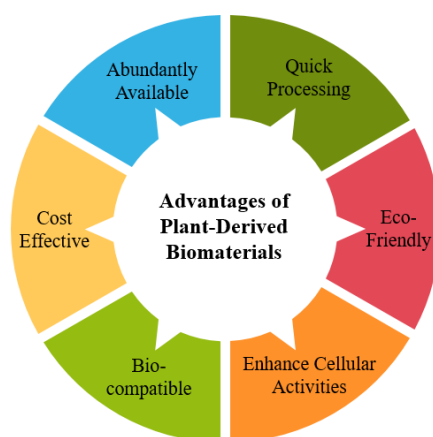


Fig. 1. Advantages of Plant-Derived Biomaterials

Table 1. Types and Characteristics of Plant-Derived Biomaterials

Type	Description	Source	Characteristics	References
Nanocellulose	Natural biopolymer with hierarchical fibrillar structure	Wood, hemp, cotton, potato tuber, algae	High mechanical strength, biocompatible, biodegradable, forms nanocrystals	[24, 25]
Alginate	Polysaccharide from brown seaweed	Marine algae (brown algae)	Biocompatible, biodegradable, hydrogel-forming, low-cost, moderate cell adhesion	[24, 26]
Pectin	Polysaccharides typical of plant cell walls	Land plants	Used as a gelling agent, biocompatible and biodegradable	[27, 28]
Starch	Polysaccharide storage molecule	Plants like potato, corn	Polysaccharide, biodegradable, widely available	[24, 29, 30]
Agarose	Polysaccharide from red algae	Red algae	Thermoreversible gel, biocompatible, structurally supportive	[31]
Fucoidan	Sulfated polysaccharide from brown algae	Brown algae	Anti-inflammatory, anticoagulant properties; biomedical applications	[32]
Carrageenan	Sulfated polysaccharide from red seaweed	Red algae	Gel-forming and bioactive	[31, 33]
Protein-based Polymers	Plant-derived proteins	Plants	Biocompatible, biodegradable, useful in scaffolds	[34]
Extracellular Vesicles	Nano-sized vesicles released by plant cells	Plant cells	Used in drug delivery, signaling	[35]
Mucilage	Polysaccharide-rich gel-like substances from plants	Plants (seeds, leaves)	Biocompatible, biodegradable	[36-38]
Decellularized Scaffolds	Plant tissues processed to remove cells but retain structure	Whole plants (after cell removal)	Natural structural framework, biocompatible	[39]

3. Mechanisms of Controlled Release

Controlled release from plant-derived biomaterials typically relies on the physicochemical and structural properties of the biopolymer matrix, enabling the regulated and sustained delivery of encapsulated bioactive agents such as nutrients, drugs, or agrochemicals [41, 42]. One of the primary mechanisms involves diffusion-controlled release, where the encapsulated compound migrates through the biopolymer matrix as a result of a concentration gradient. The rate of this diffusion can be modified by manipulating the polymer's composition, molecular arrangement, and internal porosity, allowing the release profile to be tailored from rapid to sustained over prolonged periods [8, 41].

Another common mechanism is matrix swelling, found in hydrogels and other plant-based polymer systems [8, 43]. When exposed to aqueous environments, these materials absorb water and swell, thereby enabling the contained agents to gradually escape as the hydrogel network loosens. This process is influenced by the hydrophilicity and crosslink density of the polymer network, both of which can be engineered to achieve the desired release kinetics [44].

Degradative release is also important, especially for applications that require release triggered by environmental or biological stimuli [45, 46]. Plant-derived biomaterials, such as lignin or modified cellulose, can be designed to undergo controlled degradation, either through hydrolysis or enzymatic action [47]. As the polymer structure erodes, it releases the encapsulated bioactive compound, with the release rate determined by the rate of matrix breakdown [46, 48].

Stimuli-responsive or smart release systems provide advanced controllability by the use of external or environmental triggers [49, 50]. They also react by exposing or modifying the polymer (and hence the system) to an external stimulus such as a pH change, temperature change, or the presence of particular enzymes to enable a release of the active ingredient.

Whole Plant-Based Biomass	Bulk plant material used for composite biomaterials	Plants	Renewable, eco-friendly scaffold materials	[23, 40]
---------------------------	---	--------	--	----------

For example, a material with a matrix from plant sources could provide a selective release when some enzyme sensitive linker or crosslinks are incorporated, adding a biological signal as an external signal, which is valuable for applications in targeted drug delivery or precision agriculture [51]. The versatility in tuning these mechanisms, by varying the plant biopolymer type, structural modification, or environmental responsiveness, makes plant-derived biomaterials highly attractive for developing safe, effective, and sustainable controlled release systems for applications across biomedicine, agriculture, and food technology [52].

4. Applications in Wound Healing

Applications of plant-derived biomaterials in wound healing have gained significant attention due to their natural properties, biocompatibility, biodegradability, and ability to mimic the extracellular matrix (ECM), which supports tissue regeneration and repair [53, 54]. These biomaterials are used to create wound dressings and formulations that enhance the healing process, especially by promoting cell adhesion, proliferation, moisture retention, and antimicrobial activity [55].

One example is a study by Buzzi et al [56] on the therapeutic use of *Calendula officinalis* extract in diabetic foot ulcers (DFUs), where clinical studies have shown that topical application of its hydroethanolic extract, combined with appropriate dressing, results in significant wound closure rates (up to 78% within 30 weeks), reduces exudate, and diminishes necrotic tissue without adverse effects.

The current use of plant-derived dressings in wound care reflects significant advances leveraging natural compounds for enhanced healing properties [57-59]. Various biopolymeric formulations incorporating herbal bioactives such as Aloe vera (AV), plant extracts, and polysaccharides are being developed into modern wound dressings like hydrogels, films, creams, and nanofiber scaffolds [60]. These dressings not only provide traditional protection but actively promote wound healing through antimicrobial, antioxidant, and tissue-regenerating effects [61, 62].

Hydrogels containing natural polymers and plant extracts maintain a moist wound environment that accelerates epidermal regeneration, reduces infection, and stimulates autolytic debridement [63]. For example, AV-loaded hydrogels combined with polymers like sodium hyaluronate and chitosan have demonstrated efficacy in skin tissue regeneration within days [64].

Film dressings infused with extracts from plants like *Plantago lanceolata*, *Calendula officinalis*, *Lawsonia inermis*, and *Moringa oleifera* have been optimized for properties such as antioxidant and anti-inflammatory activity, enhancing wound closure and tissue repair [65]. These polymer-based films show promising in vitro and in vivo results in accelerating healing processes [66].

Cutting-edge research also focuses on plant-based materials for transdermal delivery, exploiting biocompatible gums, mucilages, and secondary metabolites with versatile pharmacological benefits [4]. Secondary plant metabolites with antimicrobial and bioactive properties are integrated into dressings to improve therapeutic effects while leveraging the natural biodegradability and cost-effectiveness of plant-derived components [58].

Innovations include soy protein isolate-based dressings, such as NeuEsse Inc.'s OmegaSkin™, which degrade into beneficial amino acids that support cellular repair at the wound site [67]. Such bioactive, biodegradable dressings are particularly valuable for chronic and burn wounds, reducing pain and infection risk through minimal dressing changes [68, 69].

5. Future Perspectives and Challenges

Advances in materials science have enabled the design of modern wound dressings incorporating natural polymers with intrinsic antimicrobial, anti-inflammatory, and regenerative properties that align well with the complex biology of wound healing [70, 71]. These natural biomaterials, provide biocompatible matrices that facilitate cell adhesion, proliferation, moisture retention, and protection against infection, all critical for treating chronic and drug-resistant wounds [3]. An important future direction involves integrating

these plant-derived materials with smart bioactive components, such as antimicrobial phytochemicals, growth factors, and regenerative agents, to enhance therapeutic efficacy while reducing dependence on conventional antibiotics amid rising antimicrobial resistance [58, 72].

However, significant challenges remain before widespread clinical translation. Many bioactive dressings still lack rigorous clinical validation, with most studies conducted in vitro or in animal models [72]. Additionally, understanding the mechanisms of action of these natural compounds, their interactions with complex wound microenvironments, regulatory pathways to approval, scalability of production, affordability or cost-benefit to the efficacy, and integration into patient care protocols have yet to be addressed [73]. Also important are the opportunities for plant-derived wound dressings to support real-time monitoring of the wound and take action in response to smart dressing functions and/or dynamic conditions in the wound like infection or inflammation biomarkers and treatment [74].

6. Conclusion

Plant-based biomaterials represent a sustainably sourced and potentially powerful vehicle for controlled release dressings designed to treat drug-resistant wounds. Due to their natural compatibility with biologic systems, biodegradability, and bioactivity, including properties such as anti-microbial and anti-inflammatory behavior, plant-based biomaterials are ideal candidates for cutting-edge wound management products. These natural polymer materials can offer delivery of drug compounds with targeted performances, retain a boundary moisture level for healing, and contribute to a more rapid rate of tissue regeneration, without the risks and development of side effects, or resistance of synthetic systems. Furthermore, entrepreneurial application of plant-derived biomaterials as an element to other sources of biomaterials has been shown to develop mechanical strength with better therapeutic applications in the wound healing models. The use of plant-based biomaterials is in line with the emerging demand for environmentally-friendly, effective, and controllable wound dressings, particularly for the treatment of challenging infections, which include drug-resistant wounds.

Author Contributions

Mahsa Borzouyan: Conceptualization, Writing – original draft, Writing – review & editing; **Mehrasha Nikandish:** 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.

7. References

- [1] Zarepour A, Gok B, Kılıç YB, Khosravi A, Iravani S, Zarrabi A. Bacterial nanocelluloses as sustainable biomaterials for advanced wound healing and dressings. *Journal of Materials Chemistry B*. 2024. DOI: <https://doi.org/10.1039/d4tb01024h>.
- [2] Das JJ, Bal T. pH factors in chronic wound and pH-responsive polysaccharide-based hydrogel dressings. *International Journal of Biological Macromolecules*. 2024;279:135118. DOI: <https://doi.org/10.1016/j.ijbiomac.2024.135118>.

- [3] Ansari M, Darvishi A. A review of the current state of natural biomaterials in wound healing applications. *Frontiers in bioengineering and biotechnology*. 2024;12:1309541. DOI: <https://doi.org/10.3389/fbioe.2024.1309541>.
- [4] Isopencu GO, Covaliu-Mierla C-I, Deleanu I-M. From plants to wound dressing and transdermal delivery of bioactive compounds. *Plants*. 2023;12(14):2661. DOI: <https://doi.org/10.3390/plants12142661>.
- [5] 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>.
- [6] Miron A, Giurcaneanu C, Mihai MM, Beiu C, Voiculescu VM, Popescu MN, et al. Antimicrobial biomaterials for chronic wound care. *Pharmaceutics*. 2023;15(6):1606. DOI: <https://doi.org/10.3390/pharmaceutics15061606>.
- [7] Gupta MN, Rangaraju A, Ambre P. Sustainable dressings for wound healing. *Biotechnology for Sustainable Materials*. 2025;2(1):1. DOI: <https://doi.org/10.1186/s44316-024-00023-w>.
- [8] Bakhtiari A, Arabuli L, Sadeghi F, Tamimi N, Hosseinzadeh J, Rad AJ, et al. Smart biomaterial composites for controlled drug release: mechanisms and applications. *Journal of Composites and Compounds*. 2023;5(17). DOI: <https://doi.org/10.61186/jcc.5.4.3>.
- [9] Niazvand F, Cheshmi A, Zand M, NasrAzadani R, Kumari B, Raza A, et al. An overview of the development of composites containing Mg and Zn for drug delivery. *Journal of Composites and Compounds*. 2020;2(5):193-204. DOI: <https://doi.org/10.29252/jcc.2.4.4>.
- [10] Maiti S, Maji B, Yadav H. Progress on green crosslinking of polysaccharide hydrogels for drug delivery and tissue engineering applications. *Carbohydrate Polymers*. 2024;326:121584. DOI: <https://doi.org/10.1016/j.carbpol.2023.121584>.
- [11] Prasathkumar M, Sadhasivam S. Chitosan/Hyaluronic acid/Alginate and an assorted polymers loaded with honey, plant, and marine compounds for progressive wound healing—Know-how. *International Journal of Biological Macromolecules*. 2021;186:656-85. DOI: <https://doi.org/10.1016/j.ijbiomac.2021.07.067>.
- [12] Nosrati H, Khodaei M, Alizadeh Z, Banitalebi-Dehkordi M. Cationic, anionic and neutral polysaccharides for skin tissue engineering and wound healing applications. *International journal of biological macromolecules*. 2021;192:298-322. DOI: <https://doi.org/10.1016/j.ijbiomac.2021.10.013>.
- [13] Ahmadi M, Sabzini M, Rastgordani S, Farazin A. Optimizing wound healing: Examining the influence of biopolymers through a comprehensive review of nanohydrogel-embedded nanoparticles in advancing regenerative medicine. *The International Journal of Lower Extremity Wounds*. 2024;15347346241244890. DOI: <https://doi.org/10.1177/15347346241244890>.
- [14] Dey R, Mukherjee R, Biswas S, Haldar J. Stimuli-responsive release-active dressing: A promising solution for eradicating biofilm-mediated wound infections. *ACS Applied Materials & Interfaces*. 2024;16(29):37795-805. DOI: <https://doi.org/10.1021/acsami.4c09820>.
- [15] Walther M, Vestweber PK, Kühn S, Rieger U, Schäfer J, Münch C, et al. Bioactive insulin-loaded electrospun wound dressings for localized drug delivery and stimulation of protein expression associated with wound healing. *Molecular Pharmaceutics*. 2022;20(1):241-54. DOI: <https://doi.org/10.1021/acs.molpharmaceut.2c00610>.
- [16] Scafa Udrisre A, Niculescu A-G, Iliuță L, Bajeu T, Georgescu A, Grumescescu AM, et al. Progress in biomaterials for cardiac tissue engineering and regeneration. *Polymers*. 2023;15(5):1177. DOI: <https://doi.org/10.3390/polym15051177>.
- [17] Shirbacheh A, Shirbacheh K, Karbalae M. Natural Biomaterial Composites for Tissue Engineering: Challenges and Opportunities. *Journal of Composites and Compounds*. 2024;6(20). DOI: <https://doi.org/10.61186/jcc.6.3.4>.
- [18] Zhao ZQ, Liang L, Jing LY, Liu Y, Zhang YH, Shahbazi M-A, et al. Microneedles: a novel strategy for wound management. *Biomaterials Science*. 2023;11(13):4430-51. DOI: <https://doi.org/10.1039/D3BM00262D>.
- [19] Yudishtar, Shams R, Dash KK. Polysaccharide nanoparticles as building blocks for food processing applications: A comprehensive review. *Food Science and Biotechnology*. 2025;34(3):527-46. DOI: <https://doi.org/10.1007/s10068-024-01695-w>.
- [20] Ciriminna R, Petri GL, Angellotti G, Fontananova E, Luque R, Pagliaro M. Nanocellulose and microcrystalline cellulose from citrus processing waste: A review. *International Journal of Biological Macromolecules*. 2024;281:135865. DOI: <https://doi.org/10.1016/j.ijbiomac.2024.135865>.
- [21] Mokheena TC, Sefadi JS, Sadiku ER, John MJ, Mochane MJ, Mtibe A. Thermoplastic processing of PLA/cellulose nanomaterials composites. *Polymers*. 2018;10(12):1363. DOI: <https://doi.org/10.3390/polym10121363>.
- [22] Tammina SK, Priyadarshi R, Khan A, Manzoor A, Rahman RSHA, Banat F. Recent developments in alginate-based nanocomposite coatings and films for biodegradable food packaging applications. *International Journal of Biological Macromolecules*. 2025;139480. DOI: <https://doi.org/10.1016/j.ijbiomac.2025.139480>.
- [23] Li L, Zhong D, Wang S, Zhou M. Plant-derived materials for biomedical applications. *Nanoscale*. 2025;17(2):722-39. DOI: <https://doi.org/10.1039/D4NR03057E>.
- [24] Jovic TH, Kungwengwe G, Mills AC, Whitaker IS. Plant-derived biomaterials: a review of 3D bioprinting and biomedical applications. *Frontiers in Mechanical Engineering*. 2019;5:19. DOI: <https://doi.org/10.3389/fmech.2019.00019>.
- [25] Fu Y, Lin Q, Lan R, Shao Z. Ultra-Strong Protein-Based Hydrogels via Promoting Intermolecular Entanglement of the Amorphous Region. *Small*. 2024;20(48):2403376. DOI: <https://doi.org/10.1002/smll.202403376>.
- [26] Hao Y, Zheng W, Sun Z, Zhang D, Sui K, Shen P, et al. Marine polysaccharide-based composite hydrogels containing fucoidan: Preparation, physicochemical characterization, and biocompatible evaluation. *International Journal of Biological Macromolecules*. 2021;183:1978-86. DOI: <https://doi.org/10.1016/j.ijbiomac.2021.05.190>.
- [27] Zhang H, Xiao L, Qin S, Kuang Z, Wan M, Li Z, et al. Heterogeneity in Mechanical Properties of Plant Cell Walls. *Plants*. 2024;13(24):3561. DOI: <https://doi.org/10.3390/plants13243561>.
- [28] Pauly M, Keegstra K. Biosynthesis of the plant cell wall matrix polysaccharide xyloglucan. *Annual review of plant biology*. 2016;67(1):235-59. DOI: <https://doi.org/10.1146/annurev-arplant-043015-112222>.
- [29] Korbecka-Glinka G, Piekarska K, Wiśniewska-Wrona M. The use of carbohydrate biopolymers in plant protection against pathogenic fungi. *Polymers*. 2022;14(14):2854. DOI: <https://doi.org/10.3390/polym14142854>.
- [30] Asl MA, Mohammadalipour M, Karbasi S. Experimental investigation of governing parameters in the electrospinning of poly (3-hydroxybutyrate)-starch scaffolds: structural characterization. *J Compos Compd*. 2022;4(10):4-12. DOI: <https://doi.org/10.52547/jcc.4.1.2>.
- [31] Dai Y, Qiao K, Li D, Isingizwe P, Liu H, Liu Y, et al. Plant-derived biomaterials and their potential in cardiac tissue repair. *Advanced healthcare materials*. 2023;12(20):2202827. DOI: <https://doi.org/10.1002/adhm.202202827>.
- [32] Usov AI, Bilan MI, Ustyuzhanina NE, Nifantiev NE. Fucoidans of brown algae: Comparison of sulfated polysaccharides from *Fucus vesiculosus* and *Ascophyllum nodosum*. *Marine Drugs*. 2022;20(10):638. DOI: <https://doi.org/10.3390/md20100638>.
- [33] Lee ZJ, Xie C, Ng K, Suleria HA. Unraveling the bioactive interplay: Seaweed polysaccharide, polyphenol and their gut modulation effect. *Critical Reviews in Food Science and Nutrition*. 2025;65(2):382-405. DOI: <https://doi.org/10.1080/10408398.2023.2274453>.
- [34] Zahmanova G, Aljabali AA, Takova K, Minkov G, Tambuwala MM, Minkov I, et al. Green biotics: harnessing the power of plants to produce pharmaceuticals. *International journal of molecular sciences*. 2023;24(24):17575. DOI: <https://doi.org/10.3390/ijms242417575>.
- [35] Rutter BD, Innes RW. Extracellular vesicles in phytopathogenic fungi. *Extracellular Vesicles and Circulating Nucleic Acids*. 2023;4(1):90. DOI: <https://doi.org/10.20517/evcna.2023.04>.
- [36] Pozzo T, Higdon SM, Pattathil S, Hahn MG, Bennett AB. Characterization of novel glycosyl hydrolases discovered by cell wall glycan directed monoclonal antibody screening and metagenome analysis of maize aerial root mucilage. *PLoS One*. 2018;13(9):e0204525. DOI: <https://doi.org/10.1371/journal.pone.0204525>.
- [37] Cowley JM, Herliana L, Neumann KA, Ciani S, Cerne V, Burton RA. A small-scale fractionation pipeline for rapid analysis of seed mucilage characteristics. *Plant Methods*. 2020;16(1):20. DOI: <https://doi.org/10.1186/s13007-020-00569-6>.
- [38] Kokubun T. Occurrence of myo-inositol and alkyl-substituted polysaccharide in the prey-trapping mucilage of *Drosera capensis*. *The Science of Nature*. 2017;104(9):83. DOI: <https://doi.org/10.1007/s00114-017-1502-4>.
- [39] Chen Z, Xiong W, Guo Y, Jin X, Wang L, Ge C, et al. Three-dimensional pore structure of the decellularized parsley scaffold regulates myogenic differentiation for cell cultured meat. *Journal of Food Science*. 2024;89(9):5646-58. DOI: <https://doi.org/10.1111/1750-3841.17218>.
- [40] Ali N, Zhang Q, Liu Z-Y, Li F-L, Lu M, Fang X-C. Emerging technologies for the pretreatment of lignocellulosic materials for bio-based products. *Applied Microbiology and Biotechnology*. 2020;104(2):455-73. DOI: <https://doi.org/10.1007/s00253-019-10158-w>.
- [41] Lee P, Lin X, Khan F, Bennett AE, Winter JO. Translating controlled release systems from biomedicine to agriculture. *Frontiers in Biomaterials Science*. 2022;1:1011877. DOI: <https://doi.org/10.3389/fbio.2022.1011877>.
- [42] Trucillo P. Biomaterials for drug delivery and human applications. *Materials*. 2024;17(2):456. DOI: <https://doi.org/10.3390/ma17020456>.
- [43] Strankowska J, Grzywińska M, Łęgowska E, Józefowicz M, Strankowski M. Transport Mechanism of Paracetamol (Acetaminophen) in Polyurethane Nanocomposite Hydrogel Patches—Cloisite® 30B Influence on the Drug Release and Swelling Processes. *Materials*. 2023;17(1):40. DOI: <https://doi.org/10.3390/ma17010040>.
- [44] Young DA, Pimentel MB, Lima LD, Custodio AF, Lo WC, Chen S-C, et al. Design and characterization of hydrogel nanoparticles with tunable network characteristics for sustained release of a VEGF-mimetic peptide. *Biomaterials Science*. 2017;5(10):2079-92. DOI: <https://doi.org/10.1039/c7bm00359e>.
- [45] Do HD, Couillaud BM, Doan B-T, Corvis Y, Mignet N. Advances on non-invasive physically triggered nucleic acid delivery from nanocarriers. *Advanced drug delivery reviews*. 2019;138:3-17. DOI: <https://doi.org/10.1016/j.addr.2018.10.006>.
- [46] Chowdhury MA. The controlled release of bioactive compounds from lignin and lignin-based biopolymer matrices. *International journal of biological macromolecules*. 2014;65:136-47. DOI: <https://doi.org/10.1016/j.ijbiomac.2014.01.012>.
- [47] Ko JK, Um Y, Park Y-C, Seo J-H, Kim KH. Compounds inhibiting the bioconversion of hydrothermally pretreated lignocellulose. *Applied microbiology and biotechnology*. 2015;99(10):4201-12. DOI: <https://doi.org/10.1007/s00253-015-6595-0>.
- [48] Kamaly N, Yameen B, Wu J, Farokhzad OC. Degradable controlled-release polymers and polymeric nanoparticles: mechanisms of controlling drug release. *Chemical reviews*. 2016;116(4):2602-63. DOI: <https://doi.org/10.1021/acs.chemrev.5b00346>.
- [49] Mathew AP, Cho K-H, Uthaman S, Cho C-S, Park I-K. Stimuli-regulated smart polymeric systems for gene therapy. *Polymers*. 2017;9(4):152. DOI: <https://doi.org/10.3390/polym9040152>.
- [50] 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>.
- [51] Minehan RL, Del Borgo MP. Controlled release of therapeutics from enzyme-responsive biomaterials. *Frontiers in Biomaterials Science*. 2022;1:916985. DOI: <https://doi.org/10.3389/fbio.2022.916985>.

- [52] Sabaghi M, Tavasoli S, Hoseyni SZ, Mozafari M, Degraeve P, Katouzian I. A critical review on approaches to regulate the release rate of bioactive compounds from biopolymeric matrices. *Food Chemistry*. 2022;382:132411. DOI: <https://doi.org/10.1016/j.foodchem.2022.132411>.
- [53] Palanisamy CP, Cui B, Zhang H, Gunasekaran VP, Ariyo AL, Jayaraman S, et al. A critical review on starch-based electrospun nanofibrous scaffolds for wound healing application. *International Journal of Biological Macromolecules*. 2022;222:1852-60. DOI: <https://doi.org/10.1016/j.ijbiomac.2022.09.274>.
- [54] Song Y, You Y, Xu X, Lu J, Huang X, Zhang J, et al. Adipose-derived mesenchymal stem cell-derived exosomes biopotentiates extracellular matrix hydrogels accelerate diabetic wound healing and skin regeneration. *Advanced Science*. 2023;10(30):2304023. DOI: <https://doi.org/10.1002/adv.202304023>.
- [55] Li H, Wang Y, Kang Y, He Y, Nie J, Ma C, et al. Novel injectable self-healing bifunctionalized chitosan hydrogel with cell proliferation and antibacterial activity for promoting wound healing. *International Journal of Biological Macromolecules*. 2025;306:141259. DOI: <https://doi.org/10.1016/j.ijbiomac.2025.141259>.
- [56] Buzzi M, de Freitas F, Winter M. A prospective, descriptive study to assess the clinical benefits of using *Calendula officinalis* hydroglycolic extract for the topical treatment of diabetic foot ulcers. *Ostomy Wound Manage*. 2016;62(3):8-24. Available from: <https://pubmed.ncbi.nlm.nih.gov/26978856/>.
- [57] Borges A, Calvo MLM, Vaz JA, Calheta RC. Enhancing Wound Healing: A Comprehensive Review of Sericin and *Chelidonium majus* L. as Potential Dressings. *Materials*. 2024;17(17):4199. DOI: <https://doi.org/10.3390/ma17174199>.
- [58] Andreu V, Mendoza G, Arruebo M, Irusta S. Smart dressings based on nanostructured fibers containing natural origin antimicrobial, anti-inflammatory, and regenerative compounds. *Materials*. 2015;8(8):5154-93. DOI: <https://doi.org/10.3390/ma8085154>.
- [59] Firoozbahr M, Kingshott P, Palombo EA, Zaferanloo B. Recent advances in using natural antibacterial additives in bioactive wound dressings. *Pharmaceutics*. 2023;15(2):644. DOI: <https://doi.org/10.3390/pharmaceutics15020644>.
- [60] Liang J, Cui L, Li J, Guan S, Zhang K, Li J. Aloe vera: a medicinal plant used in skin wound healing. *Tissue Engineering Part B: Reviews*. 2021;27(5):455-74. DOI: <https://doi.org/10.1089/ten.teb.2020.0236>.
- [61] Yaron JR, Gosangi M, Pallod S, Rege K. In situ light-activated materials for skin wound healing and repair: A narrative review. *Bioengineering & Translational Medicine*. 2024;9(3):e10637. DOI: <https://doi.org/10.1002/btm2.10637>.
- [62] Liu H, Wang C, Li C, Qin Y, Wang Z, Yang F, et al. A functional chitosan-based hydrogel as a wound dressing and drug delivery system in the treatment of wound healing. *RSC advances*. 2018;8(14):7533-49. DOI: <https://doi.org/10.1039/c7ra13510f>.
- [63] Tahneh AN, Dashtipour B, Ghofrani A, Nejad SK. Crosslinked natural hydrogels for drug delivery systems. *Journal of Composites and Compounds*. 2022;4(11):109-23. DOI: <https://doi.org/10.52547/jcc.4.2.6>.
- [64] Lisková J, Bačáková L, Skwarczyńska AL, Musiał O, Bliznuk V, De Schampelaere K, et al. Development of thermosensitive hydrogels of chitosan, sodium and magnesium glycerophosphate for bone regeneration applications. *Journal of Functional Biomaterials*. 2015;6(2):192-203. DOI: <https://doi.org/10.3390/jfb6020192>.
- [65] Jessy Mercy D, Thirumalai A, Udayakumar S, Deepika B, Janani G, Girigoswami A, et al. Enhancing wound healing with nanohydrogel-entrapped plant extracts and nanosilver: an in vitro investigation. *Molecules*. 2024;29(21):5004. DOI: <https://doi.org/10.3390/molecules29215004>.
- [66] Nozari M, Gholizadeh M, Oghani FZ, Tahvildari K. Studies on novel chitosan/alginate and chitosan/bentonite flexible films incorporated with ZnO nano particles for accelerating dermal burn healing: In vivo and in vitro evaluation. *International Journal of Biological Macromolecules*. 2021;184:235-49. DOI: <https://doi.org/10.1016/j.ijbiomac.2021.06.066>.
- [67] Zhao W, Yang X, Li L. Soy protein-based wound dressings: a review of their preparation, properties, and perspectives. *ACS Applied Materials & Interfaces*. 2024;16(31):40356-70. DOI: <https://doi.org/10.1021/acsami.4c05106>.
- [68] Cui R, Zhang L, Ou R, Xu Y, Xu L, Zhan X-Y, et al. Polysaccharide-based hydrogels for wound dressing: Design considerations and clinical applications. *Frontiers in bioengineering and biotechnology*. 2022;10:845735. DOI: <https://doi.org/10.3389/fbioe.2022.845735>.
- [69] Daristotle JL, Lau LW, Erdi M, Hunter J, Djoum Jr A, Srinivasan P, et al. Sprayable and biodegradable, intrinsically adhesive wound dressing with antimicrobial properties. *Bioengineering & translational medicine*. 2020;5(1):e10149. DOI: <https://doi.org/10.1002/btm2.10149>.
- [70] Luneva O, Olekhovich R, Uspenskaya M. Bilayer hydrogels for wound dressing and tissue engineering. *Polymers*. 2022;14(15):3135. DOI: <https://doi.org/10.3390/polym14153135>.
- [71] Jangra N, Singla A, Puri V, Dheer D, Chopra H, Malik T, et al. Herbal bioactive-loaded biopolymeric formulations for wound healing applications. *RSC advances*. 2025;15(16):12402-42. DOI: <https://doi.org/10.1039/d4ra08604j>.
- [72] Nur MG, Rahman M, Dip TM, Hossain MH, Hossain NB, Baratchi S, et al. Recent advances in bioactive wound dressings. *Wound Repair and Regeneration*. 2025;33(1):e13233. DOI: <https://doi.org/10.1111/wrr.13233>.
- [73] Georgescu M, C Chifiriuc M, Marutescu L, Gheorghe I, Lazar V, Bolocan A, et al. Bioactive wound dressings for the management of chronic wounds. *Current Organic Chemistry*. 2017;21(1):53-63. DOI: <http://dx.doi.org/10.2174/1385272820666160510171040>.
- [74] Pang Q, Lou D, Li S, Wang G, Qiao B, Dong S, et al. Smart flexible electronics-integrated wound dressing for real-time monitoring and on-demand treatment of infected wounds. *Advanced Science*. 2020;7(6):1902673. DOI: <https://doi.org/10.1002/adv.201902673>.