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Mini-Review

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

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A B S T R A C T

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.

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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].

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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.

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.

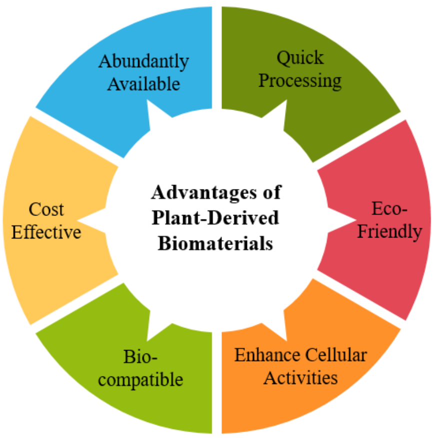

Fig. 1. Advantages of Plant-Derived Biomaterials

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]

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; **Mehrasa 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.

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