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Review Article

Mucilage-Based Nanocomposite Film: Novel Herbal Biomaterial for Wound Healing

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ABSTRACT

Healing of wounds is a highly intricate and dynamic process that depends on creating the right conditions for tissue repair and regeneration. Traditional wound dressings often provide limited benefits because they may not maintain proper moisture levels, lack antimicrobial action, or fail to deliver bioactive support; factors that can slow healing and increase the risk of infection. In recent years, natural polymers of plant origin have attracted attention as eco-friendly and biocompatible alternatives. Among them, mucilage, a polysaccharide obtained from various medicinal plants, has shown great promise due to its excellent film-forming ability, biodegradability, and inherent therapeutic properties. When mucilage is combined with nanoparticles or herbal bioactive to form nanocomposite films, its properties are significantly enhanced, including mechanical strength, moisture retention, antimicrobial activity, and controlled release of drugs. These multifunctional films create a favourable environment for wound repair by protecting against microbial invasion and promoting faster tissue regeneration. This work highlights the potential of mucilage-based nanocomposite films as innovative herbal biomaterials, discussing their preparation, structural characteristics, and application in wound care. The integration of natural polymers with nanotechnology presents a safe, cost-effective, and sustainable strategy for next-generation wound management solutions.

INTRODUCTION

Plant-derived polymeric materials are gaining significant attention across the food, pharmaceutical, and cosmetic industries due to their versatile properties—such as thickening,

emulsifying, water retention, coating, and film-forming capabilities (1). Driven by growing concerns about the environmental impact and potential health effects of plastic-based synthetic polymers, the search for biodegradable, eco-

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friendly, biocompatible, and non-toxic alternatives has gained significant momentum.

In advanced wound care, there is a rising demand for dressings that can actively participate in the healing process, rather than merely serving as a barrier. Bio-based films and scaffolds, particularly those derived from natural sources, offer a sustainable and therapeutically beneficial alternative. The focus has shifted to materials that can maintain an optimal moist wound environment, control infection, and provide sustained release of healing agents. This review focuses specifically on the emerging role of plant mucilages combined with nanotechnology to create novel nanocomposite films for superior wound management. (Mujtaba et al., 2019)

2. Mucilage as a Natural Biopolymer: -

Among the many natural biopolymers explored for wound dressing applications, plant-based mucilaginous substances have emerged as promising candidates. Their appeal lies in being low-cost, widely available, and environmentally friendly, along with offering benefits like biocompatibility, biodegradability, and inherent antimicrobial and antioxidant properties. One such plant, okra (*Abelmoschus esculentus*), from the Malvaceae family, has gained attention in medical research for its rich mucilage and impressive nutritional profile, which includes carbohydrates, proteins, vitamins, minerals, and trace elements. Beyond its nutritional value, okra contains active compounds such as tannins, saponins, flavonoids, and alkaloids, which have demonstrated a range of therapeutic effects—including antidiabetic, antioxidant, antibacterial, anticancer, analgesic, and anti-inflammatory activities (Tosif et al., 2021).

Methyl cellulose (MC), a naturally derived polymer and cellulose derivative, is another

material of interest due to its abundance and water solubility. Its popularity is growing, especially in the development of biomaterials, thanks to its affordability, ease of processing, and clear, stable properties. MC is extensively used across various industries—including food, pharmaceuticals, ceramics, cosmetics, paints, and construction—for its functions as a binder, coating, thickener, emulsifier, and stabilizer. Its strong mechanical properties and chemical resilience make it particularly suitable for film formation. The high tensile strength of MC films is primarily due to hydrogen bonding, which also influences their hardness and brittleness. To enhance its performance further, MC is often combined with other natural or synthetic polymers to create composite materials with tailored properties (Sharafi et al., 2025).

3. Nanocomposite Film in Wound Healing: -

Nanocomposites are advanced materials formed by incorporating nanoparticles (nano-reinforcements) into a continuous polymer matrix. This integration significantly enhances the mechanical, barrier, and functional performance of the base material, making the resultant film highly effective for wound care. (Yudaev et al., 2022)

3.1. Role of Therapeutic Nanoparticles

Nanoparticles, particularly metal-based ones, are incorporated into mucilage matrices to provide potent antimicrobial activity and enhance tissue regeneration.

Silver Nanoparticles (AgNPs): AgNPs, especially those synthesized via green methods, are widely recognized for their strong broad-spectrum antibacterial activity, crucial for managing acute and chronic wounds and burns. Their mechanism primarily involves the generation of Reactive Oxygen Species (ROS),



which destroy bacterial cell walls (3). A challenge with AgNPs is their low colloidal stability, which is effectively overcome by using polyanionic biopolymers like mucilages and cellulose, which stabilize the particles through electrostatic repulsion (3).

Zinc Oxide Nanoparticles (ZnO NPs): ZnO NPs demonstrate significant potential by offering antimicrobial properties and actively promoting tissue regeneration. Studies have shown that ZnO NP-enhanced hydrogels can significantly accelerate wound closure, improve collagen fiber formation, and remain non-toxic to skin cells. The films typically exhibit porous structures, optimal swelling capacity, and high Water Vapor Transmission Rate (WVTR), which are critical for functional wound dressings (Yudaev et al., 2022)

4. General Formulation Strategies for Mucilage-Based Films

Reviewing the literature indicates that the majority of mucilage-based films and scaffolds are prepared using two primary techniques: Solvent Casting and Electrospinning.

4.1. Extraction and Preparation of Mucilage

Mucilage is typically extracted from plants using standard procedures which include:

1. Washing and removing non-mucilaginous parts (e.g., seeds, peel).
2. Crushing/soaking the material in water for hydration.
3. Heating the mixture to optimize mucilage release (e.g., at 60°C).
4. Filtering the solution (marc removal) and precipitating the polymer by adding a non-solvent, usually ethanol.
5. Drying and pulverizing the extracted polymer into a fine powder. (Mujtaba et al., 2019)

4.2. Nanocomposite Film Fabrication

The following general methods are used to fabricate the functional films:

Solvent Casting: This technique is simple and involves dissolving the mucilage and other polymers (e.g. CMC, gelatin) in a solvent (usually water), adding the dispersed nanoparticles (ZnO, AgNPs) and plasticizers (e.g., glycerol), degassing the mixture, and pouring it into a mold (e.g., Petri dish) to dry under controlled temperature and humidity (Biswas et al., 2023)

Electrospinning (ES): ES is highly valued for producing non-woven nanofiber mats that structurally mimic the skin's extracellular matrix (ECM). The process uses a high-voltage electric field applied to a mucilage-polymer solution, stretching the fluid into a charged jet that solidifies into long, thin filaments upon solvent evaporation (6). ES is advantageous because it avoids heat, preserving the integrity of bioactive compounds. The resulting mats offer flexibility, high porosity, and a large surface area, supporting tissue repair and drug release (Forouzande et al., 2025)

5. Evaluation Parameter:-

Physiological parameter-

1. Dynamic Mechanical Analysis

Dynamic mechanical testing of the mucilage-based composite films (mucilage–CNF 3%, mucilage–CNF 6%) and mucilage without CNF as control was performed using a PYRIS Diamond DMA (Perkin-Elmer, Waltham, MA, USA) in tensile mode. The temperature sweep ranged from –30 °C to 100 °C at a heating rate of 2 °C/min, with a frequency of 1 Hz and amplitude of 10 μm. Film samples were prepared with dimensions of approximately 20 mm in length, 5 mm in width, and 40–50 μm in thickness.



2. Tensile Properties

To study the non-linear mechanical response of the films, tensile tests were conducted on an Instron universal testing machine equipped with a 100 N load cell. Tests were carried out at 25 °C using a crosshead speed of 10 mm/min. Samples were cut to uniform dimensions, and three specimens of each formulation were analyzed.

3. Transparency

Film transparency was evaluated over the wavelength range 200–800 nm using a UV–Visible spectrophotometer (Lambda 35, Perkin-Elmer).

4. Optical Properties

The optical transmittance of the mucilage–CNF composites (3%, 6%) and the control films was determined using a Shimadzu UV-3600 UV–VIS–NIR spectrophotometer. Measurements were recorded at room temperature, with a step interval of 1 nm, within the visible range (400–700 nm).

5. Contact Angle

Surface wettability of the films was characterized by measuring the contact angle using an OCA20 video-based contact angle analyzer (Data Physics). Measurements were carried out for mucilage–CNF 3%, mucilage–CNF 6%, and control samples.

6. Water Solubility

Water solubility was assessed to evaluate the films' resistance to dissolution. Rectangular pieces of each film (2 × 3 cm²) were dried at 60 °C until they reached a constant weight. Each specimen was then immersed in 20 mL of distilled water and stirred for 48 h at predefined time intervals. After soaking, the films were dried again to a constant

weight. The percentage of weight loss (%WL) was calculated using the formula (Mujtaba et al., 2019)

Biological Parameter:-

1. Antioxidant Activity of the Biocomposite Films (DPPH Assay):-

The antioxidant capacity of the CMC-based biocomposite films was assessed using the DPPH free radical scavenging method. For sample preparation, 0.1 g of each film was dissolved in 10 mL of distilled water. The mixture was vortexed for 3 minutes and then placed in a shaking incubator for 30 minutes to ensure thorough extraction. After incubation, the solution was centrifuged at 2700 × g for 10 minutes, and the clear supernatant was collected for analysis.

To determine the radical scavenging activity, 0.1 mL of the film extract was mixed with 3.9 mL of a 0.1 mM DPPH solution, producing a final DPPH concentration of 0.1 mM. The mixture was vortexed again and kept in a dark chamber to prevent light degradation. After the reaction period, absorbance was measured at 517 nm using a UV–Vis spectrophotometer (Model T60U, PG Instruments Ltd., Leicestershire, UK). The percentage of DPPH radical inhibition was calculated based on the decrease in absorbance.

2. Antimicrobial Activity of the Biocomposite Films :-

The antibacterial efficiency of the films was evaluated by measuring the inhibition zones against common pathogens, an important criterion for active packaging materials. The Kirby–Bauer disc diffusion method was employed according to Clinical and Laboratory Standards Institute (CLSI) guidelines.

Film samples were tested against *Staphylococcus aureus* (Gram-positive) and *Escherichia coli*



(Gram-negative). Overnight cultures of each bacterium were adjusted to approximately 1.0×10^6 CFU/mL (100 μ L) and spread onto Mueller–Hinton agar plates. Circular discs of the films (6 mm in diameter), prepared using a hole punch, were placed at the center of inoculated plates.

The plates were incubated at 37 °C for 24 h, after which the clear zones of growth inhibition surrounding the films were measured with a digital caliper. The inhibition zone was reported as the diameter of the clear area minus the diameter of the film disc. All experiments were performed in triplicate, and results were expressed as mean \pm standard deviation. (Biswas et al., 2023)

In vitro and In vivo :-

1. In-vitro antibacterial assessment

The antimicrobial potential of the developed composite dressings was tested using the disc-diffusion technique. Two bacterial strains were selected: *Escherichia coli* (Gram-negative) and *Staphylococcus aureus* (Gram-positive). All procedures were carried out in a Class II biological safety cabinet (Techno Scientific, Pakistan). Mueller–Hinton agar broth was prepared, sterilized in an autoclave at 121 °C and 15 psi for one hour, and then poured into sterile Petri dishes to solidify. The bacterial cultures were evenly spread over the agar surface using a sterile glass rod. Circular paper discs (5 mm diameter) impregnated with standard ciprofloxacin solution (10 μ L of 0.005%) and silver nanoparticles (10 μ L of 0.005% Ag) were positioned on the plates as references. Discs containing the composite dressings loaded with ciprofloxacin or silver nanoparticles were also placed, along with blank controls. The plates were incubated at 37 °C for 24 h, and the antibacterial effect was evaluated by measuring the zones of inhibition around each sample. (Massey et al., 2022)

2. In-vivo wound-healing study

To investigate the wound-repair efficiency of the composite dressings, Wistar rats (180–250 g) were used. Animals were anesthetized with ketamine (50 mg/kg) and diazepam (5 mg/kg) administered subcutaneously. Hair from the dorsal region was shaved, and the skin surface was disinfected with 75% ethanol. A full-thickness wound of approximately 1 \times 1 cm was carefully created with a sterile surgical blade. The rats were divided into five groups (three animals per group). The control wounds were covered with a commercial non-medicated gauze (Soft Surgi Gauze, Karim Industries, Lahore, Pakistan). The experimental groups (LRO2, LRO4, LRI5, and LRI7) received the composite wound dressings. After application, each rat was housed individually. Dressings were replaced on days 3, 5, 7, and 9, and photographs were taken at each interval to document healing progress. (Massey et al., 2022)

6. Recent Research and Case Studies :-

Recent literature underscores the potential of mucilage-based nanocomposites as versatile wound care systems:

Magnetic Nanobiocomposites: Flaxseed mucilage and silk fibroin combined with Fe₃O₄ magnetic nanoparticles have been developed as scaffolds. *In vivo* evaluations demonstrate good biocompatibility and support for tissue regeneration, with the magnetic component offering potential for controlled drug delivery or cell guidance.

Modified Hydrogels: Chemically modified okra mucilage hydrogels and sponges have been explored for sustained drug release. Studies show these carriers maintain a moist wound environment, accelerate closure compared to



controls, and exhibit favorable histological healing markers.

Multifunctional Films: Films combining balangu seed mucilage, gelatin, and TiO₂ nanoparticles demonstrate improved mechanical properties and multifunctional characteristics, including photocatalytic and antimicrobial activity, supporting their potential as next-generation dressings.(Radinekiyan et al., 2023)

7. Challenges and Future Perspective: -

Despite their therapeutic promise, mucilage-based nanocomposites face several hurdles related to large-scale adoption (Sharafi et al., 2025)

- **Source Variability:** The quality and yield of mucilage are heavily dependent on environmental conditions, plant variety, and extraction methods, leading to standardization challenges.
- **Toxicity and Contamination:** The potential for contamination by heavy metals from the plant source requires stringent safety assessments (e.g., OECD guidelines) before biomedical use.
- **Techno-Economic Hurdles:** Processing costs, limited market awareness, and the need for optimized formulations slow their widespread adoption compared to established synthetic materials.
- **Structural Instability:** While mucilage is biodegradable, its uncontrolled hydration, pH sensitivity, and thermal instability may limit its use in certain applications unless targeted chemical modifications are performed.

Future research should focus on chemical modification and cross-linking strategies to enhance the mechanical strength and stability of

mucilage, optimize the controlled release kinetics of loaded bioactives, and scale up production using GMP-compliant methods to fully realize the potential of these sustainable biomaterials.(Tosif et al., 2021)

CONCLUSION

Plant-derived biopolymers, especially mucilage, offer a sustainable and therapeutically active alternative to petroleum-based polymers for advanced wound care. Their incorporation with inorganic nanoparticles (ZnO, AgNPs) and other components significantly enhances crucial properties such as mechanical strength, moisture retention, antimicrobial activity, and biocompatibility. Research demonstrates that mucilage-based nanocomposites can actively support tissue regeneration and control infection, establishing them as innovative and promising wound dressings. While challenges related to source standardization, extraction complexity, and production costs remain, continued focus on advanced formulation and extensive {in vivo} validation will be key to transitioning these safe, multifunctional materials from the lab to clinical practice.

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