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"Carbopol-Based Hydrogel Formulation For A Topical Wound-Healing Gel Containing Moringa Oleifera Root Extract"

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Abstract

Diabetic wounds, particularly diabetic foot ulcers (DFUs), remain one of the most challenging complications of diabetes mellitus, affecting up to 25% of diabetic patients in their lifetime. Impaired wound healing arises from hyperglycemia-driven oxidative stress, chronic inflammation, angiogenic dysfunction, neuropathy, and a high susceptibility to infection. Conventional dressings often fail to address the multifactorial pathology of diabetic wounds. Hydrogel-based dressings have emerged as promising biomaterials, providing a moist wound environment, exudate absorption, and delivery of therapeutic agents. Carbopol, a synthetic cross-linked polyacrylic acid polymer, has demonstrated favourable physicochemical and rheological properties for hydrogel formulations. Meanwhile, Moringa oleifera, known as the "miracle tree," possesses root-derived phytochemicals such as flavonoids, alkaloids, tannins, and phenolic compounds, which exhibit potent antioxidant, anti-inflammatory, and antimicrobial effects. Incorporating Moringa oleifera root extract into Carbopol hydrogels offers a novel therapeutic strategy to accelerate wound closure, reduce infection, and modulate oxidative stress in diabetic wounds. This review explores the pathology of diabetic wounds, hydrogel-based interventions, formulation approaches, mechanisms of action,

evaluation, applications, and future perspectives for Carbopol-based hydrogels containing Moringa oleifera root extract.

Key Words

Moringa oleifera, Antioxidant activity, Anti-microbial activity, Diabetic foot ulcer, Phytochemicals, Chronic wound healing, Smart hydrogel dressing

1. Introduction

Diabetes mellitus (DM) is a chronic metabolic disorder characterised by persistent hyperglycaemia due to defects in insulin secretion, insulin action, or both [1]. The global prevalence of diabetes has risen dramatically, with estimates indicating that more than 460 million adults are currently living with diabetes worldwide, and projections suggest that this number will rise to 700 million by 2045 [1,2]. Among the multiple complications associated with uncontrolled diabetes, diabetic foot ulcers (DFUs) remain one of the most severe, affecting approximately 15–25% of diabetic patients during their lifetime [2,3]. These ulcers not only impair quality of life but also represent a leading cause of lower-limb amputations, with significant morbidity, mortality, and healthcare costs [3,4].

The pathogenesis of diabetic wounds is multifactorial and complex, involving persistent inflammation, oxidative stress, impaired angiogenesis, neuropathy, and recurrent infections [13–15]. Hyperglycaemia leads to the overproduction of reactive oxygen species (ROS), which induces cellular damage, impairs endothelial function, and delays tissue repair [16,17]. In addition, the reduced expression of growth factors and impaired extracellular matrix (ECM) remodelling contribute to poor wound closure [18]. Furthermore, microbial colonisation, particularly by resistant pathogens such as Staphylococcus aureus and Pseudomonas aeruginosa, exacerbates delayed healing and increases the risk of systemic infections [3,14]. Thus, the chronic wound environment in diabetes is characterised by an imbalance between tissue destruction and tissue repair [15].

Conventional wound dressings, including gauze, foams, and films, have been widely employed to manage DFUs [5,6]. However, these dressings are largely passive and do not provide bioactive intervention. They often fail to address the core pathological issues such as oxidative stress and microbial colonisation [5,6]. Therefore, there is a growing interest in advanced wound care technologies that not only protect the wound but also actively participate in the healing process. Among these, hydrogels have gained attention for their unique ability to maintain a moist wound environment, provide controlled drug release, and enhance tissue regeneration [5,19,22].

Hydrogels are three-dimensional, hydrophilic polymeric networks capable of absorbing large amounts of water while maintaining structural integrity [19]. They provide an ideal wound healing milieu by ensuring oxygen permeability, promoting autolytic debridement, and supporting cellular migration and proliferation [22,23]. Importantly, hydrogels can be engineered to incorporate bioactive agents, antioxidants, antimicrobials, and growth factors that directly modulate the wound microenvironment [8,19]. One of the most widely studied synthetic polymers for hydrogel preparation is Carbopol (carbomer), a high molecular weight, cross-linked acrylic acid polymer recognised for its excellent gelling, mucoadhesive, and biocompatible properties [7]. Carbopol hydrogels are stable, transparent, and capable of accommodating both hydrophilic and lipophilic drugs, making them a popular choice in topical formulations [7,19].

In parallel, plant-derived phytochemicals are increasingly being explored as therapeutic agents in wound healing due to their antioxidant, antimicrobial, and anti-inflammatory properties [31,34,41]. Among various medicinal plants, Moringa oleifera, commonly known as the “drumstick tree” or “miracle tree,” has

attracted significant attention for its wide range of pharmacological benefits [9,10]. Native to South Asia and widely cultivated in tropical regions, M. oleifera has been traditionally used for its nutritional and medicinal value. Different parts of the plant—leaves, seeds, bark, and roots—are rich in bioactive compounds such as flavonoids, alkaloids, tannins, saponins, and phenolic acids [10,12,37].

The root extract of Moringa oleifera in particular is reported to exhibit strong antioxidant and antimicrobial activities [11,12]. These properties are crucial in diabetic wound healing, where oxidative stress and infection act as major impediments to tissue repair [15,16]. Studies have demonstrated that Moringa extracts scavenge free radicals, reduce lipid peroxidation, and modulate inflammatory mediators [9,24,37]. Additionally, phytochemicals present in Moringa roots inhibit bacterial growth, including resistant strains, thus reducing wound bioburden [11,12]. Collectively, these bioactivities make Moringa oleifera an attractive candidate for integration into wound dressings.

Combining Carbopol hydrogels with Moringa oleifera root extract thus represents a promising bioactive formulation for diabetic wound management. The hydrogel provides the structural and physicochemical benefits of moisture retention, controlled drug release, and patient comfort, while the Moringa extract contributes natural antioxidant and antimicrobial properties [9,10,19,22]. This synergistic approach addresses multiple aspects of the diabetic wound pathology: reducing oxidative stress, controlling infection, modulating inflammation, and promoting tissue regeneration [15,16,42].

Moreover, the interest in herbal hydrogel dressings aligns with the global push toward sustainable, affordable, and culturally acceptable healthcare solutions, particularly in low- and middle-income countries where the burden of diabetes is high [20,31,41]. Unlike expensive synthetic bioactives or growth factor therapies, Moringa is widely available, inexpensive, and culturally accepted in many regions [9,10,37]. This positions Carbopol–Moringa hydrogels as not only a biomedical innovation but also a public health solution with high translational potential [50].

Recent research has explored similar herbal hydrogel formulations, incorporating plant extracts such as aloe vera, curcumin, and honey, with encouraging results in wound contraction and epithelialisation [26,31,36]. However, few studies have specifically focused on Moringa oleifera root extract within a Carbopol-based hydrogel system. This knowledge gap presents an opportunity for innovative pharmaceutical development, combining modern polymer technology with traditional herbal medicine.

In summary, the introduction of a Carbopol-based hydrogel loaded with Moringa oleifera root extract offers a multifaceted approach to diabetic wound management. It builds on the established benefits of hydrogels as advanced dressings [5,22], the unique gelling properties of Carbopol [7], and the phytochemical richness of Moringa oleifera [9,10,12]. By tackling oxidative stress, infection, and impaired tissue repair simultaneously, this formulation holds promise as a next-generation wound dressing. The subsequent sections of this review explore the pathology of diabetic wound healing, the advantages and limitations of hydrogel dressings, methods of preparation, mechanisms of action, evaluation techniques, applications, and future perspectives of Carbopol–Moringa hydrogels in diabetic wound care.

2. The pathology of diabetic wound healing

Normal wound healing

Wound repair is a dynamic, highly regulated process consisting of four overlapping stages: haemostasis, inflammation, proliferation, and remodelling [13]. Platelets, cytokines, growth factors, fibroblasts, and keratinocytes coordinate to form granulation tissue, re-epithelialise, and remodel the extracellular matrix (ECM) [14].

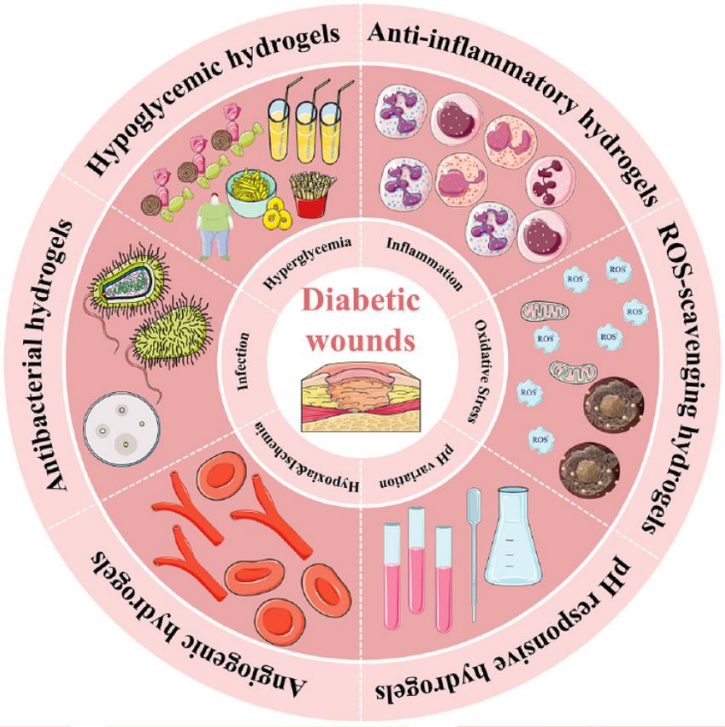


Fig.1 Types of Functional Hydrogels for Diabetic Wound Healing

Pathological changes in diabetes

Diabetic wounds exhibit several pathological impairments:

Prolonged inflammation: Hyperglycemia induces continuous production of pro-inflammatory cytokines (TNF-α, IL-1β, IL-6) with persistent neutrophil infiltration [15,16].

Oxidative stress: Diabetes enhances reactive oxygen species (ROS) production while impairing antioxidant defences, leading to DNA, lipid, and protein damage [16,17].

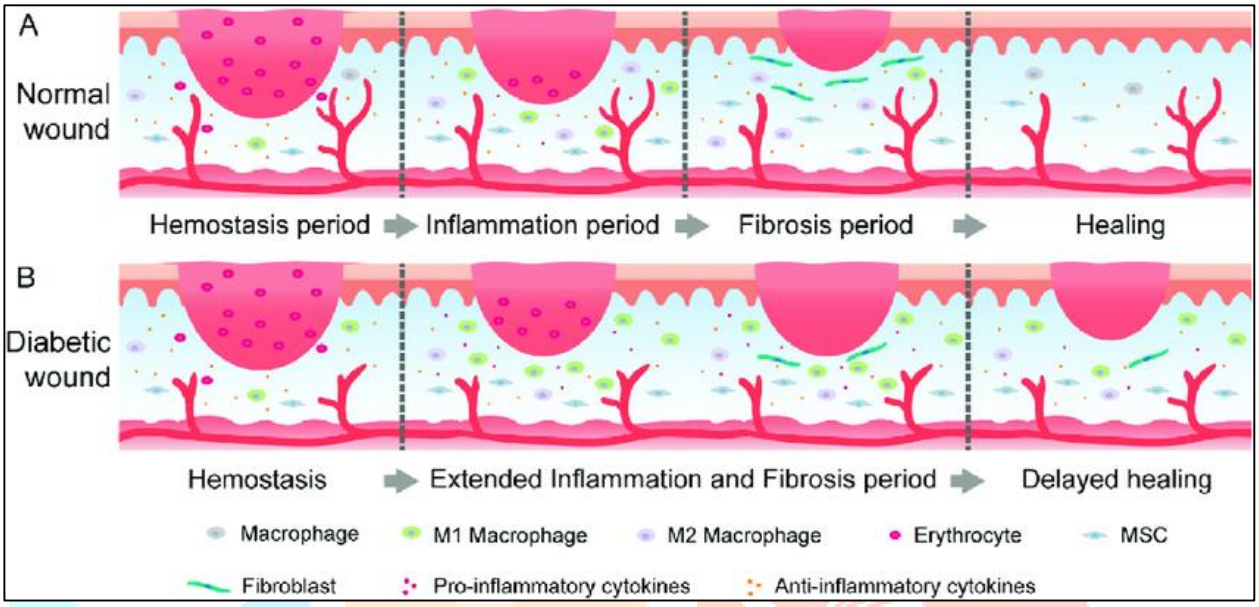
Impaired angiogenesis: Downregulation of VEGF, endothelial dysfunction, and microangiopathy compromise blood supply [18].

Protease imbalance: Excessive matrix metalloproteinase (MMP) activity and reduced tissue inhibitors lead to ECM degradation [19].

Neuropathy and infection: Reduced sensation causes unnoticed injuries, while impaired immunity promotes bacterial colonisation and biofilm formation [20,21].

Collectively, these factors result in chronic, non-healing wounds with high risk of infection and amputation [4,15,20]. This justifies the use of multifunctional hydrogel dressings with antioxidant, antimicrobial, and pro-healing effects [6,10].

Fig.2 Comparative Pathophysiology of Normal and Diabetic Wound Healing Stages



3. Advantages and disadvantages

Advantages of Carbopol-based Moringa hydrogel

Provides moist wound healing environment [5,7].

Carbopol offers excellent viscosity, spreadability, and biocompatibility [7,8].

Moringa oleifera root extract delivers antioxidant and antimicrobial phytochemicals [9–11].

Enhances cell proliferation, collagen deposition, and angiogenesis [12,18].

Allows controlled release of bioactives at wound site [6].

Cost-effective compared to synthetic growth factors or advanced dressings [10].

Disadvantages

Carbopol is synthetic and may cause irritation in sensitive individuals [7].

Stability of phytochemicals from Moringa root may be affected during formulation [11].

Requires optimisation of pH and viscosity for maximum bioactivity [8].

Lacks intrinsic haemostatic effect compared to some natural biopolymers [19].

Limited clinical trial data available for Moringa-based hydrogels [12,20].

4. Classification

Hydrogels can be classified based on multiple parameters [22,23]:

1. Source of polymer

Natural: Chitosan, alginate, gelatin.

Synthetic: Carbopol, polyethylene glycol.

2. Crosslinking type

Physical: Hydrogen bonding, ionic interactions.

Chemical: Covalent crosslinking.

3. Responsiveness

Conventional: Non-responsive gels.

Stimuli-responsive: pH-sensitive, temperature-sensitive, ROS-responsive hydrogels.

4. Formulation form

In-situ gelling liquids.

Preformed hydrogel sheets.

5. Therapeutic load

Blank hydrogels for moisture balance.

Drug-loaded hydrogels for controlled delivery [22].

5. Ideal characteristics of Carbopol-based Moringa hydrogel for diabetic wounds

An effective wound dressing should not only protect the wound but also actively promote healing. The ideal characteristics of a Carbopol hydrogel loaded with Moringa oleifera root extract include [1,5,7,22]:

1. Moisture retention – Maintains a hydrated wound bed to accelerate epithelialisation.

2. Exudate absorption – Prevents maceration of surrounding tissues.

3. Biocompatibility – Non-toxic, non-irritant, and safe for long-term topical use [7,8].

4. Antimicrobial properties – Prevents bacterial colonisation and biofilm formation, aided by Moringa phytochemicals [9–11].

5. Antioxidant activity – Scavenges ROS to reduce oxidative stress [12,16].

6. Controlled drug release – Sustained delivery of bioactive molecules directly at the wound site [6,19].

7. Ease of application and removal – Should not cause trauma upon removal.

8. Cost-effectiveness and accessibility – Particularly important in low-resource settings [10].

9. Mechanical stability – Retains structure during application and storage.

10. pH responsiveness – Carbopol exhibits swelling and gelling properties dependent on pH, enabling adaptable release kinetics [7,22].

These characteristics combine the physicochemical robustness of Carbopol with the therapeutic multifunctionality of Moringa extract.

6. Limitations

Despite their promise, Carbopol–Moringa hydrogels face certain limitations:

1. Phytochemical stability – Bioactives such as flavonoids and phenolics may degrade upon exposure to heat, light, or prolonged storage [11,12].

2. Synthetic polymer drawbacks – Carbopol, while biocompatible, is synthetic and may not be biodegradable in the long term [7,19].

3. Limited haemostatic effect – Unlike chitosan or alginate, Carbopol has no inherent clotting ability [22].

4. Scaling challenges – Large-scale extraction and standardisation of Moringa root extract require strict quality control [9].

5. Regulatory gaps – Limited clinical data on herbal hydrogels means regulatory approval can be complex [20].

6. Storage concerns – High water content hydrogels are prone to microbial contamination without preservatives [7].

7. Method of preparation

A Carbopol-based Moringa oleifera root hydrogel can be prepared using the following general method [7,9,22,23]:

1. Extraction of Moringa root

Roots are washed, dried, powdered, and subjected to extraction using solvents (ethanol, methanol, or aqueous).

Extract is concentrated and dried under reduced pressure.

2. Preparation of Carbopol gel base

Carbopol 940/934 is dispersed in distilled water with continuous stirring until hydrated.

The dispersion is allowed to swell overnight for uniform viscosity.

3. Neutralisation

The Carbopol solution is neutralised with triethanolamine (TEA) or sodium hydroxide until a gel forms (pH ~6–7).

4. Incorporation of Moringa extract

Pre-weighed extract is dissolved or dispersed in a suitable solvent and added gradually to the Carbopol gel with stirring.

5. Addition of excipients

Preservatives (e.g., parabens) and humectants (e.g., glycerin, propylene glycol) may be added to enhance stability and hydration [7].

6. Evaluation of hydrogel

Viscosity, spreadability, pH, drug content, swelling ratio, and in vitro release studies are carried out.

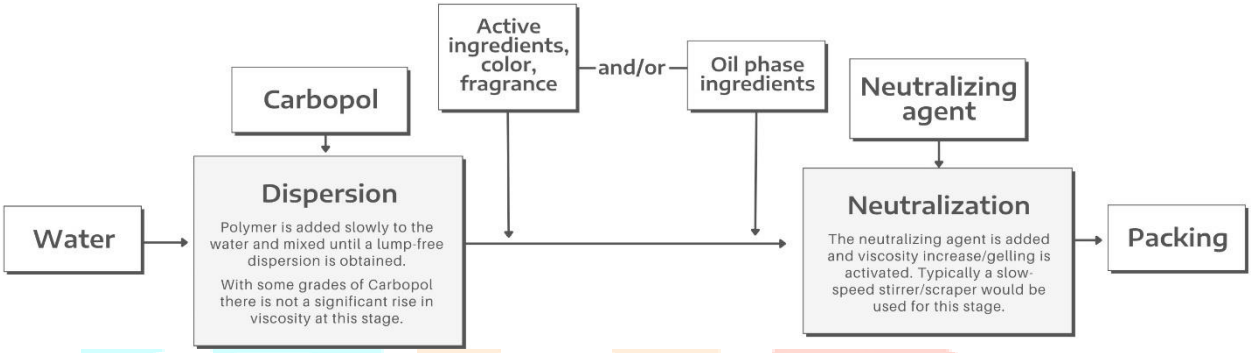


Fig.3 Schematic Representation of Carbopol-Based Hydrogel Preparation Process

8. Hydrogel dressing

Hydrogel dressings are widely used in wound care because they provide hydration, conformability, and bioactive delivery [5,6,22]. Carbopol–Moringa hydrogel dressings offer specific advantages:

Moist wound environment: Promotes autolytic debridement and faster epithelialisation [5].

Cooling effect: Provides soothing action on inflamed wounds.

Transparency: Allows wound monitoring without removal [7].

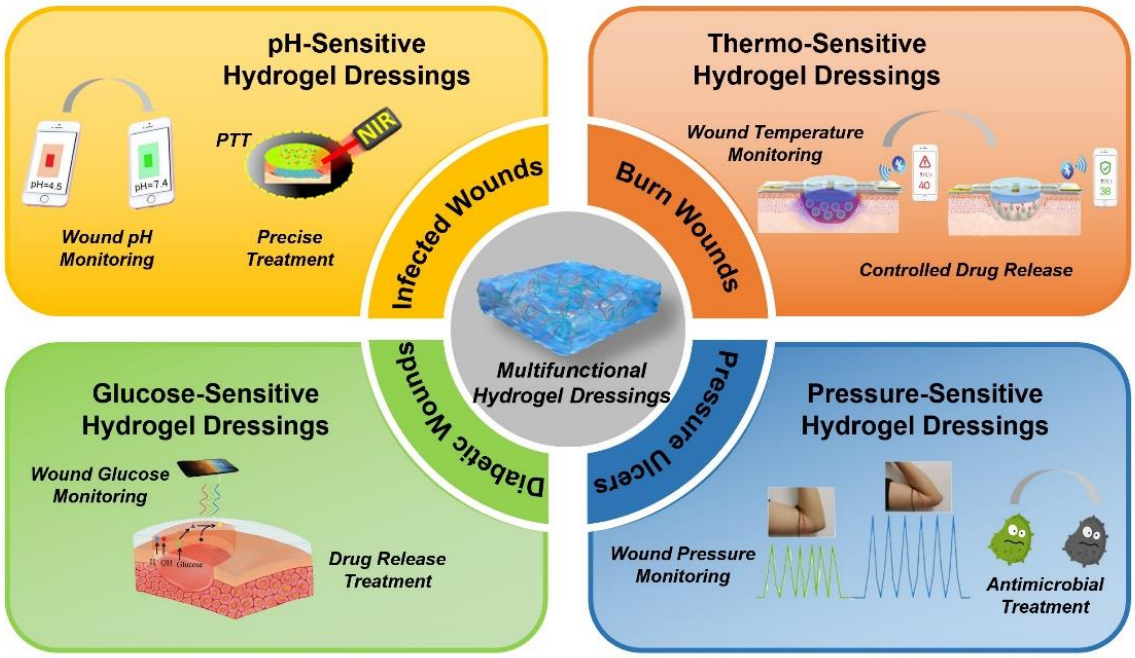


Fig.4 Multifunctional Smart Hydrogel Dressings for Wound Management

Infection control: Moringa root extract prevents microbial colonisation [10,11].

Customisable forms: Available as gels, sheets, or sprayable formulations [22].

Biological mimicry: Hydrogels structurally resemble the ECM, supporting fibroblast and keratinocyte migration [14].

These dressings not only act as passive barriers but actively modulate the wound microenvironment, which is critical in diabetic wound healing [3,16].

9. Mechanism of action

The mechanism of wound healing using Carbopol–Moringa hydrogel involves both polymer-based effects and phytochemical bioactivity:

1. Hydrogel scaffold effects (Carbopol)

Maintains a hydrated wound bed for cellular migration [5].

Provides controlled release of incorporated Moringa extract [7].

Forms a protective barrier against external contaminants [6].

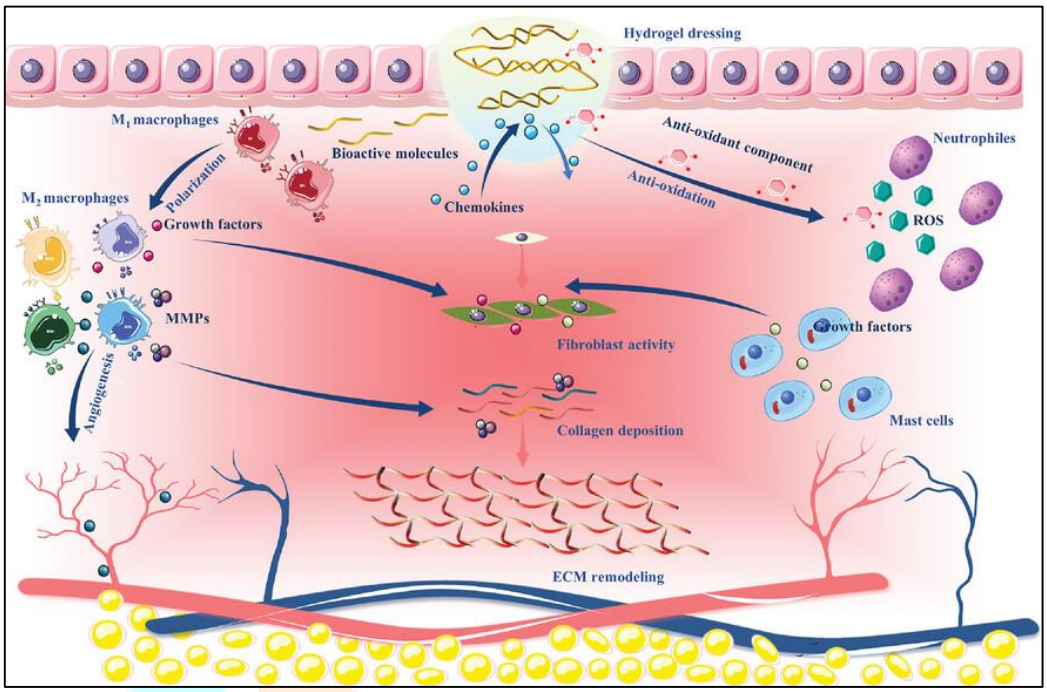


Fig.5 Mechanisms of Hydrogel Dressings in Wound Healing

2. Bioactivity of Moringa oleifera root extract

Antioxidant action: Flavonoids and phenolics scavenge ROS, reducing oxidative tissue damage [11,12,16].

Antimicrobial action: Alkaloids, tannins, and isothiocyanates inhibit bacterial growth (e.g., Staphylococcus aureus, Pseudomonas aeruginosa) [9,10].

Anti-inflammatory effect: Suppresses pro-inflammatory cytokines (IL-1β, TNF-α), allowing transition to proliferative phase [16].

Angiogenesis stimulation: Certain phytochemicals promote VEGF and endothelial function [18].

Collagen synthesis: Enhanced fibroblast activity and collagen deposition accelerate tissue remodelling [12].

The synergistic combination of synthetic polymer support and herbal therapeutic action enables accelerated closure of chronic diabetic wounds.

10. Evaluation

The evaluation of a Carbopol–Moringa oleifera root hydrogel is crucial to ensure quality, stability, and therapeutic efficacy. Parameters include physicochemical, microbiological, and biological assessments [7,9,22,23]:

Physicochemical evaluation

Appearance: Colour, clarity, and absence of particulate matter.

pH: Should be in the skin-compatible range (5.5–7.0) [7].

Viscosity and rheology: Measured using Brookfield viscometer; determines spreadability and retention [8].

Spreadability: Essential for patient compliance and uniform application.

Swelling index: Indicates fluid absorption capacity [22].

Drug content uniformity: Confirms even distribution of Moringa extract [9].

In vitro release studies

Carried out using Franz diffusion cells with phosphate buffer (pH 7.4) to assess controlled release of phytochemicals [7,23].

Antimicrobial activity

Tested using agar well diffusion or broth dilution against wound pathogens (S. aureus, P. aeruginosa, E. coli) [9,10].

Antioxidant assays

DPPH radical scavenging, FRAP, and ABTS assays confirm antioxidant potential of Moringa extract-loaded hydrogels [11,12].

In vivo wound healing studies

Performed in diabetic rodent models (alloxan or streptozotocin-induced), evaluating wound contraction, epithelialisation time, histopathology, and collagen deposition [12,16,18].

Stability studies

Conducted under ICH guidelines (temperature and humidity) to assess shelf life and phytochemical stability [7,20].

11. Applications

The Carbopol–Moringa hydrogel has diverse applications in wound care:

1. Diabetic foot ulcers (DFUs) – Accelerates closure, reduces infection risk, and promotes angiogenesis [2,3,10].

2. Chronic wounds – Beneficial in venous leg ulcers, pressure sores, and ischemic wounds [5,6].

3. Acute wounds – Burns, surgical incisions, and traumatic wounds [22].

4. Topical antioxidant therapy – Protects skin from oxidative stress-related damage [12].

5. Antimicrobial dressing – Prevents colonisation by multi-drug resistant organisms [9].

6. Combination therapy – Potential co-delivery with silver nanoparticles, growth factors, or antibiotics [19,21].

12. Opportunities

Several opportunities exist for further research and application of Carbopol–Moringa hydrogels [9,10,19,22]:

1. Nanotechnology integration

Incorporation of Moringa phytochemicals into nanoparticles within hydrogels could enhance bioavailability and sustained release.

2. Smart wound dressings

pH-responsive or ROS-responsive hydrogel systems could release drugs only under pathological conditions [22,23].

3. Tissue engineering applications

Hydrogels can act as scaffolds for cell-based therapies (e.g., fibroblasts, stem cells).

4. Synergistic combinations

Co-formulation with honey, curcumin, or aloe vera to enhance wound healing outcomes [9].

5. Commercialisation

Low-cost, plant-based hydrogel dressings have strong potential for resource-limited healthcare systems.

13. Challenges

Despite its promise, several challenges limit clinical translation:

1. Standardisation of Moringa extract

Variability in phytochemical content due to geographical, seasonal, and extraction differences [11,12].

2. Regulatory barriers

Herbal hydrogels lack established regulatory pathways for approval [20].

3. Clinical validation

Most evidence is preclinical; randomised controlled trials in humans are scarce [3,16].

4. Long-term safety

Chronic use of Carbopol–herbal gels needs safety confirmation [7,19].

5. Stability and preservation

Hydrogels with high water content require preservatives, which may reduce natural bioactivity [7].

6. Scalability

Large-scale manufacturing must maintain phytochemical stability and batch-to-batch consistency [9].

7. Patient adherence

Acceptance of herbal dressings may vary culturally and geographically.

14. Future perspectives

The integration of Carbopol-based hydrogels with Moringa oleifera root extract offers a transformative approach for diabetic wound care. However, future research must focus on several critical areas [9,10,16,19,22]:

1. Clinical trials

Robust randomised controlled trials (RCTs) are required to validate preclinical findings and establish clinical efficacy and safety in human populations.

2. Advanced drug delivery systems

Development of stimuli-responsive hydrogels (pH, ROS, or enzyme-sensitive) will enable on-demand release of Moringa bioactives tailored to the wound microenvironment [22,23].

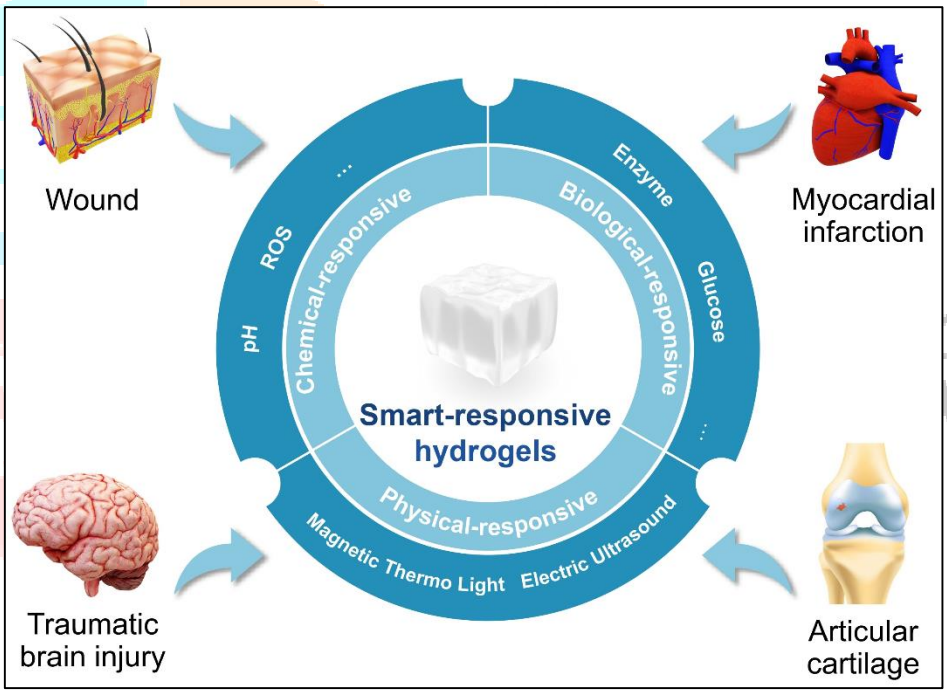


Fig.6 Smart-Responsive Hydrogels and Their Biomedical Applications

3. Synergistic combinations

Integration with nanoparticles, growth factors, or antimicrobial peptides could enhance wound healing outcomes beyond monotherapy [18,21].

4. Biodegradability and sustainability

Future work should explore biodegradable Carbopol derivatives or hybrid natural–synthetic composites to reduce environmental and biological accumulation [19].

5. Regulatory and commercial pathways

Establishing standardised phytochemical fingerprinting, Good Manufacturing Practices (GMP), and cost-effective scale-up processes will be crucial for clinical translation [20].

6. Patient-centred design

Research should consider ease of use, comfort, and accessibility, particularly for low-resource diabetic populations worldwide [2,10].

15. Conclusion

Diabetic wounds represent a complex pathological challenge characterised by persistent inflammation, oxidative stress, impaired angiogenesis, and microbial colonisation [3,15]. Conventional dressings often fail to address these multifactorial barriers.

Carbopol-based hydrogels provide an ideal wound environment, maintaining hydration, enabling drug delivery, and offering biocompatibility [5,7]. Moringa oleifera root extract contributes antioxidant, antimicrobial, and anti-inflammatory phytochemicals that directly modulate diabetic wound pathology [9–12].

The combination of Carbopol with Moringa root extract thus represents a synergistic therapeutic platform capable of enhancing wound closure, reducing infections, and supporting tissue regeneration. While promising preclinical data exist, clinical validation, standardisation, and large-scale commercial development remain essential.

In conclusion, Carbopol–Moringa root hydrogels have the potential to emerge as an affordable, multifunctional, and effective wound dressing system for managing diabetic ulcers and chronic wounds, especially in resource-constrained settings [10,19,22].

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