Chapter 9
Herbal Polymer-Infused Hydrogel Dressings for Enhanced Wound Healing

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ABSTRACT

This chapter explains the role and development of herbal-infused hydrogels in wound healing. This discussion starts with wounds; the wound healing mechanism and factors affecting wound healing and then focuses on the development of wound dressing from the ancient period. It also covers the evolution, and specialized characteristics. Hydrogels are classified based on composition, cross-linking, and functions. This chapter also explains the incorporation of herbal compounds into hydrogels. This chapter shows hydrogel development over the years in wound healing, even though it has challenges that will reduce by future innovation such as development of smart hydrogels in wound management.

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INTRODUCTION TO WOUND HEALING

Innovative biomedical applications, particularly, in the field of wound care, have considered hydrogels as one of the key components owning to their modifiable-properties to maintain a moist environment as well as to facilitate cellular regeneration. The first use of hydrogels can be attributed to the 1960s when Wichterle and Lim fabricated crosslinked poly (2-hydroxyethyl methacrylate) hydrogels for contact lenses (Wichterle & Lim, 1960). Accordingly, hydrogels have been developed using a diverse set of materials ranging from synthetic polymers to natural biopolymers to hybrid systems each providing unique properties appropriate for specific clinical applications.

Moving away from dry traditional dressings to moist wound healing is a significant change in the science of wound repair. It is now well recognized that a moist wound environment not only protects a wound from drying out but can also promote the process of epithelialization, decrease scarring, and enhance the body's own autolytic debridement mechanism (Boateng et al., 2008). Hydrogels with high water content and a 3D porous network system are especially useful to achieve this perfect wound-healing microenvironment.

Furthermore, the progress towards more complex hydrogel chemistries has allowed for the creation of "smart" dressings that respond to stimuli, such as pH, temperature, or bacterial presence. These dynamic systems offer personalized medicine for challenging wounds, including diabetic ulcers, burns and surgical incisions. An emerging trend is the integration of herbal bioactive (e.g., curcumin, aloe vera, and neem) within hydrogel networks.

Smart hydrogels are development higher than traditional wound dressing they can specifically take care the wound healing.

Types of Wounds

Wounds fall into two types: acute and chronic. The type depends on how the wound happens how it recovers, and how much time healing takes. Acute wounds include things like surgical cuts, scratches, or injuries from accidents or medical treatments. These heal in a normal way without major issues (Rodrigues et al. 2019; Boateng & Catanzano 2015). Surgical wounds are classified under ICD-10 code T81, while trauma injuries are grouped in S01–S91 codes. Burns listed under T20–T32, are a more serious kind of acute wound. Their classification depends on depth. First-degree burns affect the outer skin layer second-degree burns go deeper, and third-degree burns damage every layer of the skin.

Hydrogel sheets, a type of special wound dressing, help by cooling the area and keeping it hydrated. Chronic wounds are unique since they fail to heal. They remain trapped in the inflammation stage of the healing process. Examples include pressure ulcers (ICD-10: L89). These often happen to older adults or People stuck in bed for a long time.

Diabetic foot ulcers (ICD-10: E11.621) – develop because of nerve damage and restricted blood flow.

Arterial ulcers (ICD-10: I70.233) – arise from limited blood supply linked to clogged arteries.

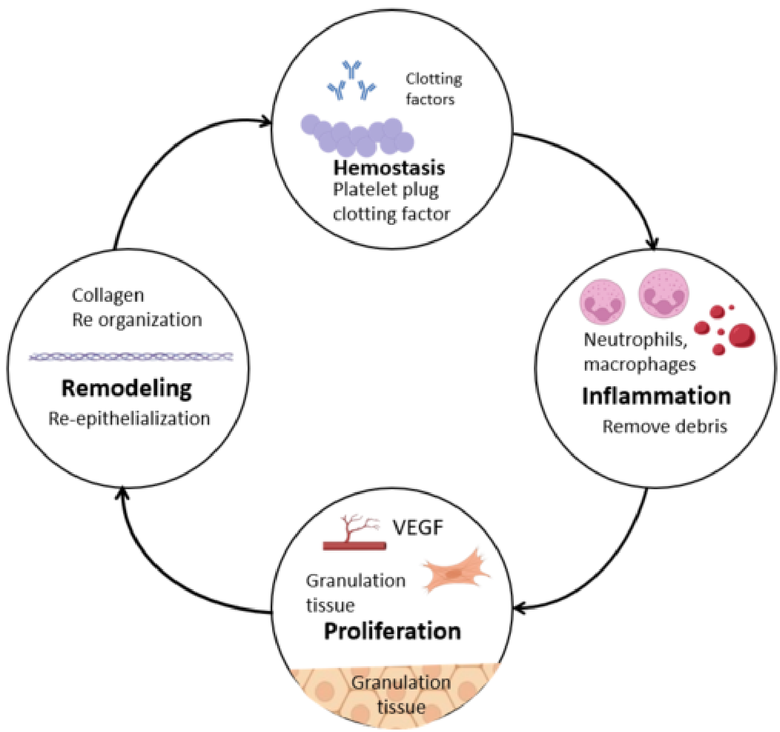
Venous leg ulcers (ICD-10: I83.0) – result from vein problems and fluid buildup in the legs.

Chronic wounds need special treatments like hydrogel dressings containing herbal extracts to lower microbes and support granulation tissue growth. Using the stage (I-IV) and type of exudate helps doctors pick the right hydrogel during treatment.

Phases of Wound Healing

Four stages of wound healing process that naturally occur in immune system as shown in Figure 1:

Figure 1. Four phases of wound healing



Wound healing happens in four steps: haemostasis, inflammation, proliferation, and remodelling. Each step depends on the role of immune cells, cytokines, and the activity of the extracellular matrix.

Haemostasis

Process of vasoconstriction (decrease in size of blood vessel), formation of clotting to stop the bleeding released by platelets and cytokines initiates the repairing process.

Inflammation

The body responses by involvement of macrophages and neutrophils to remove the debris and pathogens in wound area.

Proliferation

Formation of new tissues includes granulation tissue and capillaries in the wound by cells such as fibroblasts, keratinocytes and endothelial cells.

Remodelling

Remodeled extracellular matrix to improve tensile strength over time and collagen fibers are reorganized (Velnar et al., 2009).

Factors Affecting Wound Healing

Multiple environmental and patient related factors are affecting wound healing such as:

Age

Immune system of elder people is weak that delayed the wound healing process and also aged people have uneven immune response and decrease in cellular activity.

Infection

The wounds are affected by bacterial contamination that increases inflammation, and risk of chronic wound development by delaying tissue regeneration.

Comorbidities

Presence of one or more medical conditions in the same person such as diabetes, peripheral vascular disease, malnutrition, compromise in the oxygen supply, metabolic activity leads to impairing wound healing outcomes (Guo & Dipietro, 2010).

TRADITIONAL VS ADVANCED WOUND DRESSINGS

Overview of Conventional Dressings

Traditional wound dressing is the use of primarily designed material to protect a wound from some factors is also called as passive wound dressings like gauze, cotton pads and bandages. These are used for the protection from contamination and absorb exudate (Boateng et al., 2008). Gauze is the porous fabric of cotton or synthetic fibers that helps for sir circulation in the wound but it also affects the healing time by drying the wound quickly. For protection and secure of the gauze, the bandages are designed it offers the light compression to control bleeding (Gupta et al., 2010).

Even though these conventional dressings are low cost and easily accessible that doesn't have any features like antimicrobial properties, bioactivity, moisture holding capacity and don't provide an optimal healing environment which all of these are important to reduces infection and increases wound healing.

Limitations of Traditional Approaches

Even with historical importance of traditional methods affects in several limits like dehydration in the wounds due to poor water content maintenance leads to decreases rate of tissue generation which is called as epithelialization (Davis & Perez, 2009). Additionally, gauze dressings strongly attached to the wounds when its dries lead to trauma (pain, discomfort) to the patient during removal of dressings and also it has potential to reopening the wound (Dhivya et al., 2015).

Also, the traditional dressings don't provide antibacterial protection and develops risks of infection mainly in chronic wounds due to this the dressings have to change continuously that increases the contamination risks and costs in healthcare for long-term dressing procedure (Gupta et al., 2010).

Evolution of Advanced Dressings

These are the limits that led to the development of advanced wound dressings. These advanced materials are designed to improve healing, secure moist in the wound area, and act as a delivery system for the bioactive compounds such as antibiotics, herbal extract, and growth factor. It also protects the wounds from infection (Vowden & Vowden, 2017).

For advanced dressings specific materials like hydrogels, hydrocolloids, alginate and foam dressings are used to promote oxygen penetration, wetness in the wound site and also it manages the exudate from the wound. Compared to traditional dressings, advanced wound dressing materials are increasing the rate of tissue regeneration through innovative properties (Mogoşanu & Grumezescu, 2014).

Moreover, advanced wound dressing materials like hydrogels are incorporated with herbal extract such as neem, turmeric, aloe vera gel, honey to improve antioxidant and antibacterial activity for enhancing healing ability of dressings. The appearance of smart hydrogels in recent times developed especially as an environmental-stimuli such as pH, temperature and enzyme activity and advanced in drug release control adaptation of dynamic wounds (Li & Mooney, 2016).

INTRODUCTION TO HYDROGELS

Hydrogels are 3D and water loving polymer which is said to be hydrophilic compound, that polymer networks have capability to store huge amount of water inside its structure and also maintains the mechanical properties like biomedical application especially in wound healing. Hydrogels can be natural, synthetic, and semi-synthetic which have specific functionality like high water content, biocompatibility, soft and flexible in nature leads to response to environmental stimuli like ionic strength, temperature, and pH (Ahmed, 2015).

Out of many polymers, hydrogels especially used for wound healing due to their ability of moist wound maintenance, improve autolytic debridement, and accelerate cell motility (Kamoun et al., 2017). Hydrogels have most special features that specifically treat the wound and maintain the wound environment. Hydrogels can be customized depends on the injuries.

Definition and Characteristics

Hydrogels have hydrophilic character in nature and it has composition of polymer chains which can elaborate by storing water without mixing in it. Hydrogels have more than 90% of water content in their structure, which is helps to cell adherence, tissue regeneration, and nutrient transport (Ahmed, 2015).

Hydrogels is a material that have a porous nature, which helps in combination of delivering therapeutic agents, cell attachment and growth in the wound area. Hydrogels have many functional groups like hydroxyl (-OH), carboxyl (-COOH), and amide (-NH_2) helps in their swelling nature and its mechanical strength (Gholamali, 2019). Features like these improves hydrogels in the uses of wound dressings, contact lenses, and infusionable drug delivery in the immune systems.

Types of Hydrogels

Hydrogels can be classified into various types depends on the source and composition of hydrogels extracted or developed, divided as natural—which is derived from plants, animals or human's macromolecules like hyaluronic acid, alginate, chitosan and alginate. These polymers naturally have the ability of biodegradation, bioactivity and non-toxicity that helps cell adherence (attachment to the wall) and proliferation. For example, brown seaweed used in extraction of alginate which created ionic cross-linking in presence of calcium ions that develops the biocompatibility and soft matrix for suitable wound healing (Boateng et al., 2008).

Next type is synthetic hydrogels—that are engineered polymers from chemical compounds like polyacrylamide, and polyvinyl alcohol (PVA). These are modified specifically for the features of long-term usage, mechanical strength and degradation rate control. Synthetic hydrogels are more useful when the drug needs to integrate in particular desire, still they lack in bioactivity of natural hydrogels (Peppas et al., 2006).

The evolution of hydrogels leads to the innovation of semi-synthetic hydrogels—the combination of bioactivity feature of natural and strength & properties of synthetic hydrogels, both blends to form semi-synthetic polymer compounds (Li & Mooney, 2016). For example, PVA is a hydrogel that combines with aloe vera extract for antibacterial activities and quick tissue regeneration in chronic wounds (Hanif et al., 2021).

Hydrogels are highly varied in their composition and that may change the function and makes hydrogels more specific in wound healing. Natural hydrogels have high bio degradation and compatibility, on other hand synthetic hydrogels are great in strength and selectable properties (see table 1).

Classification of Hydrogels

Hydrogels are classified into different types based on their **structural** and **functional** activities.

Based on Composition

Hydrogels can be divided into three categories: natural, synthetic, and hybrid. Natural types like gelatin chitosan and alginate tend to be used because they are safe, work with living tissues, and break down. On the other hand, synthetic options such as polyethylene glycol (PEG), polyvinyl alcohol (PVA), and polyacrylamide (PAM) provide better control over their swelling breaking down, or resistance to stress.

Hybrid hydrogels mix natural and synthetic polymers to balance biological activity with mechanical strength. Recent examples use combinations like PVA with aloe vera, PEG with curcumin, and gelatin with turmeric. These blends include herbal compounds to offer antimicrobial and antioxidant benefits.

Based on Cross-Linking

Scientists group hydrogels by their structure in a few ways like, weak forces like hydrogen bonds or ionic ties allow physical cross-linking to create reversible structures. Strong covalent bonds drive chemical cross-linking giving hydrogels more durability and longer usage (Qiu & Park, 2012). Enzymatic cross-linking uses enzymes such as horseradish peroxidase or tyrosinase to help gels solidify.

These systems treat wounds effectively and are easy on the body since they avoid causing harm (Lei et al. 2023). Dual cross-linked hydrogels rely on both chemical and physical bonds. This combination allows the hydrogels to offer strength, flexibility, and a controlled way of breaking down. They perform well as dressings for joints or areas that experience frequent movement.

Based on Functionality

Hydrogels work in different ways such as, Passive ones that serve as moist covers for wounds, Active ones that deliver drugs to fight germs or promote healing, and Smart ones, which respond to changes such as pH levels, heat, or enzyme activity (Li & Mooney, 2016).

pH-sensitive hydrogels release medication in alkaline environments, like in infected wounds. Heat-sensitive hydrogels such as PNIPAM, shift their structure at body temperature letting them form gels on site. Enzyme-sensitive hydrogels break down when triggered by matrix metalloproteinases (MMPs) found in long-lasting wounds, which helps with controlled drug release and tissue repair.

The different hydrogels functions result the specific repair mechanism in the wound. The design of hydrogel properties depends on patients' conditions.

Table 1. Difference between natural and synthetic hydrogels in wound dressings

Features	Natural Hydrogels	Synthetic Hydrogels
Source	It is derived from biological materials like plants, animals or humans	It is developed using chemical compounds.
Biocompatibility	Fantastic in nature	Moderate, that is depends on the polymer.
Mechanical strength	Low in strength	It has high specific strength
Reproducibility	Varies depends on the batch production	It has high consistent synthesis using chemicals
Biodegradability	It has degradability naturally	It is non-degradable but it can degrade when modified
Cost	Usually high due to extraction process.	It cost is low and it can produce in high quantity.
Examples	Chitosan, Alginate and Gelatin	Polyacrylamide, PEG, PVA

Adapted from Boateng et al. (2008); Kamoun et al. (2017).

Clinical Notes. The study of Erdagi et al. (2020) innovates a Genipin-crosslinked gelatin-diosgenin-nanocellulose hydrogels, that shows great antibiotic release and mechanical activities in the wound area. These hydrogels are efficiently reducing the bacterial contamination, mainly in diabetic wounds explains its advanced care in wound healing.

ROLES OF HYDROGELS IN WOUND HEALING

Moist Wound Environment

Hydrogels are widely used due to their unique role of maintenance moist in wound environment that is increases healing rate and decreases scar evolution. Moisture is the one of the main environments needs to maintain in the wound site, that improves the epithelialization, and autolytic debridement process. This required also supports relocation of keratinocyte and increases in fibroblast, which is essential for regeneration of tissue (Jones et al., 2006). Hydrogels set this moist condition in the injured place that prevents wound desiccation and reduces pain when wound dressing changed.

Hydrogels act through several interdependent pathways which support all phases of the normal wound healing process, including four phases of wound healing. The most significant activity of hydrogel is moisture absorption as its application reduces exudate and desiccation and will support autolytic debridement, which is auto clean process due to action of body own enzymes to necrotic tissue (Okan et al., 2007). This absorbative capability also can reduce pain by protecting nerve endings.

Exudate Absorption

Hydrogels have exudate absorption feature that is main role to prevent infection from the fluid discharge in the wound. Moderate level of absorption done by hydrogels due to its porous matrix and it protects the new skin from maceration, reduces bacterial contamination, also maintain hydration in the wound (Gounden & Singh, 2024). Hydrogels also decrease the rate of changing the wound dressing and protects wound not damage furtherly. By this absorption, hydrogels prevent the wound from conversion from acute to chronic wound—which takes more time to heal.

Pain Reduction and Ease Removal

Hydrogels are not attached to the wounds deeply. So, the trauma reduces when the dressing removal and the chilling effect of hydrogels gives relief in inflamed chronic ulcers and burned wounds for the pediatrics—medicinal care for the infants and children, also for geriatrics—medicinal care of elder people (Thomas, 1990). Hydrogels are better than gauze or cotton pads, because unlike hydrogels they are stick to the wounds and make the pain even worse during wound dressing changes.

Barrier to Microbes

Hydrogels don't have an anti-microbial activity until they incorporate with some material which have anti-bacterial and anti-microbial properties. Even though hydrogels act like a semi-permeable barrier which protects the wounds from external contamination while serves gas exchange frequently. Recent studies and research from 2000's in hydrogels incorporate with silver nanoparticles or herbal extracts shows more effective in anti-microbial activity (Rujitanaroj et al., 2008). This feature of double action prevents colony formation of bacteria and disrupts the biofilm development in the wound bed surface.

Mechanistic Insights and Biofilm Disruption

From biochemical point of view, hydrogels adjust the wound pH to a degree, which may not be conducive for the growth of microorganisms. Indeed, many chronic wounds are characterised by an alkaline pH (>7.4) that promotes bacterial growth and hinders tissue healing. Acid hydrogel matrices contribute to correct these discrepancies, stimulating fibroblast migration and angiogenesis (Leveen et al., 1973).

In hydrogel systems based on plant hydrocolloids, further things have to be considered. Flavonoids and polyphenols, which are active plant compounds, have an antioxidant effect on the body. They clean up harmful oxygen molecules lowering stress on the wound as it heals. As an example, scientists have put curcumin in hydrogels. These gels block a signal called NF-κB, which cuts down on proteins that cause swelling, like IL-6 and TNF-α (Jirofti et al., 2021). Controlling how fast a drug comes out is also key.

Scientists can make hydrogels to release plant-based drugs. These gels might respond to outside changes like heat or inside factors like enzymes. Some plastics, like PNIPAM, can swell up or shrink based on body heat. This changes how the drug comes out. Breaking up biofilms has become a new focus in designing hydrogels. Harmful bacteria like *Pseudomonas aeruginosa* and *Staphylococcus aureus* form biofilms that fight off antibiotics and slow down healing.

Some hydrogels now include plant-based ingredients such as tea tree oil or clove extract. These have shown promise in breaking down the biofilm structure and helping antibiotics work better. To wrap up, the porous structure of hydrogels allows oxygen to flow through, cells to stick, and move around. These factors play a key role in helping skin grow back. Hydrogels also cut down on water loss through the skin. This keeps the wound area stable and helps the body heal itself.

SMART HYDROGELS AND THEIR BIOACTIVE FUNCTIONS

Smart hydrogels is advanced development of hydrogels which is basically response to environment of wounds like temperature, pH, or enzyme activities and most smart hydrogels have bioactive in function that means the wound dressing can carry drugs, antibiotics, herbal extract and some factors which helps to improve the wound healing. This section is about the different types of smart hydrogels as shown in Figure 2.

Drug-Loaded Hydrogels

Hydrogels act as a drug carrier to the wounds, drugs like antibiotics, pain relief medicines—known as analgesics and even be a growth factor for wound healing. These smart hydrogels are specifically designed for direct delivery of drug to the wound site and it serves as an advantage in sustainable drug release control, maintain the therapeutic levels of drug at the wound. By using this hydrogel, the continuous use of drugs can be reduced.

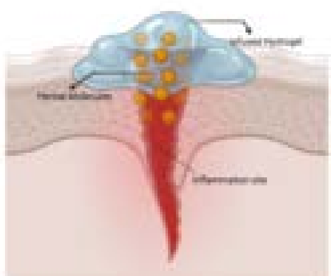
Ampicillin, azithromycin and gentamicin are drugs used to control infections, speed up the wound repair by the growth factors like EGF, VEGF and analgesics like paracetamol or acetaminophen are given to reduce pain in wound area (Lin et al., 2024). Also, hydrogels are loaded with natural and herbal based medicines such as curcumin, neem, aloe vera to improve patient comfort zone, drug stability, bioactivity, and reduces pain along with decrease in side effects.

Stimuli-Responsive Hydrogels

These hydrogels are designed especially for response to the changes in the wound environment. These smart hydrogels are change the drug release and its structure involuntarily corresponding to the conditions like temperature, pH, and enzymes metabolism. For instance, when temperature changed in the wounds, hydrogel dressings can sense it in real-time and release needed antibiotic that loaded in it (Zhang et al., 2025).

Recently, the smart hydrogels are tested in burn wounds and diabetic ulcers for enzyme-responsive. because in such burn wounds, the activity of enzymes changed, and these hydrogels are helps to control the situation in injured area. By this method, the overuse of drug in wound is avoided and maintain healing process, these smart hydrogels act like intelligent system for drug release at right place in needed time without disturbing patient's comfort.

Figure 2. Controlled release from herbal-infused hydrogels



A hydrogel matrix tailored to wounds reacts to triggers like pH levels or enzymes and controls how medication is dispensed. Herbal agents like curcumin focus on the injured area to promote healing while minimizing impact on the rest of the body.

Self-Healing and Shape-Memory Hydrogels

These smart hydrogels can heal itself, when its broken or torn apart that is most helpful in chronic wounds due to its long-term usage and these polymers called as self-healing hydrogels (Zhang et al., 2024).

They have the capacity to maintain their structure by rejoining polymer chains naturally after a mechanical breakage.

Other hand, shape-memory hydrogels which can change it structure based on temperature, pH, or even in light (Xuan et al., 2023). This type hydrogels are still in studies and research but definitely these polymers are amazing use to fill an uneven wound, some unreachable areas and also provide customized dressing to wound site. In results of research, the shape-memory hydrogels give promising variations in regenerative medicine and some personal wound dressing care.

Both self-healing and shape-memory hydrogels are significantly useful in various medicine fields and so much convenient to the patient's pain and healing at the wound site. Recently the incorporation of herbal and other compounds like drugs, with smart hydrogels becomes more powerful.

Some Examples and Uses of Smart Hydrogels are Shown Below

- pH-responsive hydrogels are maintaining pH when it becomes alkaline, by antibiotics releasing
- Temperature responsive hydrogels controls heat in the immune system by using drug
- Enzyme-responsive hydrogels are releasing growth factors to control and heal the chronic wounds
- Self-healing hydrogels can rejoin itself after the breakage in the structure.
- Shape-memory hydrogels can change its structure in uneven wound and return to its normal shape

Adapted from Lin et al. (2024); Zhang et al. (2024); Xuan et al. (2023); Zhang et al. (2025).

SOURCES AND FABRICATION TECHNIQUES

Natural Polymers in Hydrogels

Natural polymers are used in wound dressings because of its biodegradability and compatibility in nature. For example, alginate developed from brown seaweed for hydrogel production by using calcium ions and alginate is more effective in exudate absorption (Lee & Mooney, 2012).

Chitosan is another example of natural polymer which is produced from crustacean shells, reveals antibacterial and hemostatic properties that is making chitosan useful in wound healing progress (Dutta et al., 2004). The other example which is normally used by people that is gelatin, created from hydrolysis of collagen, mostly used for supporting in cell attachment, and proliferation to promote wound healing (Van Den Bulcke et al., 2000).

Hyaluronic acid that is a polymer widely known for its hydration properties and a particle of an extracellular matrix, which is helps in angiogenesis process, improves cell migration and important for tissue regeneration (Collins & Birkinshaw, 2013).

Even though, natural hydrogels lack in mechanical strength—to improve its stability, properties and functionalities these hydrogels combine with synthetic hydrogels or modified using chemicals for enhancement (Peppas et al., 2000).

Synthetic Polymers in Hydrogels

Synthetic hydrogels are chemically synthesis with specific modification like polyvinyl alcohol (PVA), which is used to form hydrogels by physical cross-linking methods such as frost-thaw weathering— that means expansion by using water filling in the gap then freeze it to get great elasticity and also water retention (Peppas et al., 2000). Polylactic-co-glycolic acid (PLGA) which has biodegradability in nature and it is mainly used for drug release control in drug-loaded hydrogels, particularly used in chronic wounds (Jain, 2000).

Polyethylene glycol (PEG) that is a polymer, and it is highly hydrophilic, also biocompatible. It is used to improve bioavailability, solubility and more used in modification of natural polymers (Zhu, 2010). Synthetic polymers also have a negative because its lacks in biological activity, even though synthetic hydrogels provide consistency and with tunable functions. So, these polymers also incorporated with natural polymers or some bioactive compounds to enhance in wound healing process (Hoffman, 2002).

Fabrication Techniques

Varieties of fabrication methods are used in innovative production of hydrogels in specific properties or even in the way of hydrogel wound dressing usage:

Freeze-Drying

This method is used to develop porous hydrogel dressing to improve mechanical structure and its stability.

3D-Printing

This technique helps to create customized wound matrices for adaptation to uneven wounds and allows to combination of cells or drugs (Murphy & Atala, 2014).

In-situ Gelation

This process produces hydrogels that significantly used for irregular and deep wounds by directly forming hydrogels at wound area in response to the physical conditions like temperature, pH (Ruel-Gariepy & Leroux, 2004).

Electrospinning

This procedure helps to make nanofiber mats with high surface area, to enhance drug release control and drug-loading into the polymer for better wound healing (Bhardwaj & Kundu, 2010).

These are the techniques widely used for hydrogels influence in activity and properties of polymers.

ANTIBACTERIAL AND ANTIOXIDANT PROPERTIES IN WOUND HEALING

The combination of antioxidant and antibacterial with hydrogels, to improve wound healing by prevents microbial infections, reducing biofilm formation and stress. Traditional wounds are don’t have sustainable antimicrobial activity, but modern smart hydrogels specifically designed to protect the wound site by direct delivery of antimicrobial agents, this provides stable control in infection and avoid side effects.

Antibacterial and Antioxidant Agents

There are many compounds provides antimicrobial activity and recent development in nanotechnology gives a way in wound healing like silver nanoparticles which is widely used antimicrobial agent for healing applications. These nanoparticles easily incorporate with hydrogel scaffolds improves antibacterial property without toxicity production. The AgNPs mechanism is disturbs microbial membrane, produce ROS (reactive oxygen species) and disrupts DNA replication in the cells (Rigo et al., 2013). Silver nanoparticles are mostly loaded into polymer due to its activity against both gram-negative and gram-positive bacteria such as *pseudomonas aeruginosa, staphylococcus aureus.*

The continuous production of Ag+ ions from hydrogel scaffolds provides long-term protection and reduces inflammation, cytotoxicity and improves re-epithelialization. For examples, chitosan hydrogels loaded with silver nanoparticles increasing rate of healing in wounds (Paladini & Pollini, 2019). As well, the porous material of hydrogels distributes the nanoparticles evenly in the wound and improves the contact with surface microorganism.

Another example is zinc oxide (ZnO) nanoparticles, which has many types of antibacterial property. Also, zinc oxide supports angiogenesis process, fibroblast proliferation and increases the ROS generation and disruption of bacterial cell membrane makes it useful of tissue regeneration. Zinc oxides are cost-effective and has low toxicity, which is suitable for long-term wound management (Raghupathi et al., 2011).

Next one is honey, which is widely used in food products as a sweetener and it has antibacterial with antioxidant property. Honey can develop an unpleasant surrounding for bacterial growth because it has acidic pH, high osmolarity, and hydrogen peroxide. When honey combined with hydrogels, which is improved antimicrobial activity as well water retention and manuka honey is well-known documented for chronic wound treatment (Molan, 2001).

Recently, hydrogels are incorporate with herbal extracts such as neem, aloe vera, green tea and curcumin, due to their duality of both antimicrobial and antioxidant activities. For example, aloe vera infused hydrogels are supports re-epithelialization and wound closure (Maan et al., 2018). Also, curcumin loaded hydrogels are improves collagen production, maintains anti-inflammatory activity and neem extract, which is other side provides antimicrobial agent along with reduces the odor from the wound site.

Role of Antibacterial and Antioxidant Properties

Antibacterial is a process of protecting wounds from inflammation and antioxidant is the way of removing free radicals, to prevent cell damages.

This antioxidant is important in ischemic and diabetic wounds, where oxidative level is high, those cell damage by free radicals reduces the rate of healing, causing by the destruction of proteins, lipids and nuclei acid. Some herbal extracts have phenolic, flavonoids, terpenoids compounds have antioxidant property. For instance, resveratrol, grape seed extract and green tea catechins are mostly infused in hydrogels because they show high antioxidant property (Salehi et al., 2018).

These compounds reduce scars by control collagen deposition, activity of fibroblast, and improves vascularization in addition of tissue regeneration.

Duality of antibacterial and antioxidant activity is more effective in inflammation, infection and it increases the rate of wound healing in chronic injuries, that duality effects come from the combination of both agents like zinc-resveratrol, silver-curcumin.

Biofilm Prevention

Biofilm is a bacterial consortium that fixed to the polymer and attached to the wound, it has antibiotic resistance function. Biofilms are protecting bacteria in the wound and makes bacteria strong against action of drugs, immune responses, and delayed the healing process. Incorporation of hydrogels with zinc, silver, as well herbal extracts affects the bacterial attachment, quorum sensing and breakdown the formation of biofilm.

For example, silver nanoparticles are disturbing the gene expression in *pseudomonas aeruginosa* by inhibiting biofilm-association (Percival & McCarty, 2015). Hydrogels are keeping the wound in moist environment and prevents biofilm formation by protecting wounds from crusting and scabbing. Recent studies of hydrogels showing some of them have DNase and proteases which breakdown the biofilm scaffolds.

CASE STUDIES AND CLINICAL TRIALS OF HYDROGELS

Hydrogel wound dressings are clinically tested, showed promising results in both acute and chronic wounds. Recent cases and clinical trials proved the real-life evolution of traditional dry wound dressings to advanced customized wound dressings, also hydrogel dressings become commercially successful and many case studies in the documents of patient's recovery shows the unimaginable features of hydrogels.

Commercial Hydrogel Dressings

A shapeless hydrogel dressings are commercialized successfully in a different form. For example, Intrasite® Gel fabricated by Smith & Nephew, it contains carboxymethylcellulose, propyl glycol that helps in autolytic wound care, provides moisture and removes necrotic tissue without affecting healthy tissue in the wound.

By use of hydrogels, reports increased in rate of healing along with decrease in pain and increasing in cosmetic results in clinical evaluations (Jones, A., & Vaughan, D. (2005).

On the other hand, hydrogel sheets are providing extra structural integrity, used in chronic superficial wounds and its easier for application. For instance, Vigilon® and DermaFilm® are useful in moist maintenance in wound area till proper healing.

Another example, NuGel® is produced by Johnson & Johnson, which is widely used for pressure ulcers and burns treatment. It is a hydrogel have cross-linking polymer structure improves bacterial barrier, water retention and healing activity (Aswathy et al., 2020).

Case Studies of Wound Healing

Various case studies proves that hydrogel based advanced wound dressings is way better than traditional dressings. There are two different types of hydrogels case studies mentioned below for example:

Silver Nanoparticle Infused Hydrogels. In severe burns patients are treated with silver nanoparticle infused hydrogels because, AgNPs hydrogels are heal the wounds faster and reduces pain compared to silver sulfadiazine cream. This study explains that hydrogels can develop re-epithelialization and bacterial colonies reduction (Nguyen et al., 2019).

Aloe Vera-Gelatin Hydrogels. In clinical case of skin scrapping, hydrogels completely heal the skin within 10 days. This case shows the biocompatibility and tissue regeneration activities, also patients gave feedback about hydrogels which reduces the itching, scarring, and the rate increases in crust detachment (Saenchoopa et al., 2025). These case studies highlight the development of hydrogels healing process in chronic wounds like donor sites, infected surgical cuts, and venous leg ulcers.

Curcumin-Chitosan Hydrogels. Researchers tested a curcumin-loaded chitosan hydrogel to heal diabetic foot ulcers infected with *Staphylococcus aureus*. In 28 days, the hydrogel group showed more closed wounds and formed more granulation tissue than the group treated with saline. They also felt less pain, noticed less odor, and experienced less fluid discharge. When researchers studied the tissue, they found increased blood vessel growth and more collagen buildup. This highlighted the antioxidant and germ-fighting effects of curcumin combined with the biopolymer traits of chitosan (Li et al. 2019).

Clinical Trials and Practice Performance

The efficacy of hydrogels is tested in large number of people and runs a number of randomized controlled trials (RCTs). Two examples are followed below:

Hydrocolloids vs Hydrogels Dressings

For pressure ulcers, multiple studies are done to compare hydrogel dressings with other kind of dressings by Cochrane review. This review explains hydrogels are more effective than others in pressure ulcers, but there is no solid proof to confirm if hydrogels are more effective than all other various types of dressings (Dumville et al., 2015).

Honey-Infused Hydrogels

This study proves the honey-infused hydrogels are more efficient in wound healing. Because these hydrogels have antimicrobial activity and also maintain moisture in the wound site (El-Kased et al., 2017). In high level meta-analyses of wound dressing trials, hydrogels topped in one due to reduction dressings change frequency and patients' satisfaction. As for now, many hospitals use hydrogel-based procedures in part of wound debridement by improvement in clinical results.

Graphene Oxide–Gelatin Smart Hydrogel

Researchers carried out a double-blind randomized trial to test a graphene oxide–gelatin hydrogel on burns classified as second-degree. This smart hydrogel responded to heat by releasing silver ions when the local temperature rose above 38°C, mimicking the body's inflammation. The study shows that it sped up re-epithelialization by 30%. Pain levels dropped, and infections came back compared to using standard silver sulfadiazine cream. Its electric conductivity and ability to adapt drug release proved useful to treat burns caused by heat (Chen et al., 2024).

Emerging Clinical Use

Along with the products and trials we talked about earlier, a few important clinical uses of hydrogel-based dressings have shown how well they work. A recent study with 80 people who had diabetic foot ulcers tested a hydrogel containing Centella asiatica extract. It healed wounds 40% faster than salt water over six weeks (Chen, 2022). People in the study said they had less fluid coming out less pain, and better tissue growth.

This shows that herbal hydrogels can help with long-lasting wounds where swelling won't go away and normal antibiotics don't work well. Another study looked at an aloe vera-gelatin hydrogel to treat skin damage from radiation in breast cancer patients. The hydrogel reduced skin peeling and redness. Patients said they felt much more comfortable during their radiation treatment (Farrugia et al. 2019). One less-talked-about but important use of hydrogel sheets is in healing donor sites after skin grafts.

Researchers compared paraffin gauze to hydrogel dressings and found that sites treated with hydrogel healed in half the time and showed less hyperpigmentation (Kujur & D'Souza, 2019). These examples back the idea that active hydrogel matrices not only cover wounds but also help deliver phytopharmaceuticals boosting recovery in various wound types. More studies with bigger groups and multiple centers are needed to confirm this and push hydrogel into standard treatments.

LIMITS AND CHALLENGES OF HYDROGELS

Hydrogels wound dressing have various advantages as well specific properties. Mainly, hydrogel infused with drugs and herbal extract dressings have smart functions in wound healing. But still in real-life, these smart hydrogels have many challenges in industrial scale-up, clinical applications and some regulatory schemes.

The Relation of Economic Issues to Cost Effectiveness

The use of hydrogel dressings is still limited in low-middle-income countries due to the high cost compared to traditional gauze and foam dressings. There are multiple factors contributing to the overall cost of hydrogels that include:

Sterilization, infusion of nanoparticles, incorporation of natural extracts, and synthesis of crosslinking networks (Al-Gharibi et al., 2018). Despite the reduction in healing time and hospital stays with the use of hydrogels, the initial cost is still an obstacle for public healthcare systems to overcome.

In an attempt to improve cost, biopolymers derived from biomass waste like Cellulose and Pectin Gels, along with low-cost biosynthesis from plant waste material is being researched (Hamed et al., 2025). Although, these methods are in early stages of development and lack standard operating procedures, inhibiting their efficacy.

Limited Shelf-Life and Stability Concerns

Any gels containing live bioactive such as probiotics, enzymes and herbal oils tend to degrade quickly in uncontrolled environments; so, do hydrogels containing natural polymers. Unpreserved gels have a shelf-life of only two weeks.

In addition, microbial contamination and hydrolytic instability are primary concerns which make cold-chain logistics a necessity (Luong et al., 2014). Preservation techniques such as UV sterilization or lyophilization change one form of preservation for another by compromising physical integrity and active compound bioavailability.

Allergenicity and Patient Differences

Some components of hydrogels, especially acrylates and glutaraldehyde (preservatives), synthetic monomers, and herbal infusions, have been reported to induce allergic type reactions or delayed type hypersensitivity among sensitive patients (Küçük et al., 2025).

While herbal extracts type irritable are biocompatible, if not properly standardized for purity and dosage, contact dermatitis can ensue.

Because of these reasons, thorough background checks and preclinical testing for immunogenicity is required for safe clinical use. In addition, formal-checked medical herb blends lack dose consistency from batch to batch which is difficult due to the unpredictable composition of plant compounds.

Biodegradability vs Mechanical Strength

The trade-off between mechanical stability and biodegradability poses one of the greatest difficulties. Natural hydrogels such as gelatin, chitosan, or alginate readily undergo in vivo biodegradation, but do not possess the requisite tensile strength and elasticity for irregular or deep wounds.

On the other hand, some synthetic hydrogels like PEGDA and polyacrylamide possess mechanical strength but do not metabolize; instead, they burden the tissues and necessitate surgery for extraction (Dodda et al., 2023). The focus is on hybrid systems which incorporate natural biopolymers with tunable synthetic crosslinkers, providing better equilibria of the aforementioned properties. However, the degradation rates in biological environment are still not easily predictable and may change due to the wound's pH, moisture level, or enzymatic activities.

Scientists have developed biodegradable synthetic monomers such as polylactic acid and polycaprolactone to create a mix of strength and resorption. They are also studying bio-inks with bonds that break down based on how a wound is healing.

Regulatory Barriers and Clinical Translation

The majority of herbal-infused or bioactive hydrogels falls under the combination products category of the FDA, requiring separate assessments as a medical device and as a drug (Pawar et al., 2025).

This bifurcation leads to longer approval pathways and increased time to market. In addition, there are no universal protocols for wound care that advise the use of a specific type of hydrogel. XL Clinical guidelines vary from hospital to hospital and from one country to another, leading to diluted usage regardless of efficacy.

There are few training courses available for clinicians and nursing staff on proper application of hydrogel dressings.

FUTURE TRENDS AND KEY RESEARCH AREAS

The rapid evolution of hydrogel wound dressings is mostly derived from the integration of biotechnology, additive manufacturing, and digital health monitoring. Emerging trends are focusing on overcoming existing limitations by adding real-time biosensing, targeted drug release, and personalized scaffolds for wound care.

Customized Hydrogel Dressings Through 3D Printing

Additive manufacturing or 3D printing has transformed the design and production of hydrogel dressings by allowing customization to the wound's geometry, depth, and individual biology. Bioinks containing gelatin methacrylate, alginate, or fibrinogen can be mixed with cells, drugs, or herbal extracts, and such bioinks are printable and can generate layered structures fitting anatomical sites (Chia & Wu, 2015). The complex healing needs of chronic wounds can be simulated by 3D hydrogels incorporating several zones with different release profiles. Also, it is possible to bio print vascular channels or oxygen reservoirs. Some examples are specified (see Table 2).

Table 2. Examples of 3D-printed hydrogels

Type of Hydrogel	Additional Function	Application
Alginate–Gel MA	VEGF & fibroblasts	Diabetic ulcers
PVA–Curcumin	Herbal Extract	Burn Injuries
Gelatin–PEGDA	Antibiotics	Infected Wounds

Adapted from Kumi et al. (2024); Li et al. (2021); Thapa et al. (2021).

Integration with Wearable Sensor Technologies

The future of wound care lies in intelligent dressings with embedded biosensors that continuously track parameters like: pH and temperature - to identify infection, Oxygenation levels – to evaluate ischemia, and Exudate composition – to analyse inflammation.

Intelligent hydrogels can wirelessly send feedback to clinicians or on-the-go apps, which allow remote wound monitoring, particularly useful for diabetic patients, bedridden patients, or geriatric populations (Tang et al., 2021). Using Bluetooth Low Energy (BLE) modules or Near-Field Communication (NFC) allows immediate data sharing without needing large external gadgets.

These advances help patients follow treatments better and cut down on hospital trips leading to a move toward personalized wound care at home.

Regenerative Medicine and Tissue Engineering

Hydrogels act as a biological scaffold for cell migration, attachment, and differentiation. Infused with mesenchymal stem cells (MSCs), exosomes, or platelet-rich plasma, such scaffolds can stimulate angiogenesis, collagen remodelling, and tissue regeneration (Khayambashi et al., 2021).

Advanced research addresses CRISPR-edited MSCs to create hydrogels that deliver gene-controlled healing cues. Another trend is 3D bio printed skin patches with incorporated hydrogel layers for stratified skin healing and limited scarring.

AI-Driven Hydrogel Design

Artificial intelligence and machine learning codes are being employed to develop hydrogel formulations that can forecast: Swelling ratio, Drug diffusion profile, Degradation time, and Mechanical strength.

This computational simulation largely decreases laboratory experimentation and opens the door for customized hydrogel formulation kits (Memon et al., 2025). In the future, pharmacies will provide AI-designed hydrogel matrices based on a patient's wound information and treatment objectives.

Emerging Innovations in Smart Hydrogel Systems

One less-talked-about but important use of hydrogel sheets is in healing donor sites after skin grafts. Researchers compared paraffin gauze to hydrogel dressings and found that sites treated with hydrogel healed in half the time and showed less hyperpigmentation (Kujur & D'Souza, 2019). These examples back the idea that active hydrogel matrices not only cover wounds but also help deliver phytopharmaceuticals boosting recovery in various wound types. More studies with bigger groups and multiple centers are needed to confirm this and push hydrogel into standard treatments.

A new trend is self-healing hydrogels. These can fix themselves through dynamic bonds like Schiff base connections or hydrogen bonds and can repair damage (Devi et al., 2021). This is good for wounds in flexible areas like joints over time. Another cool thing is using blockchain in hydrogel supply chain to verify the authenticity and traceability of herbal bioactive. Problem of variability and contamination in plant extracts has always been an issue in making herbal hydrogels. Blockchain can document where materials are sourced, batch test results and handling details so clinicians can follow regulations and get trust from clinicians.

The living wound dressings is widely on-going research which is bacterial wound dressing infused with hydrogels like lactobacillus strains produce growth factors when inflammation occurs (Yu et al., 2022). Researchers are also looking into voice assisted AI systems to monitor wounds. These systems work with hydrogel sensors. They can be helpful to elderly or blind patients by giving spoken updates using data from smart dressings. Experts predict a move towards smarter, more versatile and patient specific wound care solutions. Although researchers are still testing these in labs and on prototypes initial clinical trials suggest they will work in real life.

Researchers are looking into combining adaptive hydrogels with wearable energy sources or systems that can recharge themselves to keep sensors running without breaks. These are opening up possibilities for future "autonomous healing platforms". These systems bring together monitoring, decision making and treatment into one functional unit.

GLOBAL MARKET AND SOCIETAL IMPACT OF HERBAL HYDROGELS

Herbal hydrogel wound dressings are becoming more popular worldwide because they are safe for the body, have fewer side effects, and are eco-friendly. Allied Market Research reports that the global hydrogel wound dressing market could hit USD 1.5 billion by 2030. This growth comes from an increase in chronic wounds older populations, and interest in using advanced natural materials.

Role in Rural and Low-Resource Settings

Herbal hydrogels provide a cheap method to heal wounds in areas with low income. People in regions like South Asia, Africa, and Latin America often depend on plants such as neem, turmeric, and aloe vera to treat skin problems. Combining these natural options with hydrogel materials creates an affordable treatment that is simple to use and trusted by the community.

Research shows aloe–chitosan and curcumin–gelatin hydrogels can be made from leftover crops on farms (Arshad et al. 2023). This reduces the need to bring in medical supplies from other countries. These hydrogels are easy to store and break down. This makes them helpful to take to mobile clinics or for health professionals working in local areas.

Public Health and SDG Impact

Herbal hydrogels align with SDG-3, which aims to boost health and well-being. They provide effective ways to treat long-term wounds easing pain for patients and raising their quality of life. Using hydrogels instead of antibiotics also helps fight the rising issue of antimicrobial resistance, a major global health concern today.

Local Manufacturing and Job Creation

Producing herbal hydrogels creates jobs in villages and connects biotechnology with old systems of medicine. Strict rules and proper quality checks can help these small community-based units thrive while supporting the growth of Ayurveda or Unani medicine with proof-based methods.

In short herbal hydrogel wound dressings are more than a new invention. They blend advanced biotech with ancient knowledge to move society forward. This mix supports new ideas and makes healthcare easier to reach for all.

CONCLUSION

Wound dressings based on hydrogel have revolutionized the approach to wound treatment by integrating the effects of moisture retention, antimicrobial coverage, and regenerative capacity into a unifying therapeutic modality. This chapter summarized the characterization, formulation, mechanisms, and clinical effects of conventional and intelligent hydrogels.

Herbal-infused and bioactive hydrogels are the new generation of natural therapeutics that harness centuries of traditional medicine with a science-optimized mode. Clinical trials and commercial success have substantiated their efficacy in angiogenesis, infection reduction, and epithelialization enhancement. There still exist hurdles in the form of expense, short shelf-life, risk of allergic reaction, and regulative issues. These need to be overcome by means of biotechnological advancement, training in clinics, and policy initiatives for widespread use.

Futures directions are thrilling. From 3D-printed personalized hydrogels to smart dressings embedded with biosensors, wound care is turning highly personalized, data-driven, and regenerative. With the convergence of machine learning, synthetic biology, and material science, we may see fully autonomous hydrogel systems with real-time sensing, adaptation of drug release, and scaffold-driven regeneration soon. Thus, hydrogel dressings for wounds—especially those which are mixed with herbal medicine—have the potential to sharply reduce health costs, improve outcomes of recovery, and provide equal care to communities.

Hydrogels have revolutionized wound care from the state of being just passive cover-ups to active healing tools. They maintain wound hydration, they transport drugs, and they assist in the functions of cells. These properties make them a valuable ingredient in wound treatments for long-term and short-term wounds. The inclusion of plant extracts made them safer to use. It also augmented their germ-killing power as well as their role in eliminating swelling without triggering drug resistance.

This chapter has reviewed the production of hydrogels how they work, and how they are taken to actual applications in the form of clinical conditions. It also mentioned challenges like cost and regulation while giving a glimpse of new developments like AI for customized solutions, blockchain to verify products, and scaffolds that respond to body response. Hydrogel dressings can decrease hospitalization, conserve unnecessary antibiotic use, and increase patient compliance with therapy if used with remote monitoring devices. For the treatment of wounds in resource-poor settings, herbal hydrogels offer a low-cost fit, and a welcoming choice. But to move forward in developing hydrogel dressings several challenges require attention.

Reducing manufacturing costs, establishing clinical guidelines, and training healthcare personnel will be key. Teamwork between biotechnologists herbal medicine experts, and doctors will help move these solutions from research labs to patient care. With the development of fourth-generation hydrogels, which sense, react, repair, and report, these materials are set to not just help with wound care but also cause a major shift in how healing is approached.

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