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MEDICINAL PLANTS AND BIOACTIVE COMPOUNDS: TRADITIONAL AND MODERN APPROACHES TO WOUND HEALING

OBAIDULLAH ALIMYAR[1], SAYEDWALI SEDIQI[2], AZIZAQA AZIZI[1], ABDUL BARI HEJRAN[3], PARWIZ NIAZI[4], ABDUL WAHID MONIB[4]

[1]*Department of Biology, Faculty of Education, Parwan University, 1101, Afghanistan.*
[2]*Department of Biology, Faculty of Education, Urozgan Higher Institute, Urozgan, Afghanistan.*
[3]*Department of Biology, Faculty of Education, Helmand University, 3901, Afghanistan.*
[4]*Department of Biology, Faculty of Education, Kandahar University, Kandahar, 3801, Afghanistan.*

**Corresponding author Email; Parwiz Niazi; parwiz60@gmail.com*

ABSTRACT

Wound healing is a complex biological process crucial for tissue restoration, and its disruption, especially in chronic wounds, poses significant global health challenges. Medicinal plants have been utilized for centuries in traditional medicine to promote wound healing, offering a viable alternative to synthetic treatments. This review explores both traditional and modern approaches to wound healing using medicinal plants and their bioactive compounds, such as alkaloids, flavonoids, terpenoids, and phenolic acids. These compounds demonstrate anti-inflammatory, antimicrobial, and antioxidant properties, playing key roles in reducing inflammation, promoting tissue regeneration, and accelerating wound closure. Modern advancements, including nanotechnology, have further enhanced the therapeutic potential of plant-based treatments by improving bioavailability and targeted delivery. Despite the promising benefits, challenges remain in the standardization, dosage, and regulatory aspects of herbal therapies. The integration of traditional knowledge with contemporary scientific innovations offers a comprehensive strategy for effective wound care, particularly for chronic wounds.

KEYWORDS: Wound healing, medicinal plants, bioactive compounds, wound dressing, secondary metabolites.

INTRODUCTION

The skin serves as the body's first line of defense, acting as a vital barrier against external threats *(Matejuk, A. 2018)*. Wounds, which disrupt the structural integrity of the skin, can result from various factors such as burns, scalds, incisions, pressure sores, diabetic foot ulcers, and venous ulcers, these injuries compromise the skin's protective function, increasing the risk of infections and delayed healing. Over recent years, phytochemicals have shown considerable potential in preventing and treating microbial infections related to wounds *(Kumari et al., 2024)*. Wounds are often associated with high morbidity, leading to extended healing times, chronic complications, and significant healthcare costs *(Sharma et al., 2024)*. Phytochemicals, recognized for their antioxidant, antimicrobial, and wound-healing properties, play a crucial role in expediting the healing process by promoting clot formation, combating infections, and facilitating tissue regeneration *(Riaz et al., 2024)*. Medicinal plants rich in polyphenols, particularly phenolic compounds with astringent properties, have been noted for their exceptional wound-healing capabilities *(Cedillo-Cortezano et al., 2024)*. Microbial infections can significantly delay healing, often leading to chronic wounds that demand urgent medical attention, especially in high-risk groups such as infants and the elderly *(Odeku et al., 2025)*.

The application of natural medicine and traditional healing practices has long been a cornerstone of therapeutic approaches, many plant-based remedies lack widespread clinical validation, certain natural compounds have shown significant efficacy in managing inflammation, cancer, and chronic wounds through various stages of research *(Trivedi et al., 2025; Alimyar et al., 2023)*. Nanotechnology has emerged as an innovative solution for enhancing the effectiveness of phytochemicals in wound healing *(Uriostegui-Pena et al., 2025)*. By encapsulating natural compounds in nanostructures, their bioavailability and therapeutic potential can be improved. Nanocarriers, due to their high surface area-to-volume ratio, can modulate the physicochemical properties of active ingredients, making this approach one of the most promising strategies for improving wound-healing outcomes using natural products *(Yadav et al., 2025; Azizi et al., 2023)*.

A wound is essentially a physical disruption or damage to functional tissue, and its healing is a multifaceted process comprising four overlapping phases: hemostasis, inflammation, proliferation, and tissue remodeling, this coordinated biochemical and cellular sequence is vital for repairing damaged tissues *(Sadeghi-avalshahr et al., 2025)*. The effectiveness of the repair process is influenced by various factors, including the extent of the damage, the regenerative capacity of the tissue, the presence of necrotic debris, and the presence of foreign bodies or infections *(Liao et al., 2025)*. Notably, wound healing is not a straightforward process it can advance or regress based on intrinsic and extrinsic factors, such as cytokines, growth hormones, patient age, wound size, location, and comorbid conditions like diabetes or systemic infections. At the physiological level, wounds compromise both the protective and functional roles of the skin, necessitating immediate treatment (Faria, A. V., & Andrade, S. S. 2025). Medicinal plants have been historically used across cultures for wound treatment due to their antimicrobial and regenerative properties *(Sediqi et al., 2023)*.

Wound healing is a sophisticated and dynamic biological process aimed at restoring the structure and functionality of tissues following injury *(Wang et al., 2025)*, this essential mechanism for survival unfolds in three overlapping phases: the inflammatory phase, the proliferative phase, and the maturation phase. The inflammatory phase begins immediately after an injury and focuses on preparing the wound site for repair *(Pletts et al., 2025)*. Initially, vasoconstriction occurs to control bleeding, followed by vasodilation, which facilitates the migration of immune cells like neutrophils and macrophages to the injury site. These immune cells play a vital role in clearing pathogens, cellular debris, and necrotic tissue while releasing cytokines and growth factors that trigger the repair process *(Hejran et al., 2024)*. The proliferative phase, typically starting 3 to 5 days post-injury, is marked by tissue regeneration and repair. Fibroblasts migrate to the wound site, synthesizing collagen and extracellular matrix (ECM), which form the structural foundation for new tissue development. Granulation tissue, rich in blood vessels from angiogenesis, provides a steady supply of oxygen and nutrients to the regenerating tissue. Simultaneously, keratinocytes at the wound edges initiate re-epithelialization, covering the wound with new skin cells. The final stage, known as the maturation or remodeling phase, can extend over weeks or even months, depending on the wound's severity. During this phase, collagen is remodeled and cross-linked to improve the tensile strength of the tissue. Meanwhile, fibroblasts and other repair cells undergo apoptosis, and newly formed capillaries regress, leaving behind a less dense and avascular scar tissue *(Plum et al., 2025; Bouwman et al., 2025)*.

The clinical importance of wound healing cannot be overstated, as it is crucial for preventing complications and restoring patients to full health *(Tettamanzi et al., 2025)*. Effective wound healing acts as a protective measure, sealing the wound and preventing harmful pathogens from entering, which could otherwise result in severe infections like sepsis *(Shi et al., 2025)*. Beyond infection prevention, successful wound healing ensures the restoration of tissue functionality, which is especially significant in cases where the wounds affect mobility or involve vital organs, timely and efficient wound healing greatly improves a patient's quality of life by reducing pain, preventing disability, and mitigating the psychological distress associated with chronic wounds or prolonged recovery *(Kumar et al., 2025)*. From a healthcare perspective, efficient wound management minimizes risks of complications, such as chronic wounds, amputations, or extended hospital stays, thereby alleviating the burden on healthcare systems *(Nazari et al., 2025)*. Factors such as a patient's underlying health conditions, nutritional status, and the application of proper wound care practices significantly influence the healing process *(Niazi et al., 2023)*. This underscores the need for clinicians to have a deep understanding of the phases of wound healing and the appropriate interventions required to support each stage. Optimizing wound care practices not only enhances patient outcomes but also reduces healthcare costs associated with wound-related complications *(Sarwari et al., 2024; Arezina, D. J., and Li, D. 2025)*.

In healthy individuals, acute wounds typically heal within days if there are no complicating factors such as infections. Conversely, chronic wounds are marked by disrupted healing processes, prolonged inflammation, and excessive neutrophil infiltration, resulting in delayed recovery *(Chrisdianto et al., 2025)*. The physiological stages of wound healing include hemostasis, which halts bleeding; inflammation, which clears pathogens and debris; proliferation, which involves angiogenesis and ECM deposition; and remodeling, during which collagen is reorganized, and tensile strength is restored *(Akram et al., 2025)*. This sequential process enables damaged tissues to regain their structure and function. Optimal wound healing often requires the use of specialized dressings, which create a favorable microenvironment for repair *(Debnath et al., 2025)*. Ideal wound dressings should be flexible, permeable, and moisture-retentive while also serving as a temporary protective barrier, they must support cell migration, proliferation, and differentiation while offering antimicrobial and biocompatible properties *(Chen et al., 2025)*.

Biomedical textile materials, developed through advanced manufacturing techniques, are commonly used in wound care, these materials include fibres, yarns, nonwoven fabrics, woven and knitted textiles, composites, and electro-spun nano-fibrous materials, as well as foams, films, hydrogels, matrices, and hydrocolloids *(Chibinyani et al., 2025)*. Modern wound dressings have evolved to fulfill various functions, such as absorbing exudates, maintaining moisture, reducing microbial infections, and delivering therapeutic agents directly to the wound environment. Examples of advanced wound dressings include foams, alginates, hydrogels, hydrocolloids, hydro-fibers, and tissue-engineered skin, despite their benefits, conventional wet and dry dressings have limitations, including their potential to adhere to wounds and cause additional tissue damage during removal *(Ghosh et al., 2025; Rumon et al., 2025)*.

This review aims to emphasize the importance of medicinal plants in wound healing and examine existing research on their therapeutic properties. It seeks to gather insights into the phytochemicals used in wound care, their mechanisms of action, and their potential applications, the review explores advancements in wound-healing technologies, particularly the incorporation of nanotechnology into plant-based therapeutic delivery. Numerous studies have demonstrated that medicinal plants and their derivatives can accelerate tissue regeneration in both in vivo and in vitro settings. Ethnobotanical research highlights the therapeutic potential of plant-derived substances, which strengthen the immune system, combat infections, and promote tissue repair. Advancing our understanding of wound healing mechanisms and developing novel natural product delivery systems are essential steps toward establishing effective and safe treatments for chronic wound conditions.

METHODOLOGY

This review examines the therapeutic potential of phytochemicals in wound healing. It begins with an overview of essential information regarding wounds and the anatomy of the skin to provide a foundation for understanding the healing process. A concise discussion follows on the stages of wound healing, highlighting the physiological events that contribute to tissue repair, the article then presents a comprehensive review of current advancements in conventional treatments for skin wound healing, with a particular focus on the medicinal properties of natural substances. Special emphasis is placed on exploring the mechanisms of action of these phytochemicals, supported by clinical studies that validate their effectiveness.

ROLE OF MEDICINAL PLANTS IN WOUND HEALING

Historical Use of Plants in Wound Care

The use of medicinal plants in wound care dates back thousands of years, with evidence of their application found in ancient texts, traditional pharmacopeias, and archaeological sites *(Takahashi, N. 2025)*. Civilizations such as the Egyptians, Greeks, Indians, and Chinese recorded the therapeutic use of plants for treating wounds, burns, and skin infections *(Ahmad et al., 2020)*. Ancient Egyptians, for instance, used honey, myrrh, and aloe vera as topical treatments for wounds due to their antimicrobial and anti-inflammatory properties *(Chelu et al., 2023)*. Similarly, in ancient Greece, Hippocrates documented the use of herbal poultices to promote healing and reduce infections. In traditional Indian Ayurveda and Chinese medicine, plants like turmeric, neem, and centella (commonly known as gotu kola) were used for their ability to stimulate tissue repair and prevent microbial contamination *(Abdieva et al., 2024)*. This historical reliance on plants stemmed from their widespread availability, low cost, and observed efficacy in healing wounds, long before synthetic antibiotics and modern pharmaceuticals became accessible *(Gurib-Fakim, A. 2006)*.

Traditional Knowledge and Cultural Practices in Wound Healing

Traditional knowledge systems have played a critical role in preserving and promoting the use of medicinal plants for wound healing *(Shedoeva et al., 2019)*. Indigenous communities across the globe have developed unique cultural practices and remedies using local flora to treat wounds and other ailments. For example, Native American tribes used the bark of willow trees, which contains salicin (a precursor to aspirin), to reduce pain and inflammation in wounds *(Aziz et al., 2018)*. Similarly, African traditional medicine employed shea butter and extracts from plants like guava leaves and African wormwood for their antiseptic and regenerative properties. In rural areas of Asia, poultices made from turmeric and neem were common, as these plants possess strong antimicrobial and anti-inflammatory qualities. These practices were often passed down orally through generations, ensuring the continuity of botanical knowledge. Rituals and spiritual beliefs were sometimes integrated into these healing practices, reflecting the holistic view of health and well-being in traditional cultures *(Afreen et al., 2021)*.

Plants Commonly Used for Wound Healing Across Different Regions

A variety of medicinal plants have been traditionally utilized for wound care in different regions, reflecting the rich biodiversity and ethnobotanical knowledge of each area. Aloe vera is one of the most widely recognized plants, valued for its soothing, hydrating, and antimicrobial properties, and it has been used globally for burns, cuts, and ulcers *(Mahboob et al., 2023)*. In South Asia, turmeric (Curcuma longa) is renowned for its curcumin content, which promotes wound healing through anti-inflammatory and antioxidant mechanisms. Gotu kola (Centella asiatica), another staple in Asian traditional medicine, has been used to enhance collagen synthesis and accelerate wound closure. In Africa, plants like bitter leaf (Vernonia amygdalina) and marigold (Calendula officinalis) are frequently used for their antimicrobial and skin-repairing properties. Similarly, tea tree oil derived from Melaleuca alternifolia in Australia is celebrated for its potent antiseptic effects *(Awuchi, C. G., & Morya, S. 2023)*. In Europe and North America, herbs like chamomile, lavender, and yarrow have been historically used to clean and disinfect wounds, as well as promote tissue regeneration *(Olalere et al., 2024)*.

These plants are often applied in various forms, including poultices, oils, extracts, or powders, depending on cultural preferences and availability. Modern research has begun validating the traditional use of many of these plants, confirming their wound-healing properties through scientific studies and paving the way for their integration into modern medicine. As global interest in natural and sustainable remedies grows, medicinal plants continue to play a vital role in wound care practices worldwide *(Omirbekova et al., 2024)*.

BIOACTIVE COMPOUNDS IN MEDICINAL PLANTS

Medicinal plants owe their therapeutic effects to a diverse array of bioactive compounds, which are natural chemicals synthesized by plants to defend against environmental stressors, pathogens, and herbivores *(Pandey et al., 2023)*. These compounds are classified into various groups based on their chemical structures and biological activities. The primary types of bioactive compounds in medicinal plants relevant to wound healing include alkaloids, flavonoids, terpenoids, and phenolic compounds. Each group exhibits specific mechanisms of action that contribute to the wound healing process through their anti-inflammatory, antimicrobial, antioxidant, and tissue-regenerative properties *(Akhundzada et al., 2023)*.

Types of Bioactive Compounds

1. **Alkaloids:** Alkaloids are nitrogen-containing compounds found in various plants and are known for their potent biological activities *(Sawicka et al., 2024)*, they possess anti-inflammatory and antimicrobial properties, making them essential in managing wound infections and reducing inflammation at injury sites. For example, berberine, an alkaloid

extracted from plants like Berberis vulgaris, exhibits significant antibacterial activity against pathogens that commonly infect wounds *(Mansoor et al., 2023)*.

2. **Flavonoids:** Flavonoids are polyphenolic compounds that serve as powerful antioxidants, protecting cells from oxidative stress caused by free radicals generated during the wound healing process. They also have anti-inflammatory and angiogenic properties, which support tissue repair and promote the formation of new blood vessels. Quercetin, a well-known flavonoid, has been shown to accelerate wound healing by enhancing collagen synthesis and reducing inflammatory responses *(Rao, M. J., & Zheng, B. 2025)*.
3. **Terpenoids:** Terpenoids are a large class of organic compounds derived from isoprene units and are responsible for the characteristic aroma of many plants. They exhibit antimicrobial and anti-inflammatory activities, making them crucial for wound healing. For instance, artemisinin, a sesquiterpenoid derived from Artemisia annua, has demonstrated antimicrobial properties that help prevent infections in wounds *(Thompson et al., 2025)*.
4. **Phenolic Compounds:** Phenolic compounds are characterized by one or more hydroxyl groups attached to an aromatic ring. They possess strong antioxidant and astringent properties that protect tissues from oxidative damage and promote wound contraction. Tannins, a subgroup of phenolic compounds, help in the formation of a protective layer over wounds, which prevents microbial infections and accelerates tissue repair. Gallic acid, a phenolic compound, has been extensively studied for its wound-healing properties, including its role in enhancing fibroblast proliferation and collagen production *(Rahime et al., 2024)*.

Mechanisms of Action of Bioactive Compounds in Wound Healing

1. **Anti-Inflammatory Activity:** Inflammation is a critical initial phase of wound healing, but prolonged or excessive inflammation can delay recovery. Bioactive compounds like curcumin (from turmeric) and saponins reduce the production of pro-inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α). By modulating the inflammatory response, these compounds prevent chronic inflammation and prepare the wound site for tissue repair *(Helmy et al., 2025)*.
2. **Antimicrobial Activity:** Wound infections caused by bacteria, fungi, or viruses can significantly impede healing. Bioactive compounds such as berberine, tannins, and tea tree oil exhibit antimicrobial effects by disrupting microbial membranes, inhibiting biofilm formation, or interfering with microbial DNA replication, these actions protect the wound from infections and reduce the risk of complications *(Afghan et al., 2024; Wadhwa et al., 2024)*.
3. **Antioxidant Activity:** Oxidative stress is a major factor that damages cells and delays wound healing. Bioactive compounds like quercetin, ascorbic acid, and epigallocatechin gallate (EGCG) from green tea scavenge free radicals, reducing oxidative damage to tissues. These antioxidants also enhance fibroblast activity and collagen synthesis, which are vital for tissue regeneration *(Niazi, P. 2024)*.
4. **Tissue Regeneration and Collagen Synthesis:** Many bioactive compounds directly promote the proliferation of fibroblasts, keratinocytes, and endothelial cells, all of which are necessary for tissue repair. Compounds like asiaticoside from Centella asiatica and

resveratrol from grapes stimulate angiogenesis and ECM production, accelerating wound closure and restoring skin integrity *(Vinchhi et al., 2024)*.

Examples of Key Bioactive Compounds and Their Therapeutic Effects

- **Curcumin (from turmeric):** Curcumin is widely recognized for its anti-inflammatory, antimicrobial, and antioxidant properties, it reduces pro-inflammatory cytokines, protects tissues from oxidative stress, and promotes granulation tissue formation, making it highly effective for chronic wounds (Boroumand et al., 2018).
- **Berberine (from Berberis species):** Known for its broad-spectrum antimicrobial activity, berberine prevents infections and supports tissue repair by reducing inflammation (Murshed et al., 2024).
- **Tannins (from various plants):** Tannins are phenolic compounds that create a protective layer over wounds, reducing microbial contamination and facilitating contraction of the wound site (Schilrreff, P., & Alexiev, U. 2022).
- **Asiaticoside (from Centella asiatica):** This compound enhances fibroblast proliferation, stimulates angiogenesis, and accelerates collagen synthesis, making it particularly effective for improving skin elasticity and minimizing scarring (Davey et al., 2007).
- **Quercetin (from fruits and vegetables):** Quercetin's antioxidant and anti-inflammatory properties help protect against oxidative stress, stimulate keratinocyte migration, and support the re-epithelialization of wounds (Polerà et al., 2019).
- **Resveratrol (from grapes):** Resveratrol promotes angiogenesis and collagen deposition, contributing to faster healing and reduced scar formation (Hecker et al., 2022).

Table 1 *(Lists medicinal plants, their properties, and the mechanisms of action used in wound healing.)*

Plant	Main Bioactive Components	ABP (Antibacterial Properties)	AI (Anti-inflammatory Properties)	RP (Regeneration Properties)	AO (Antioxidant Properties)	AV (Antiviral Properties)	Mechanism of Action
Aloe Vera	Polysaccharides, flavonoids, saponins	Yes	Yes	Yes	Yes	No	1. Aloe Vera's gel accelerates wound healing by promoting collagen synthesis 2. Reducing inflammation 3. Offering antimicrobial effects.
Achillea millefolium	Flavonoids	Yes	No	Yes	No	No	1. Reduces inflammatory mediators NO and PGE2. 2. Modulates the inflammatory cytokine and growth factor. 3. 3. Stimulates keratinocyte differentiation and motility.

							4. Stimulates collagen expression.
Calendula	Flavonoids, triterpenes, carotenoids	Yes	Yes	Yes	Yes	No	1. Increases keratinocytes and fibroblast proliferation. 2. Promotes expression of mediators of the inflammatory response. 3. Stimulates collagen production and angiogenesis. 4. Promotes expression of mediators of the inflammatory response. 5. Reduced glutathione levels. 6. Inhibits lipoxygenase activity.
Neem	Alkaloids, flavonoids, terpenoids	Yes	Yes	Yes	Yes	Yes	1. Neem's compounds possess antimicrobial, anti-inflammatory. 2. Antioxidant properties. 3. Supporting immune function and tissue repair.
Turmeric	Curcumin, flavonoids, phenolic compounds	Yes	Yes	Yes	Yes	No	1. Curcumin's anti-inflammatory and antioxidant properties promote wound healing by modulating cytokine production 2. Reducing oxidative stress.
Lavender	Linalool, linalyl acetate, flavonoids	Yes	Yes	Yes	Yes	No	1. Lavender's compounds enhance healing through antimicrobial effects, modulation of inflammation. 2. Relaxation of surrounding tissues.
Gotu Kola	Triterpenoids, saponins, flavonoids	Yes	Yes	Yes	Yes	No	1. Triterpenoids and flavonoids in Gotu Kola promote collagen synthesis. 2. Enhance microcirculation, and reduce inflammation.

							3. Speeding tissue regeneration.
Datura innoxia	Alkaloids, phenols, carbohydrates, flavonoids, saponins, Terpenoids	Yes	Yes	Yes	Yes	Yes	1. It significantly inhibited the markers of inflammation. 2. Potent in vivo anti-inflammatory, antinociceptive, and antidepressant effects.
Reynoutria japonica	Polyphenols, Tannins	Yes	Yes	Yes	Yes	Yes	1. Increased synthesis of collagen III. 2. Strongly stimulated fibroblast proliferation and migration.
Rosmarinus officinalis	Flavonoids	Yes	Yes	Yes	Yes	No	1. Reduces inflammatory cytokines expression (IL-1β, IL-6, TNF-α). 2. Reduces the expression of iNOS, COX-2, P-IκB, and NF-κB/p65. 3. Inhibits NO production.
Plantago L.	Monoterpenoids	Yes	No	Yes	Yes	No	1. Reduces pro-inflammatory cytokine level (PGE2, TNF-α). 2. Reduces superoxide anion. 3. Inhibits NO production. 4. Decreases fibroblast's hydrogen peroxide cytotoxicity.
Glycyrrhiza glabra	Flavonoids, Terpenoids	Yes	Yes	Yes	Yes	No	1. Reduces superoxide anion. 2. Increases the wound healing rate. 3. Increases fibroblast proliferation. 4. Inhibits NO production. 5. Increases collagen deposition.
Malva sylvestris	Polysaccharides, Flavonoids	Yes	Yes	Yes	No	No	1. Increases the wound healing rate. 2. Increases collagen deposition. 3. Enhances vascularization. 4. Modulates the inflammatory response.
Casearia sylvestris	Triterpenoids, Phenolic acid	Yes	No	No	No	No	1. Reduces myeloperoxidase activity. 2. Reduces early and late edema.
Crocus sativus	Carotenoids, Monoterpenoids, Flavonoids, Phenolic acids.	No	Yes	Yes	Yes	No	1. Increases fibroblast proliferation. 2. Increases the level of anti-inflammatory cytokines (IL-4 and IL-10). 3. Reduces the level of pro-inflammatory cytokines (TNF-α and IL-6). 4. Enhances vascularization. 5. Inhibits lipid peroxidation.

Curcuma longa	Curcuminoids	No	Yes	Yes	Yes	No	1. Enhances fibroblast migration. 2. Enhance the granulation tissue formation. 3. Enhance the collagen deposition. 4. Regulates many genes implicated in the initiation of inflammatory responses (NF-(κ) B, AKT, PI3K, IKK). 5. Increases TGF-β production. 6. Increases fibroblast Proliferation.
Bletilla striata	Flavonoids, Polysaccharides, Triterpenoids, Stilbenoids.	Yes	Yes	Yes	Yes	Yes	1. Increases the NO and promotes, 2. Promotes epithelial cell growth and fibroblast proliferation. 3. Promotes the expression of mediators of the inflammatory response. 4. Promotes the expression of mediators of the neutrophils, monocytes, and macrophages chemotaxis.
Salvia officinalis	Terpenes, Sesquiterpenes	Yes	No	Yes	No	Yes	1. Reduces pro-inflammatory cytokines. 2. Downregulates mRNA expression levels of IL-6, IL-1 β, and TNF-α augment fibroblast proliferation via enhancing cyclin-D1 expression.

TRADITIONAL APPROACHES TO WOUND HEALING

Traditional approaches to wound healing have been practiced for centuries across cultures, relying heavily on the preparation and application of plant-based remedies, these methods, often rooted in indigenous knowledge and cultural traditions, continue to offer valuable insights into natural wound care *(Leavesley et al., 2019)*. Plants are used in various forms, such as poultices, extracts, and ointments, to clean wounds, prevent infections, and promote healing. The efficacy of these practices is supported by the bioactive compounds present in medicinal plants, which possess antimicrobial, anti-inflammatory, antioxidant, and tissue-regenerative properties *(Hashim et al., 2024; Fahmawi et al., 2024)*.

Preparation and Application of Plant-Based Remedies

1. **Poultices:** Poultices are one of the oldest methods of wound treatment, involving the direct application of crushed or macerated plant materials onto the wound. The mixture is often wrapped with a cloth or bandage to ensure prolonged contact. For example, crushed leaves of Plantago major (plantain) have been traditionally used to reduce inflammation, control bleeding, and prevent infections *(Jarić et al., 2018)*.
2. **Extracts:** Plant extracts are prepared by steeping, boiling, or macerating plant parts in water, oil, or alcohol to isolate active compounds. These extracts are applied directly to wounds or mixed with other agents to create salves or lotions. For instance, neem (Azadirachta indica) leaf extracts, known for their antibacterial properties, are used to disinfect wounds and promote healing.
3. **Ointments and Balms:** Ointments are made by mixing plant extracts or powders with a base such as animal fat, beeswax, or vegetable oils. These formulations provide a protective barrier over the wound while delivering therapeutic compounds. Calendula officinalis (marigold) ointments are commonly used in traditional medicine to soothe inflamed skin and accelerate tissue repair *(Ozturk et al., 2023)*.
4. **Infusions and Washes:** Infusions, prepared by steeping plant materials in hot water, are used as antiseptic washes to clean wounds. For example, turmeric (Curcuma longa) infusions are applied to wounds in India to prevent infection and reduce inflammation *(Maver et al., 2015)*.

Common Plant Species Used Traditionally

1. **Aloe Vera (Aloe barbadensis miller):** Known as the plant of immortality in ancient Egypt, aloe vera has been widely used for treating burns, cuts, and ulcers. Its gel contains polysaccharides, glycoproteins, and vitamins that promote cell proliferation, reduce inflammation, and provide a soothing effect on wounds *(Saibhavani et al., 2022)*.
2. **Calendula (Calendula officinalis):** Marigold flowers are valued for their anti-inflammatory and antimicrobial properties. Calendula extracts are traditionally used in Europe and Asia to treat minor wounds, burns, and skin irritations by enhancing granulation tissue formation and promoting re-epithelialization *(Albahri et al., 2023)*.
3. **Neem (Azadirachta indica):** Neem is a staple in Ayurvedic medicine for its broad-spectrum antimicrobial effects. Neem leaf pastes or oils are applied to wounds to disinfect the area, reduce inflammation, and accelerate healing *(Singh et al., 2021)*.
4. **Turmeric (Curcuma longa):** Turmeric, a cornerstone of traditional Indian medicine, is renowned for its anti-inflammatory and antimicrobial compound curcumin. It is used in powdered form or mixed with oils to create wound dressings that enhance collagen deposition and reduce oxidative stress *(Tripathi, T. 2024)*.
5. **Plantain (Plantago major):** Commonly used in Europe and North America, plantain leaves are applied as poultices to reduce swelling, control bleeding, and protect against infections. Its bioactive compounds, such as allantoin, promote cell proliferation and wound contraction *(E'atelaf, A. 2013)*.

Case Studies and Regional Examples of Traditional Practices

1. *India (Ayurveda and Tribal Medicine):* In Ayurvedic medicine, turmeric and neem are central to wound care. Tribes in India also use the paste of Terminalia arjuna bark for deep wounds due to its astringent and healing properties. For burns, Aegle marmelos leaves are boiled and applied as compresses to soothe the skin *(Maas, P. A. 2018)*.
2. **Africa:** Traditional healers across Africa use Centella asiatica (gotu kola) for wound healing and scar reduction. In Kenya, crushed leaves of Carica papaya (papaya) are applied to wounds to accelerate tissue regeneration, aided by its proteolytic enzymes like papain, which debride necrotic tissue *(Mgonja et al., 2022)*.
3. **South America:** Indigenous communities in the Amazon basin use Croton lechleri (dragon's blood), a red latex sap from tree bark, to treat cuts and ulcers. The sap forms a protective barrier over the wound and provides antimicrobial and antioxidant effects, enhancing tissue repair *(King et al., 2020)*.
4. **China (Traditional Chinese Medicine):** Chinese medicine emphasizes the use of Panax ginseng to invigorate blood circulation and promote healing. Another common remedy includes applying powdered pearls mixed with honey to wounds for their antiseptic and regenerative properties *(Sang et al., 2021)*.
5. **Europe:** In traditional European herbal medicine, Symphytum officinale (comfrey) root is used for wound care due to its high allantoin content, which stimulates cell proliferation and accelerates healing *(Melnyk, N., & Vlasova, I. 2022)*.

MODERN APPROACHES IN WOUND HEALING

With the growing recognition of the therapeutic potential of medicinal plants, modern medicine has increasingly incorporated their bioactive compounds into advanced wound care solutions, these innovations aim to harness the healing properties of plants while addressing the challenges of standardization, safety, and efficacy. Advances in phytochemical formulations, the integration of herbal medicines into modern wound care, and rigorous quality control measures have paved the way for plant-based treatments to complement or even replace conventional therapies in certain contexts.

Advances in the Use of Medicinal Plants in Contemporary Medicine

The application of medicinal plants has evolved significantly, moving from traditional poultices and extracts to scientifically formulated products tailored for modern wound care *(Elendu, C. 2024)*.

1. **Phytochemical Formulations:** Advances in biotechnology and pharmacology have enabled the extraction, isolation, and synthesis of plant-derived bioactive compounds, leading to the development of creams, gels, and sprays specifically designed for wound healing. For example, creams containing curcumin (from turmeric) are now used for their anti-inflammatory and antioxidant properties, while aloe vera-based gels are marketed globally for treating burns and cuts *(Niazi, P. 2024)*.
2. **Advanced Wound Dressings:** Modern dressings infused with plant-derived compounds combine traditional wisdom with cutting-edge technology. Examples include hydrocolloid and alginate dressings enriched with antimicrobial agents from neem or honey. Additionally, dressings impregnated with essential oils, such as tea tree or lavender oil, provide sustained antimicrobial activity while maintaining a moist healing environment *(Ovington, L. G. 2007)*.

3. **Nanotechnology Applications:** Recent advancements involve the use of nanotechnology to enhance the delivery of plant-based bioactive compounds. Nanoformulations improve the stability, bioavailability, and efficacy of these compounds, enabling sustained release and targeted action. For instance, curcumin-loaded nanoparticles have shown promise in promoting wound healing by accelerating angiogenesis and reducing oxidative stress *(Silva, G. A. 2004)*.

The Role of Herbal Medicines in Modern Wound Care

Herbal medicines have emerged as valuable tools in wound management due to their multifaceted therapeutic effects *(Kolimi et al., 2022)*. Unlike conventional drugs, which often target specific aspects of wound healing, plant-based treatments offer a holistic approach that simultaneously addresses multiple phases of the healing process.

1. **Antimicrobial Effects:** Many herbal medicines, such as neem oil and tea tree oil, are effective against a broad spectrum of bacteria, fungi, and viruses, these properties are particularly useful in preventing or managing wound infections, which remain a major challenge in clinical wound care *(Hsieh et al., 2001; Hejran et al., 2025; Wadhwa et al., 2024)*.
2. **Anti-Inflammatory Properties:** Plant-derived compounds such as flavonoids and terpenoids help modulate inflammation, reducing pain, swelling, and tissue damage. For instance, calendula extracts are widely used in modern ointments to soothe inflammation in burns and abrasions *(Kciuk et al., 2024)*.
3. **Antioxidant Activity:** Herbal medicines such as aloe vera and green tea extracts combat oxidative stress, which can delay healing. By neutralizing free radicals, these compounds protect tissue cells and promote regeneration *(Nahiz et al., 2024)*.
4. **Promotion of Tissue Regeneration:** Certain plant-derived compounds, like asiaticoside from Centella asiatica, stimulate fibroblast proliferation, collagen synthesis, and angiogenesis, accelerating the repair of damaged tissue *(Arribas-López et al., 2022)*.
5. **Adjunctive Therapy for Chronic Wounds:** In conditions such as diabetic foot ulcers, where conventional treatments often fall short, herbal medicines can complement standard care. For example, honey-based wound dressings have been shown to enhance healing in chronic wounds by promoting a moist environment, reducing bacterial load, and stimulating tissue repair *(Hunt, S., & Elg, F. 2017; SAKEN et al., 2024)*.

Standardization and Quality Control of Plant-Based Treatments

A major challenge in integrating medicinal plants into modern wound care is ensuring the consistency, safety, and efficacy of plant-based treatments. Unlike synthetic drugs, herbal medicines are often subject to variability due to differences in plant species, cultivation conditions, and extraction methods *(Mason, W. W., & Ward, W. A. 1992; Kamil, M., & Naji, M. A. 2009; Efferth, T., & Greten, H. J. 2012; Nafiu et al., 2017; Karnwal et al., 2024; Hejran et al., 2024)*:

1. **Standardization of Extracts:** Modern approaches involve standardizing plant extracts to ensure a consistent concentration of active compounds. For instance, formulations containing curcumin are now standardized to include a defined percentage of curcuminoids, ensuring predictable therapeutic outcomes.

2. **Quality Control Measures:** Rigorous quality control protocols, including phytochemical analysis, microbial testing, and stability studies, are essential for ensuring the safety of plant-based treatments. Advanced techniques such as high-performance liquid chromatography (HPLC) and mass spectrometry are widely used to analyze the composition and purity of herbal products.
3. **Good Manufacturing Practices (GMP):** To meet regulatory standards, plant-based wound care products are manufactured under GMP guidelines, which ensure that products are safe, effective, and free from contaminants. These practices also involve the ethical sourcing of raw materials, ensuring sustainability and environmental responsibility.
4. **Clinical Validation:** The efficacy of plant-based treatments is increasingly being validated through clinical trials. For example, randomized controlled trials have demonstrated the effectiveness of aloe vera gel in reducing healing time for burn wounds and honey dressings in managing infected wounds.
5. **Regulatory Frameworks:** Governments and international organizations are developing regulatory frameworks to oversee the development and use of herbal medicines. In regions such as the European Union and India, herbal products must undergo rigorous evaluation to obtain approval for medical use.

SCIENTIFIC VALIDATION OF MEDICINAL PLANTS

The use of medicinal plants for wound healing has gained significant scientific interest in recent years, with a growing body of preclinical and clinical studies validating their efficacy. Modern research has provided valuable insights into the mechanisms of action of plant-based treatments and has compared the effectiveness of traditional applications with modern formulations. These findings bridge the gap between traditional knowledge and contemporary medicine, paving the way for innovative wound care solutions *(Taylor et al., 2001)*.

Preclinical and Clinical Studies on Medicinal Plants for Wound Healing

Scientific studies, including preclinical experiments and clinical trials, have extensively evaluated the potential of medicinal plants in wound management (Lordani et al., 2018; Salazar-Gómez, A., & Alonso-Castro, A. J. 2022; Herman, A., & Herman, A. P. 2023):

1. **Preclinical Studies:** Preclinical investigations, primarily conducted on animal models, have revealed the therapeutic benefits of bioactive compounds derived from medicinal plants. Aloe vera: Preclinical studies have demonstrated that aloe vera gel accelerates wound contraction, collagen synthesis, and re-epithelialization in rat models. Its anti-inflammatory and antioxidant properties have been found to mitigate oxidative stress at wound sites. Centella asiatica: The active compound asiaticoside has been shown to enhance fibroblast proliferation, angiogenesis, and collagen production, significantly improving wound healing in animal studies. Curcumin (from turmeric): Preclinical trials have highlighted its ability to reduce inflammation, promote tissue remodeling, and improve tensile strength in wounds treated with curcumin-loaded dressings or gels.
2. **Clinical Trials:** Clinical trials have provided further validation for the use of plant-based therapies in wound care. Honey-Based Dressings: Clinical studies have confirmed the efficacy

of honey dressings in chronic wound management, particularly for diabetic foot ulcers. These dressings reduce bacterial colonization, improve wound healing time, and minimize scarring. Calendula Extracts: Randomized controlled trials have shown that calendula-based creams significantly reduce healing time for post-operative wounds compared to standard care. Neem Oil: Neem oil has demonstrated effectiveness in managing infected wounds, with clinical data supporting its antimicrobial properties and ability to reduce inflammation.

Efficacy of Plant-Based Treatments Supported by Modern Research

Modern research has corroborated the traditional use of medicinal plants in wound healing, often uncovering additional benefits through advanced methodologies *(Sarris et al., 2013; Franco et al., 2016; Najmi et al., 2022; Nagella et al., 2025)*.

1. **Antimicrobial Properties:** Many plant-derived compounds, such as flavonoids, tannins, and alkaloids, exhibit antimicrobial activity, which is critical in preventing infections in wounds. For example: Neem has been shown to be effective against Staphylococcus aureus and Pseudomonas aeruginosa, common pathogens in wound infections. Essential oils from plants like lavender and tea tree have demonstrated broad-spectrum antimicrobial activity in vitro and in vivo.
2. **Anti-Inflammatory and Antioxidant Activity:** Plant-based compounds reduce inflammation and oxidative stress, crucial factors in wound healing. Research indicates that: Polyphenols and flavonoids in plants like Camellia sinensis (green tea) neutralize reactive oxygen species (ROS), promoting faster tissue regeneration. Curcumin inhibits pro-inflammatory cytokines, helping to manage chronic inflammation in wounds.
3. **Enhanced Tissue Regeneration:** Many medicinal plants stimulate fibroblast activity, collagen synthesis, and angiogenesis, speeding up wound closure and tissue remodeling. Examples include: Asiaticoside from Centella asiatica, which has been shown to promote granulation tissue formation. Aloe vera polysaccharides, which enhance epithelial cell migration and proliferation.

Comparative Analysis: Traditional vs. Modern Applications

Traditional applications of medicinal plants rely on simple preparations, while modern medicine has refined these practices through standardization and technological advancements (Sharma, S., & Vardhan, M. 2025; Zhang et al., 2025; Bennur et al., 2025).

1. **Traditional Applications:** Traditional uses involve preparing poultices, decoctions, or ointments directly from plant materials. These remedies are often used based on anecdotal evidence or cultural practices. While effective, they are limited by variability in dosage, purity, and reproducibility. For example: Turmeric is traditionally applied as a paste to wounds, providing anti-inflammatory benefits, but the exact concentration of curcumin is inconsistent. Aloe vera gel is applied directly to burns and cuts but lacks standardized formulations in traditional practice.
2. **Modern Applications:** Modern science has refined these remedies by isolating active compounds, optimizing their delivery, and ensuring consistent therapeutic outcomes.

Examples include: Nanoformulations of curcumin that enhance bioavailability and targeted action compared to traditional turmeric paste. Advanced aloe vera-based dressings with defined concentrations of polysaccharides and antimicrobial agents, offering superior wound healing compared to raw gel. Standardized extracts of calendula, incorporated into creams and ointments, with clinical validation for healing efficacy.

3. **Efficacy and Safety:** Modern formulations ensure safety by eliminating contaminants and standardizing doses, which is often a concern in traditional preparations. While traditional applications may lack robust scientific validation, modern approaches rely on rigorous clinical testing to confirm efficacy and safety, making them more reliable for widespread use.

MECHANISMS OF WOUND HEALING BY MEDICINAL PLANTS

Medicinal plants facilitate wound healing through multiple physiological mechanisms, including the reduction of inflammation, promotion of collagen synthesis, and acceleration of tissue regeneration. These effects are largely attributed to the bioactive compounds present in medicinal plants, which exhibit antimicrobial, anti-inflammatory, and antioxidant properties. By targeting various stages of the wound-healing process, medicinal plants support effective tissue repair and minimize complications such as infections and chronic inflammation (Firdaus et al., 2025).

Physiological Effects of Medicinal Plants on Wound Healing

1. **Reduction of Inflammation:** Inflammation is the initial response to tissue injury, characterized by the recruitment of immune cells to the wound site to clear pathogens and debris. Excessive or prolonged inflammation, however, can hinder the healing process. Medicinal plants reduce inflammation by modulating cytokine activity and suppressing the production of inflammatory mediators such as prostaglandins and interleukins. Curcumin (from turmeric) inhibits nuclear factor-kappa B (NF-κB), a key regulator of inflammation, thus reducing swelling, redness, and pain. Aloe vera contains bradykinase, an enzyme that reduces inflammation at the wound site by breaking down bradykinin, a peptide that promotes inflammation.
2. **Collagen Synthesis:** Collagen is a critical structural protein that strengthens and supports newly formed tissue during the proliferative and remodeling phases of wound healing. Medicinal plants stimulate fibroblast activity, leading to enhanced collagen production and cross-linking. Centella asiatica promotes the synthesis of type I and III collagen, which improves tensile strength and elasticity in healed tissue. Flavonoids and tannins from plants like Calendula officinalis stimulate fibroblast proliferation, facilitating rapid deposition of collagen in granulation tissue.
3. **Tissue Regeneration:** Tissue regeneration involves the formation of granulation tissue, re-epithelialization, and angiogenesis (new blood vessel formation). Medicinal plants accelerate these processes by activating growth factors and promoting cell migration and proliferation. Aloe vera polysaccharides enhance keratinocyte and fibroblast migration, aiding in the formation of new skin layers. Neem extract supports angiogenesis by upregulating vascular endothelial growth factor (VEGF), ensuring an adequate blood supply for tissue repair.

Antimicrobial, Anti-Inflammatory, and Antioxidant Properties of Specific Plants

Medicinal plants exert powerful antimicrobial, anti-inflammatory, and antioxidant effects, which are vital for protecting the wound from infection and oxidative stress while facilitating tissue repair *(Ottaviano et al., 2025)*.

1. **Antimicrobial Properties:** Preventing infection is essential in wound management, as microbial colonization can delay healing or lead to chronic wounds. Neem (Azadirachta indica): Neem contains nimbidin and azadirachtin, compounds with potent activity against wound-infecting bacteria such as Staphylococcus aureus and Escherichia coli. Honey: Known for its broad-spectrum antimicrobial activity, honey releases hydrogen peroxide, which sterilizes the wound environment and prevents bacterial growth.
2. **Anti-Inflammatory Properties:** Chronic inflammation can impede the healing process, making the anti-inflammatory properties of medicinal plants crucial. Turmeric: Curcumin reduces pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6), aiding in the resolution of inflammation. Calendula officinalis: Rich in triterpenoids, calendula extracts suppress inflammatory mediators and reduce swelling, making them effective for treating burns and abrasions.
3. **Antioxidant Properties:** Oxidative stress caused by reactive oxygen species (ROS) at the wound site can damage cells and delay healing. Antioxidants in medicinal plants neutralize ROS, protecting tissues from damage and supporting cellular repair. Green Tea (Camellia sinensis): Catechins in green tea exhibit strong antioxidant activity, reducing oxidative damage and promoting faster wound closure. Aloe vera: Aloe contains vitamins C and E, which act as antioxidants to mitigate oxidative stress and support tissue repair.

WOUND HEALING PROCESS

Wound healing is a complex and dynamic process that restores tissue integrity after injury. It involves a series of coordinated physiological events that aim to repair damaged tissues, stop bleeding, prevent infection, and regenerate healthy skin and other tissues. The process involves various cell types, signaling molecules, and extracellular matrix components. The healing process is divided into distinct but overlapping stages: hemostasis, inflammation, proliferation, and maturation (Kirsner, R. S., & Eaglstein, W. H. 1993; Velnar et al., 2009).

Stages of the Wound Healing Process (Hosgood, G. 2006):

1. **Hemostasis (Immediate Response):** This phase begins immediately after injury and focuses on stopping bleeding. Blood vessels constrict to reduce blood flow, and platelets aggregate to form a clot at the injury site. Clotting factors are activated, leading to the formation of a fibrin clot that seals the wound and prevents further blood loss.
2. **Inflammation (1-4 Days):** The inflammatory phase follows hemostasis and involves the body's defense mechanisms to prevent infection and clear debris from the wound site. White blood cells like neutrophils and macrophages are recruited to the site, where they remove pathogens, dead cells, and other waste material. Inflammation is characterized by redness, heat, swelling, and pain, all of which are signs of the body’s immune response. Cytokines and growth factors are released, signaling the next phase of healing.

3. **Proliferation (4-21 Days):** During this phase, new tissue starts to form. Key processes include: Angiogenesis: The formation of new blood vessels to provide oxygen and nutrients to the healing tissue. Fibroplasia: Fibroblasts migrate to the wound and produce collagen and extracellular matrix, providing structural support. Reepithelialization: Keratinocytes at the wound edges proliferate and migrate across the wound bed, covering it with new skin. Granulation tissue formation: A combination of new blood vessels, fibroblasts, and extracellular matrix forms a granular tissue that fills the wound.
4. **Maturation (Remodeling) (Months to Years):** The final phase involves the remodeling and strengthening of the new tissue. Collagen fibers are reorganized, and their alignment is adjusted to increase the tensile strength of the wound. The newly formed blood vessels regress, and the wound contracts to reduce its size. Although the tissue gains strength, it often remains weaker than the original, and scar tissue may form.

Current Therapies in Wound Healing (Braddock et al., 1999; Chopra et al., 2025):

1. **Traditional Therapies:** Dressings: Conventional wound dressings (gauze, cotton pads) help protect the wound, absorb exudate, and prevent infection. Advances include hydrogels, hydrocolloids, and alginate dressings, which maintain moisture and promote faster healing. Topical Agents: Antiseptic creams, antibiotics, and ointments such as silver sulfadiazine or honey are commonly used to manage infection and support tissue regeneration.
2. **Biological and Bioactive Therapies:** Growth Factors and Cytokines: Recombinant growth factors like platelet-derived growth factor (PDGF) and epidermal growth factor (EGF) are used to stimulate cell growth, migration, and tissue repair. Stem Cell Therapy: Stem cells, particularly mesenchymal stem cells (MSCs), are being studied for their potential to regenerate tissues and accelerate healing by promoting collagen synthesis and reducing inflammation.
3. **Modern Approaches and Innovations:** Nanotechnology: Nanoparticles and nanofibers are increasingly used in wound healing to deliver bioactive compounds like growth factors, antimicrobial agents, and antioxidants directly to the wound site. Nanomaterials improve bioavailability and promote tissue regeneration. Tissue Engineering: Advanced biomaterials and scaffolds, such as biocompatible hydrogels and electrospun nanofibers, are used to support cellular growth and tissue formation in chronic wounds. Negative Pressure Wound Therapy (NPWT): This technique involves applying controlled suction to the wound to reduce edema, improve circulation, and promote faster healing, especially in large or chronic wounds.
4. **Plant-Based and Natural Therapies:** Herbal Remedies: Medicinal plants, such as Aloe vera, calendula, and neem, are used for their anti-inflammatory, antimicrobial, and regenerative properties. Phytochemicals such as flavonoids, alkaloids, and terpenoids have demonstrated potential to enhance wound healing. Essential Oils and Phytochemicals: Natural compounds from plants, including phenolic compounds, flavonoids, and terpenoids, can reduce oxidative stress, improve circulation, and stimulate collagen production, contributing to wound healing.

CHALLENGES AND LIMITATIONS

While medicinal plants offer a promising and natural alternative for wound healing, their use in clinical practice is not without challenges. These challenges encompass issues related to the standardization and dosage of herbal treatments, potential side effects or contraindications, and regulatory and ethical concerns. Addressing these limitations is essential to ensuring the safe, effective, and consistent use of plant-based therapies in modern medicine.

Issues in Standardization and Dosage of Herbal Treatments

One of the most significant challenges in utilizing medicinal plants for wound healing is the lack of standardization and precise dosage. Unlike pharmaceutical drugs, which undergo rigorous testing and regulation to determine optimal dosages, plant-based treatments often vary in potency due to differences in plant species, cultivation conditions, harvesting times, and preparation methods. This lack of consistency can lead to variations in therapeutic outcomes *(Kumari, R., & Kotecha, M. 2016)*. **Herbal formulation variability:** The concentration of bioactive compounds in medicinal plants can fluctuate significantly. For example, the curcumin content in turmeric or the polysaccharide levels in aloe vera may differ depending on how the plant is processed and stored. **Dose determination:** Herbal treatments lack standardized dosages, making it challenging for healthcare providers to prescribe precise amounts for optimal effectiveness. Without established guidelines, the risk of underdosing or overdosing increases, potentially reducing the therapeutic benefits or causing adverse effects. To overcome these issues, further research is needed to establish standardized preparations of medicinal plants, including precise dosages and concentrations of active compounds. The development of plant-based formulations with consistent potency could enhance their therapeutic reliability.

Potential Side Effects or Contraindications of Medicinal Plants

Despite their natural origin, medicinal plants are not devoid of potential side effects or contraindications. Some plants may cause adverse reactions, particularly if used improperly or in combination with other medications *(Firdous et al., 2025)*. **Allergic reactions:** Certain plants, such as Aloe vera, may trigger allergic reactions in sensitive individuals. This can manifest as skin irritation, redness, or itching, which could worsen the wound or delay healing. **Toxicity:** Some medicinal plants contain compounds that are toxic when used in large quantities or over extended periods. For example, Echinacea may cause liver toxicity in some individuals if consumed in excessive amounts. **Drug interactions:** Some plant-based remedies may interact with conventional drugs, leading to unwanted side effects. For instance, Ginkgo biloba can increase bleeding risk and may interact with anticoagulant medications. Therefore, it is crucial for healthcare professionals to be aware of the potential risks and contraindications of specific plants, particularly for patients with underlying health conditions or those already on other medications. Conducting thorough patient assessments and monitoring for adverse effects can help mitigate these risks.

Regulatory and Ethical Concerns in Using Plants for Medical Purposes

The use of medicinal plants for wound healing raises several regulatory and ethical concerns that need to be addressed to ensure the safe and responsible use of these treatments (Padhiary et al., 2025).

1. **Lack of regulatory oversight:** In many countries, medicinal plants are not subject to the same rigorous regulations as pharmaceutical drugs. This can result in the sale of untested or

misidentified plant products, leading to variations in quality and safety. Without proper regulation, the risk of contamination with harmful substances such as heavy metals, pesticides, or microbes increases (Baseer et al., 2024; Hassand et al., 2024; Kakar et al., 2024; Ardak et al., 2024). Ethnobotanical claims vs. scientific validation: Traditional use of medicinal plants is often based on anecdotal evidence or cultural practices, which may not always be scientifically validated. This can lead to the promotion of ineffective or potentially harmful treatments.

2. **Intellectual property concerns:** The growing interest in medicinal plants has sparked debates over intellectual property rights, particularly in relation to the commercialization of traditional knowledge. Indigenous communities may have used certain plants for centuries, but they may not always benefit from the economic exploitation of their traditional knowledge by pharmaceutical companies. Biopiracy: There is concern that companies may exploit natural resources and traditional knowledge without proper compensation to the communities that have cultivated these practices. This raises ethical questions about the ownership of plant-based remedies and the fair distribution of benefits.
3. **Quality control:** Ensuring the quality and safety of plant-based treatments requires robust quality control mechanisms. As medicinal plants are often sold in various forms such as teas, extracts, or ointments, there must be consistent standards in terms of purity, potency, and safety to prevent harmful contaminants from affecting patient outcomes.

FUTURE PERSPECTIVES IN WOUND HEALING

The field of wound healing is continually evolving, with significant advancements being made in both traditional and modern approaches. Among these, plant-based wound care is gaining increasing attention due to its natural healing properties. The future of wound healing will likely be shaped by the integration of plant-based therapies with cutting-edge biotechnology, leading to more effective, targeted treatments. Here, we explore emerging trends in plant-based wound care, the potential for biotechnology to enhance the therapeutic use of plants, and future research directions in this promising area.

Emerging Trends in Plant-Based Wound Care

As the search for natural, safe, and effective wound healing treatments continues, plant-based therapies are poised to become integral components of modern wound care regimens. One of the key emerging trends is the development of bioactive plant-based wound dressings. These dressings, often made from plant-derived materials such as aloe vera, turmeric, and calendula, are designed to not only provide physical protection but also to deliver active compounds that promote healing. For example, aloe vera-based dressings are known to reduce inflammation and accelerate re-epithelialization, while turmeric's anti-inflammatory and antimicrobial properties enhance tissue regeneration.

Another emerging trend is the formulation of plant-based topical creams and gels that combine multiple bioactive compounds to target various stages of the wound healing process. Advances in phytochemical extraction methods, such as supercritical fluid extraction and nanotechnology-based encapsulation, are allowing for more efficient isolation of active compounds, which can be formulated into highly effective wound-healing products. These innovations are expected to improve the potency, stability, and bioavailability of plant-based remedies, leading to more efficient and faster healing.

The Potential for Biotechnology to Enhance the Therapeutic Use of Plants

Biotechnology holds tremendous potential in enhancing the effectiveness of plant-based wound care treatments. The combination of traditional plant knowledge with modern biotechnological tools offers exciting possibilities for more precise, controlled, and efficient therapeutic outcomes. One key area where biotechnology is poised to make a significant impact is in the genetic modification of plants to increase the concentration of bioactive compounds with wound-healing properties. By using techniques such as CRISPR gene editing, plants can be engineered to produce higher levels of beneficial compounds like flavonoids, alkaloids, or terpenoids, which are known for their antimicrobial, anti-inflammatory, and regenerative effects.

Additionally, nanotechnology is becoming increasingly integrated into plant-based wound healing. Nanoparticles derived from medicinal plants can be used to enhance the delivery of active compounds directly to the wound site. These nano-formulations not only improve the absorption and stability of plant bioactives but also enable controlled release over time, ensuring sustained therapeutic effects. Moreover, nanocarriers can be designed to target specific cells or tissues, increasing the precision and efficacy of treatments *(Yadav et al., 2025)*.

The development of biocompatible plant-based scaffolds and tissue-engineered skin is another area where biotechnology is revolutionizing wound care. These biotechnologically engineered products are designed to mimic the structure and function of human skin, providing a framework for tissue regeneration. Plant-derived materials, such as cellulose or chitosan, are being explored as substrates for these scaffolds, offering a biodegradable, non-toxic, and cost-effective alternative to synthetic materials *(Monib et al., 2023)*.

Future Research Directions and Gaps in Knowledge

While the integration of plant-based treatments and biotechnology into wound healing holds great promise, several research gaps remain that need to be addressed in order to fully harness the therapeutic potential of medicinal plants.

Comprehensive Clinical Trials: One of the major gaps in knowledge is the limited number of large-scale, well-controlled clinical trials that evaluate the efficacy and safety of plant-based wound healing products. Although numerous preclinical studies show promising results, there is a need for more robust evidence in humans to substantiate the therapeutic benefits of these treatments.

Standardization and Quality Control: The inconsistency in the potency and quality of plant-based treatments remains a challenge. Future research must focus on developing standardized methods for phytochemical extraction and quality control of medicinal plant products to ensure consistent therapeutic efficacy. Additionally, efforts should be made to establish standardized dosages and concentrations of active ingredients to guide their clinical use.

Mechanisms of Action: While much is known about the individual bioactive compounds in medicinal plants, the specific molecular mechanisms through which these compounds promote wound healing need to be better understood. More research should focus on identifying the exact biochemical pathways involved in anti-inflammatory, antimicrobial, and tissue regenerative actions of plant-derived substances. Understanding these pathways will help in optimizing treatments and combining plant-based remedies with other therapeutic approaches.

Long-Term Efficacy and Safety: The long-term safety and efficacy of plant-based wound care products need to be thoroughly evaluated. Studies that assess the potential for chronic toxicity or adverse interactions with other medications are essential to ensure the safety of these treatments, particularly for vulnerable populations like the elderly or those with comorbidities *(Gupta et al., 2024)*.

Regulatory Frameworks: As the use of medicinal plants in wound care becomes more widespread, the establishment of clear regulatory frameworks will be necessary. Future research should focus on developing guidelines for the regulation and approval of plant-based treatments in different regions, ensuring that these products meet rigorous standards for quality, safety, and efficacy.

CONCLUSION

The severity of wounds significantly impacts an individual's quality of life globally, and effective wound healing depends on the interaction between extracellular matrix components, cell types, surface receptors, and therapeutic agents. The skin's complex structure makes it challenging to develop medications that promote rapid and effective healing. Recent scientific research has deepened our understanding of the role herbal medicines play in wound healing, particularly over the past five years. All plants reviewed in this context exhibit antioxidant, anti-inflammatory, and antibacterial properties, which are key factors in their ability to accelerate healing. Carotenoids, flavonoids, and triterpenoids found in wound dressings enhance antioxidant activity and alleviate oxidative stress. Reactive oxygen species (ROS) are crucial in healing, immune cell recruitment, angiogenesis, and pathogen elimination at the wound site, though excessive ROS can hinder healing by damaging extracellular matrix proteins and impairing keratinocytes and fibroblasts. The growing interest in plant extracts and their specific phytoconstituents highlights the need for optimal dosing and administration methods in wound healing therapies. Ongoing research should focus on identifying the ideal plant compositions, origins, and delivery systems for maximum efficacy. Incorporating herbal agents into modern wound care practices offers promising new therapies, especially for chronic wounds, by accelerating healing and preventing complications. However, challenges remain in enhancing the effectiveness and safe use of natural products in wound care, requiring multidisciplinary efforts to ensure safety, monitor adverse effects, and conduct clinical trials. Rigorous adherence to good manufacturing practices and regulatory standards is essential for integrating medicinal plants into mainstream healthcare. In conclusion, the bioactive compounds in medicinal plants such as alkaloids, flavonoids, terpenoids, and phenolic compounds hold significant therapeutic potential in promoting wound healing by reducing inflammation, fighting infections, and supporting tissue regeneration. The combination of traditional knowledge with modern scientific advances, including phytochemical formulations and nanotechnology, offers an opportunity to optimize plant-based remedies for better efficacy, safety, and precision in wound care. Looking forward, the continued exploration of medicinal plants, alongside advancements in biotechnology, has the potential to revolutionize wound care, providing sustainable, cost-effective, and personalized solutions for healing. As clinical evidence and product standardization grow, plant-based treatments are likely to gain wider adoption in mainstream medicine, offering more accessible and effective options for patients.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc).

CONSENT AND ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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