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A review on wound healing herbs

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Abstract

Wound healing is a dynamic physiological process involving hemostasis, inflammation, proliferation, and remodeling phases, which collectively restore the structural and functional integrity of damaged tissue. Conventional therapies, although effective, are often limited by issues such as antimicrobial resistance, cytotoxicity, and high cost. Herbal agents have gained substantial attention as safer and cost-effective alternatives due to their multifaceted pharmacological actions and minimal side effects. Numerous medicinal plants including *Aloe vera*, *Curcuma longa*, *Centella asiatica*, *Azadirachta indica*, *Calendula officinalis*, and *Lawsonia inermis* have shown remarkable efficacy in enhancing tissue regeneration through antioxidant, anti-inflammatory, antimicrobial, and angiogenic activities. Phytoconstituents such as flavonoids, terpenoids, alkaloids, tannins, and phenolic acids contribute to collagen deposition, fibroblast proliferation, epithelialization, and faster wound contraction. Preclinical and clinical studies corroborate these effects, demonstrating improved wound closure rates and reduced infection. Despite these promising results, challenges such as poor standardization, limited bioavailability, variability in plant composition, and lack of large-scale clinical validation hinder the full clinical translation of herbal wound therapies. Recent innovations integrating herbal bioactives with nanotechnology, hydrogels, and polymeric dressings offer new directions for next-generation wound management. This review compiles current evidence, highlights mechanistic insights, and discusses limitations and future perspectives for developing effective, standardized herbal wound-healing formulations.

Keywords: Herbal agents; Wound healing; Phytochemicals; Antioxidant activity; Anti-inflammatory effect; Nanotechnology; Smart biomaterials

1. Introduction

The regeneration and repair of injured tissue are components of the biological process of wound healing. This method is necessary to keep skin healthy and free of infections. According to .and modification of extracellular matrix, particularly collagen, a variety of cellular processes, including as inflammation, migration to the injured area, proliferation, angiogenesis, deposition, and others, can be engaged in the intricate and varied process of wound healing. Ointments, creams, and powders are among the many synthetic and semi-synthetic wound healing products on the market. But in recent years, natural products have gained increased attention as possible wound healers due to their efficacy and safety. Natural substances have been used for thousands of years in traditional medicine and have shown promise in hastening the healing of wounds[1]. These natural components can be used as drug delivery vehicles or applied directly to wounds, according to by promoting the growth of new blood vessels and acting as a scaffold for cell proliferation, they can help wounds heal. The use of herbal treatments in modern medicine has become increasingly significant for wound healing and tissue repair[2]. Furthermore, studies by have demonstrated the potential of plant-

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based nanomaterials to control the wound-healing process. Given this, a thorough analysis of natural products for wound healing is required. This review will look at the effectiveness of natural chemicals in wound healing and how they work. Natural-based products may play an essential role in wound healing[3]. They not only promote tissue repair but also have antibacterial characteristics that assist prevent infection. By treating wounds with natural products, we can help the body's natural healing process. This enables us to harness the power of nature. The goal of this study is to analyze the efficiency of natural substances in accelerating tissue repair and investigating their potential for wound healing. With an emphasis on natural wound healing, this study will look into how well diverse natural substances promote tissue regeneration and manage the complex wound healing process[4]. Natural materials in wound care have received a lot of attention due to their safety, efficacy, and capacity to accelerate the healing process. Furthermore, natural products provide the patient with both physical and psychological comfort, making them a comprehensive approach to wound healing. To summarize, natural products have demonstrated encouraging outcomes in wound healing due to their efficacy, safety, and ability to induce tissue repair. By harnessing the power of nature, these products can aid in the regeneration of damaged tissue and prevent infection, thereby expediting the healing process[5].

2. Classification of Wound

Etiology, location, type of injury or presenting symptoms, depth of the wound, tissue loss, and clinical appearance are some of the ways that wounds can be categorized. Wounds are classified as open and closed wound on the underlying cause of wound creation and acute and chronic wounds on the basis of physiology of wound healing.

2.1. Open wounds

As blood exits the body in this case, bleeding is clearly visible. It is additionally categorized as an incised wound, wound from a tear or laceration, abrasions or minor injuries, wounds from punctures, Gunshot wounds andpenetration wounds[6].

2.2. Closed wounds

Blood stays in the body but leaves the circulatory system in closed wounds. Hematomas or blood tumors, contusions or bruises, crush injuries, etc. are included.

2.3. Acute wounds

Acute wound is a tissue injury that normally precedes through an orderly and timely reparative process that results in sustained restoration of anatomic and functional integrity. Acute wounds are usually caused by cuts or surgical incisions and complete the wound healing process within the expected time frame [7].

2.4. Chronic wounds

Chronic wounds are wounds that have failed to progress through the normal stages of healing and therefore entera state of pathologic inflammation chronic wounds either require a prolonged time to heal or recur frequently.

3. Physiology of Wound Healing

It is possible to think of the wound healing process as a dynamic one in which matrix and cellular components work together to replace lost tissue and restore the integrity of injured tissue [Figure 2]. Regardless of the source or the extent of tissue damage, under normal conditions the wound healing process occurs in predictable fashion in four stages: inflammation, migration, proliferation and maturation (remodelling). Wound Healing is considered to complete when the skin surface has reformed and has regained its tensile strength[8].

3.1. Stags of wound healing [hemostasis, inflammation, proliferation, remodeling]

3.1.1. Hemostasis

If the skin is injured, vasoconstriction of the vessel walls is the automatic reaction to stop bleeding. Next, two concurrent and mechanistically interconnected pathways contribute to primary hemostasis and secondary hemostasis.15The platelet plug and the fibrin mesh combine to form a thrombus that stops bleeding, releases accompaniments and growth factors, and provides a temporary scaffold for infiltrating cells that are necessary for wound healing.[9]

3.1.2. . Inflammation

The inflammatory process occurs shortly after the injury, which typically lasts between 24 and 48 hours and may, in some cases last for up to 2 weeks. The inflammatory phase initiates hemostatic pathways immediately to stop the bleeding from the site of the wound. As a result, clinically identifiable cardinal signs of inflammation, redness of the skin, color, tumor, pain, and functio-laesa emerge. Vasoconstriction and platelet aggregation to cause blood clotting and consequently, vasodilatation and phagocytosis to produce inflammation at the wound site are distinguished by this process.[10]

3.1.3. Proliferation

The proliferative process begins the following damage on the third day and continues for about 2 weeks afterward. It is characterized by fibroblast migration and newly synthesized extracellular matrix deposition, serving as a substitute for the fibrin and fibronectin provisional network. This process of wound healing can be seen at the macroscopic stage as an abundant development of granulation tissue.[11]

3.1.4. Remodeling

This final stage of wound healing involves a gradual deterioration of the granulation tissue. In order to create functional tissue, the skeletal muscle epidermis, dermal vasculature, nerves, and myofibers undergo remodeling [Figure 1]. A scar of low cellularity is created when Type I collagen, which is further rearranged into parallel fibrils, dissolves and replaces Type III collagen of the granulation tissue due to the action of collagen metalloproteinases generated by fibroblasts and macrophages. This final phase will take months to complete.[12]

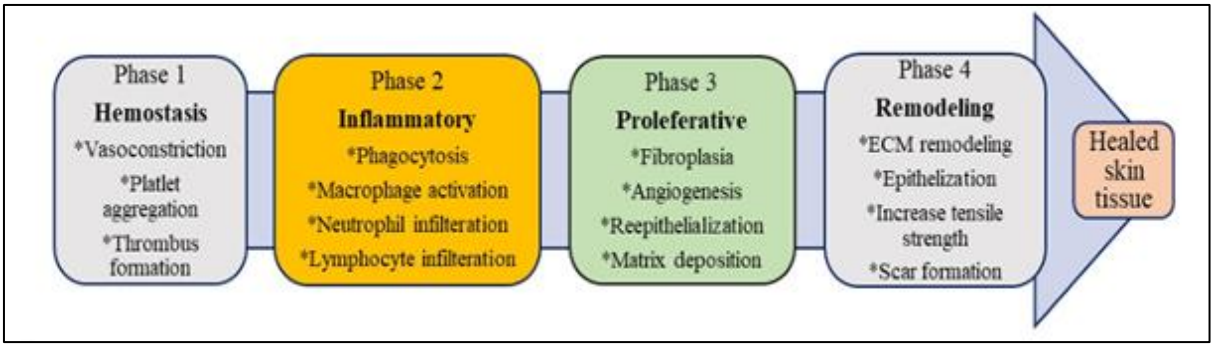

Figure 1 Different Phases of skin wound healing

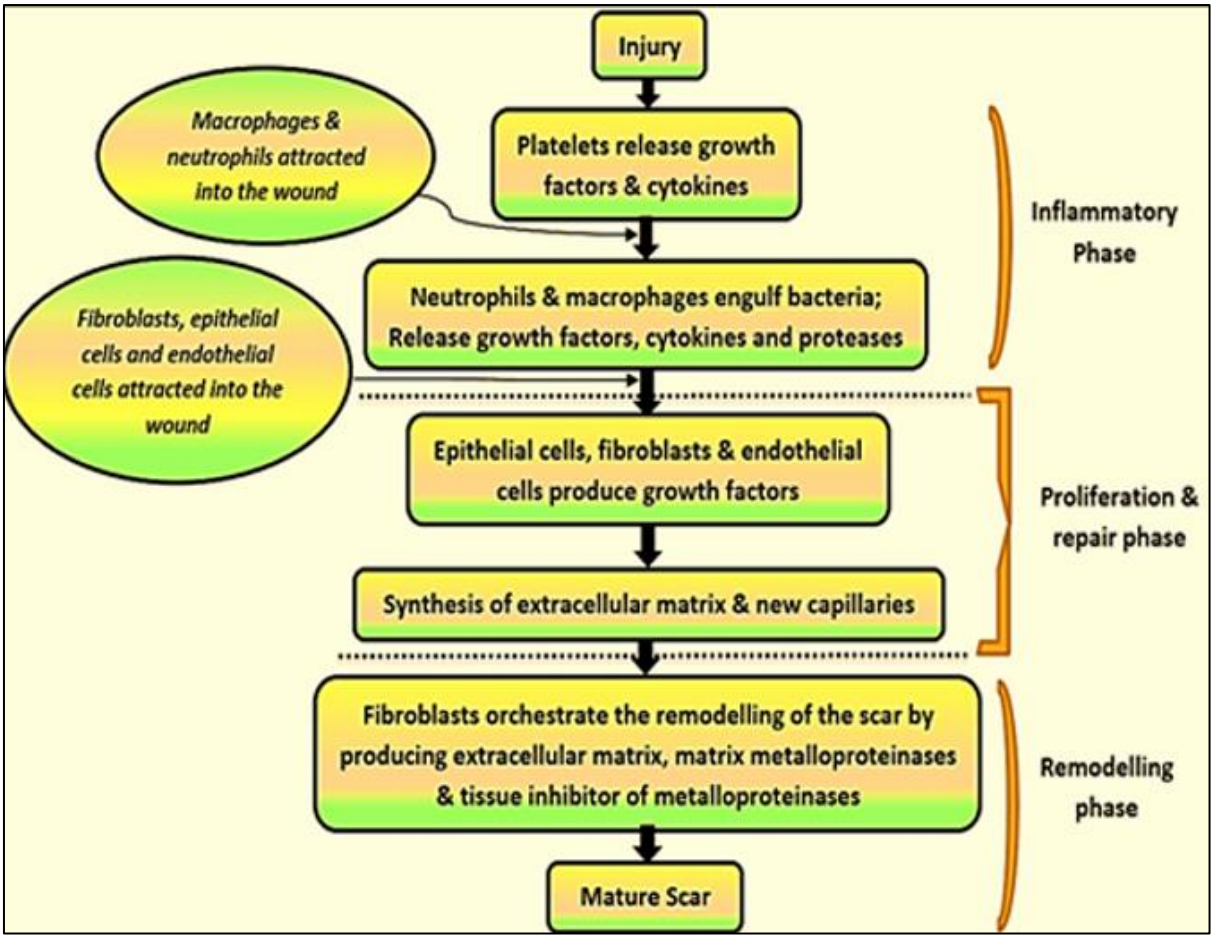

Figure 2 Physiology of Wound Healing

4. Factors affecting wound healing

The two types of factors influencing wound healing- Local &Systematic factors.39

4.1. Local factors

Local factors include infection by the organization of tissue that interrupts healing, exposure to ultraviolet light facilities curing, movement of the affected part of the healing delay, poor blood supply which shows delay in healing, exposure to ionizing radiation delay granulation, foreign bodies including sutures interferes in healing.[13]

4.2. Systematic factors

Systematic factors comprise diabetics are more prone to infection and hence delay healing, wound healing is speedy in young and slow In aged people, hematological aberrations also disturbs healing, administration of glucocorticoids (anti-inflammatory) interrupt healing, nutritional deficiency of vitamin C and zinc delay healing.[14]

4.3. Age

Epithelialization is delayed in healthy individuals as they age. While wound non-collagenous protein deposition decreases with aging, collagen synthesis remains unchanged. This deterioration may jeopardize the mechanical properties of scars in the elderly.

4.4. Body type

Body form can also influence the healing of woundsFor example, insufficient blood supply to adipose tissue might impede wound healing in obese patients. In addition, there is protein malnutrition in some obese patients, which further impedes recovery.On the other hand, when a patient is malnourished, the lack of oxygen and nutrition storage might impede the healing of wounds.[15]

4.5. Nutrition

For over a century, food has been acknowledged as a crucial factor influencing the healing of wounds. The most obvious effect on wound healing is that hunger or certain nutritional deficiencies after trauma and surgery can have a significant effect. Patients with chronic or non-healing wounds and those with nutritional deficiencies also require special nutrients. The metabolism of energy, carbohydrates, proteins, fats, vitamins, and minerals will all affect the healing process[16.]

5. Herbs with wound healing activity

5.1. Azadirachta indica

Azadirachta indica, commonly known as Neem, possesses strong wound healing properties due to its antibacterial, anti-inflammatory, and antioxidant activities. Neem extracts promote collagen formation, enhance wound contraction, and accelerate epithelialization [Figure 3]. Its bioactive compounds such as nimbidin and azadirachtin play a key role in reducing infection and supporting tissue regeneration.[17]

5.2. Curcuma longa

Curcuma longa, commonly known as Turmeric, is renowned for its potent wound healing and anti-inflammatory properties. The active compound curcumin accelerates the healing process by promoting collagen synthesis, enhancing granulation tissue formation, and reducing oxidative stress at the wound site. It also exhibits strong antimicrobial activity, preventing infection and promoting faster tissue regeneration. Additionally, curcumin modulates various growth factors and cytokines involved in wound repair, making it a valuable natural remedy for skin injuries.[18]

5.3. Barbadensis Aloe

Aloe barbadensis, commonly known as Aloe vera, is a medicinal plant widely used for its therapeutic and cosmetic properties. It contains bioactive compounds such as vitamins, minerals, enzymes, amino acids, and polysaccharides, which exhibit antioxidant, anti-inflammatory, and wound-healing effects. In cancer research, Aloe vera extracts have shown potential anticancer activity by inducing apoptosis and inhibiting tumor growth through modulation of cell signaling pathways. The gel derived from its leaves is also used to soothe burns and enhance skin regeneration. Owing to its natural healing abilities, Aloe barbadensis plays a significant role in phytotherapy and modern herbal medicine.[19]

5.4. Allium cepa

Allium cepa (Onion) is a widely cultivated medicinal and dietary plant known for its rich content of organosulfur compounds, flavonoids (especially quercetin), and phenolic acids. These bioactive molecules exhibit strong antioxidant, anti-inflammatory, antimicrobial, and anticancer properties. Studies have shown that Allium cepa extracts can inhibit cancer cell proliferation, induce apoptosis, and prevent DNA damage caused by free radicals.

5.5. Calendula officinalis

Calendula officinalis is widely used for its effective wound healing, anti-inflammatory, and antimicrobial properties. The flavonoids and triterpenoids present in the plant promote collagen production, angiogenesis, and tissue regeneration. Calendula extracts help reduce swelling, control infection, and accelerate wound closure by enhancing epithelialization. It is commonly applied in creams and ointments for burns, cuts, and ulcers.[20]

5.6. Papaya Carica

Carica papaya is well-known for its wound healing potential due to the presence of proteolytic enzymes like papain and chymopapain, which help in debridement of necrotic tissue and promote faster healing. It exhibits strong anti-inflammatory, antioxidant, and antimicrobial properties, reducing infection and oxidative stress at the wound site. Papaya extracts enhance collagen synthesis, epithelialization, and granulation tissue formation, making it effective in treating burns, cuts, and chronic wounds. Its topical application is widely studied for accelerating tissue regeneration and improving wound contraction.

5.7. Mangifera indica

Mangifera indica, commonly known as Mango, exhibits significant wound healing properties due to its rich content of polyphenols, flavonoids, and mangiferin. These bioactive compounds provide strong antioxidant, anti-inflammatory, and antimicrobial effects, which help in preventing infection and reducing oxidative stress at wound sites. Mango leaf

and bark extracts stimulate collagen synthesis, enhance epithelialization, and promote granulation tissue formation, thereby accelerating wound contraction and tissue regeneration. Its traditional use in topical formulations has been supported by various experimental studies demonstrating improved healing in burns, cuts, and chronic wounds.[21]

5.8. Eugeina Plants

Recent studies have also shown that oil from Eugenia dysenterica leaves promotes angiogenesis, cell proliferation, and anti-inflammatory responses at the site of injury, and it is not cytotoxic.

5.9. Propolis

Propolis is extracted from the plant by bees to protect their hives from microbial invasion. Therefore, this substance inherits anti-microbial characteristics. It is also a potent anti-inflammatory, anti-oxidant, and anti carcinogenic compound. Propolis is rich in multiple compound composition, which includes resin, wax, alcohol, phenolic compounds, ketones, amino acids, vitamins, and other small elements. Recent reviews have suggested that it is an efficient therapeutic option for wound treatment[22].

5.10. Blumea Balsamifera

Blumea balsamifera (BB), also known as Ngai camphor, is widely used in Chinese medicine for dermatological conditions. Extracts from leaves, roots, and branches have shown great pharmacological significance in the treatment of snake bites, as well as anti-coagulant, anti-oxidant, and anti-carcinogenic properties. Oil from BB plants also has wound-healing capacities, as seen by the stimulation of fibroplasia, angiogenesis, and collagen regeneration[23].

Figure 3 Medicinal plants with wound healing effects

S.NO	Plant Name & Biological Sources	Family Local identity	Pharmacological Activity	Images
1.	*Azadirachta indicia A. Juss.*	*Meliaceae, (Neem)*	Wound healing, Antibacterial, antiviral, and anti-inflammatory.	
2.	*Curcuma domestica Valeton*	*Zingiberaceae (Haldi)*	It has potent anti-inflammatory and antibacterial properties & Wound healing	
3.	*Olea europaea*	*Oleaceae, (Jaitoon)*	Anti-inflammatory property. Wound healing. antiseptic,	
4.	*Ocimum sanctum*	*Lamiaceae. (Tulsi)*	Wound healing, Antimicrobial, antifungal, antiprotozoal, antimalarial,	
5.	*Bryophyllum pinnatum*	*Crassulaceae, (Panfuti, miracle leaf)*	Wound healing, Antimicrobial, anti-ulcer, antihypertensive, antileishmanial, anti-cancer, anti-diabetic,	
6.	*Punica granatum*	*Lythraceae. (Annar)*	Wound healing, Antimicrobial, anti-ulcer, antihypertensive, Antileishmanial, anti-cancer, anti-diabetic,	
7.	*Elephantopus scaber*	*(Asteraceae) (Adhomukha)*	Wound healing ability. Anticancer, antimicrobial, hepatoprotective, antioxidant, antidiabetic, anti-inflammatory, analgesic,	
8.	*Alternantherasessilis*	*Amaranthaceae*	Antioxidant, anti-inflammatory, analgesic, and wound healing effects	
9.	*Arnebia densiflora*	*Boraginaceae (Arnebia)*	Wound healing, Antileishmanial, anti-cancer, anti-diabetic	
10.	*Carallia brachiata*	*Rhizophoracea Merrill*	Anti-inflammatory, Wound healing, Antidiabetic activity, Anti-Oxidant,	

6. Phytoconstituents Responsible for Wound Healing

Wound healing is a complex biological process involving inflammation, proliferation, and tissue remodeling. Medicinal plants contain a wide range of bioactive phytoconstituents that accelerate these phases by exhibiting antimicrobial, antioxidant, anti-inflammatory, and collagen-stimulatory properties [Figure 4]. The major classes of wound-healing phytoconstituents include **polysaccharides, flavonoids, curcuminoids, triterpenoids, tannins, saponins, alkaloids, and essential oils**[24].

6.1. Polysaccharides

Polysaccharides are important constituents in many wound-healing herbs such as *Aloe vera*, *Plantago major*, and *Mimosa tenuiflora*. In *Aloe vera*, the acemannan fraction enhances fibroblast proliferation, collagen deposition, and

epithelialization. These compounds also maintain a moist environment that supports cellular migration and angiogenesis.

6.2. Curcuminoids (Curcumin)

Curcumin, the principal curcuminoid of *Curcuma longa*, has strong anti-inflammatory and antioxidant effects. It downregulates NF-κB and COX-2 pathways, enhances collagen synthesis, and promotes angiogenesis . Curcumin-loaded nanoparticles and hydrogels have shown improved wound contraction and re-epithelialization in animal and clinical studies[25].

6.3. Tannins, Saponins, and Alkaloids

Triterpenoid saponins such as asiaticoside and madecassoside from *Centella asiatica* stimulate fibroblast proliferation, angiogenesis, and collagen synthesis. They also improve tensile strength and reduce scarring in healed tissue.

6.4. Flavonoids and Other Phenolics

Flavonoids such as quercetin, rutin, kaempferol, and catechins exert potent antioxidant effects by scavenging reactive oxygen species and protecting tissues from oxidative stress . They also modulate inflammatory mediators like TNF-α and IL-6 and exhibit antimicrobial properties, thereby accelerating wound contraction and closure [26].

Figure 4 Formulation of herbs

7. Mechanism of Action of Herbal Agents in Wound Healing

Wound healing is a complex, multi-stage process involving inflammation, tissue proliferation, and remodeling. Herbal agents contribute to this process through a variety of mechanisms that restore tissue integrity, minimize infection, and enhance repair [Figure 5]. The bioactive phytoconstituents present in medicinal plants — such as flavonoids, terpenoids, alkaloids, tannins, saponins, and polysaccharides — act synergistically on molecular and cellular pathways involved in wound closure [27].

7.1. Anti-inflammatory Activity

Inflammation is the initial response to tissue injury. Herbal compounds like curcumin (*Curcuma longa*), asiaticoside (*Centella asiatica*), and eugenol (*Ocimum sanctum*) inhibit pro-inflammatory mediators including tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β), cyclooxygenase-2 (COX-2), and nuclear factor kappa B (NF-κB). This modulation reduces excessive inflammation, allowing the wound to progress to the proliferative phase moreefficiently[28].

7.2. Antioxidant Activity

Reactive oxygen species (ROS) produced during inflammation can damage cellular structures and delay healing. Herbal antioxidants such as flavonoids, phenolic acids, and vitamins neutralize free radicals and enhance antioxidant enzyme

activity (superoxide dismutase, catalase, glutathione peroxidase). For example, quercetin, curcumin, and catechins protect fibroblasts and keratinocytes from oxidative stress, promoting faster wound contraction and epithelialization.

7.3. Antimicrobial and Antiseptic Effects

Infection control is critical for effective wound healing. Many herbs, including *Azadirachta indica* (neem), *Aloe vera*, and *Calendula officinalis*, contain secondary metabolites such as alkaloids, tannins, and essential oils with broad-spectrum antimicrobial properties· These phytochemicals disrupt microbial cell walls, inhibit nucleic acid synthesis, and prevent bacterial colonization of wound sites . Reduced microbial load prevents chronic inflammation and secondary infections.

Herbal agents enhance fibroblast proliferation and collagen synthesis, which are vital for granulation tissue formation and wound strength. Triterpenoids such as asiaticoside and madecassoside stimulate type I collagen synthesis through activation of the TGF-β/Smad signaling pathway. Curcumin also upregulates fibroblast migration and enhances collagen cross-linking, improving tensile strength of healed tissue[29].

7.4. Angiogenesis and Cell Proliferation

Certain herbal compounds promote angiogenesis — the formation of new capillaries — which is crucial for supplying oxygen and nutrients to regenerating tissue. Extracts from *Centella asiatica* and *Curcuma longa* increase expression of vascular endothelial growth factor (VEGF) and fibroblast growth factor (FGF-2), thereby accelerating granulation tissue formation and wound closure .

7.5. Moisture Retention and Barrier Formation

Polysaccharides from *Aloe vera* and *Plantago major* form a protective hydrogel layer that retains moisture, prevents dehydration, and provides a conducive environment for epithelial migration. This moist condition supports keratinocyte proliferation and minimizes scab formation, enhancing aesthetic healing outcomes.

7.6. Immunomodulatory Effects

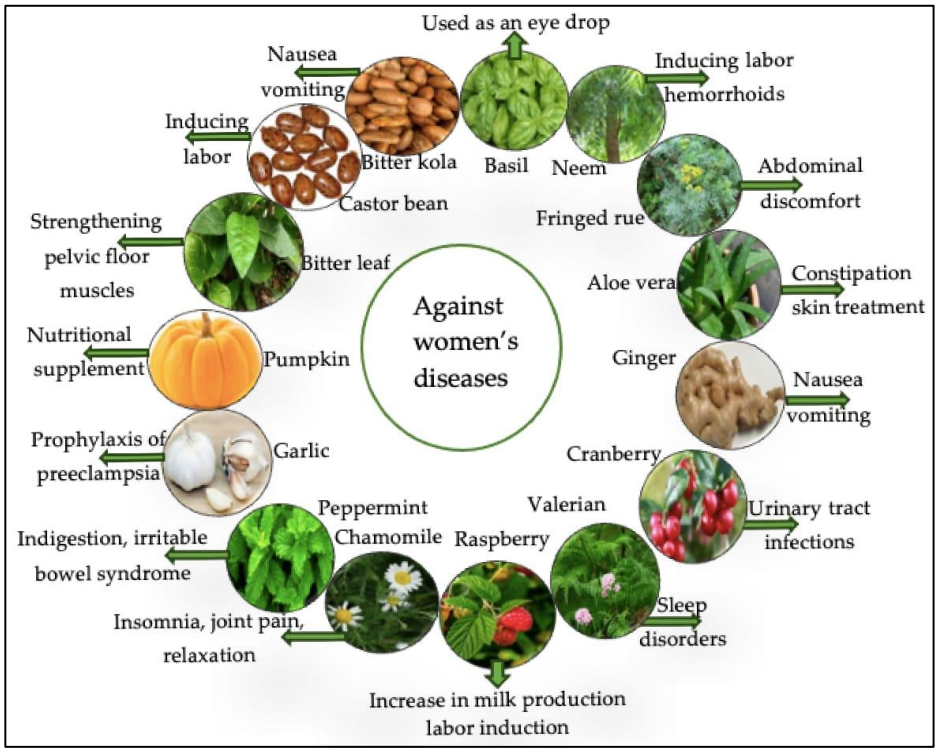

Figure 5 Herbs against womens diseases

Herbal constituents such as saponins, polysaccharides, and alkaloids modulate immune responses by enhancing macrophage activation and cytokine secretion. This activity promotes debris clearance and transition from inflammatory to proliferative phases . Improved immune regulation reduces chronic inflammation and tissue fibrosis[30]

8. Experimental and Clinical Evidence of Herbal Agents in Wound Healing

The therapeutic potential of herbal agents in wound healing has been demonstrated through numerous **in vitro**, **in vivo**, and clinical studies [Figure 6]. Experimental models have validated the biological effects of phytochemicals such as flavonoids, terpenoids, tannins, and polysaccharides, while clinical investigations have confirmed their safety and efficacy in human subjects [31].

8.1. Experimental Evidence (In vitro and Animal Studies)

Several **in vitro** studies have shown that herbal extracts enhance fibroblast proliferation, collagen synthesis, and antioxidant enzyme activity. For instance, *Aloe vera* gel and its polysaccharide acemannan stimulate fibroblast growth and increase collagen content in rat excision wounds. Similarly, ethanolic extracts of *Centella asiatica* significantly increase hydroxyproline levels and tensile strength of healing tissues, confirming their role in collagen biosynthesis.Curcumin from *Curcuma longa* has been shown to downregulate pro-inflammatory cytokines (TNF-α, IL-1β) and upregulate growth factors such as VEGF and TGF-β, promoting angiogenesis and granulation tissue formation. Studies on *Azadirachta indica* (neem) and *Lawsonia inermis* (henna) have demonstrated strong antimicrobial and wound contraction activities in excision and incision models[32].

8.2. Clinical Evidence (Human Studies)

Clinical evaluations have provided supportive evidence for the wound-healing efficacy of several herbal preparations. *Centella asiatica* extracts have been shown to improve postoperative scar quality and accelerate epithelialization in patients with surgical and burn wounds. A randomized clinical trial reported that topical *Aloe vera* gel reduced wound size and pain in patients with diabetic foot ulcers, compared to conventional treatment.Another double-blind trial demonstrated that curcumin-based formulations improved healing time and tissue regeneration in chronic wounds and post-burn scars.

8.3. Comparative Efficacy and Safety

In comparative studies, herbal agents have shown similar or superior outcomes to standard topical drugs like povidone-iodine or silver sulfadiazine, with fewer adverse reactions . Additionally, the natural origin and antioxidant-rich composition of herbal formulations contribute to better tissue compatibility and minimal irritation. However, variability in formulation, dose standardization, and patient factors remain challenges for consistent clinical outcomes [33].

Figure 6 Herbs with medicinal benefits.

9. Challenges and Limitations in Using Herbal Agents for Wound Healing

While there is promising experimental and clinical evidence for the efficacy of herbal agents in wound healing, several important challenges and limitations hinder their translation into routine medical practice. These issues span from

quality control and standardization, through regulatory and clinical trial design problems, to bioavailability, safety, and ethical concerns.

9.1. Variability and Standardization

Herbal products inherently show **batch-to-batch variability** due to differences in plant species, geographic origin, harvesting time, and post-harvest processing (e.g. drying, storage). Without well-defined chemical characterization and marker compounds, it's difficult to ensure that every batch has consistent potency or composition. Lack of reference standards or validated methods for quantification of active constituents complicates comparison between studies and reproducibility [34].

9.2. Bioavailability, Solubility, and Pharmacokinetics

Many phytoconstituents (such as flavonoids, phenolics, curcuminoids) are poorly water soluble, rapidly metabolized, or have low skin penetration, which limits their effectiveness in vivo even if they show potent activity in vitro. Poor solubility and limited absorption require higher doses or advanced delivery systems to attain therapeutic levels, which increases cost and complexity.

9.3. Designing Robust Clinical Trials

Clinical evidence is often limited by **small sample sizes**, heterogeneity in patient populations (age, co-morbidities like diabetes, nutrition, infection), variations in wound type (size, duration, location), and inconsistent endpoints (healing time, percent wound contraction, infection control). Blinding and placebo controls may be difficult due to the distinct appearance, texture or smell of herbal preparations. These factors reduce the statistical power and generalizability of findings [35].

9.4. Regulatory, Safety, and Quality Concerns

Quality issues include **contamination** (e.g. heavy metals, pesticides, microbial pathogens), adulteration, and misidentification of plant species. Safety concerns include allergenicity, irritant or toxic reactions, and potential interactions with conventional drugs, especially in patients with underlying conditions or when using multiple agents. Many herbal formulations lack long-term toxicity studies. Regulatory frameworks for herbal wound healing products are often underdeveloped or inconsistent across regions.

9.5. Ethical, Cost, and Accessibility Issues

Developing herbal products into approved therapeutic agents often requires substantial resources for standardization, safety testing, clinical trials, and quality control, which may be prohibitive for small companies or traditional medicine practitioners. Patients may also lack access to high quality herbal formulations due to cost, supply chain issues, or lack of regulatory oversight, sometimes leading to use of non-standardized or substandard products .

9.6. Understanding Mechanism and Molecular Targets

Although many studies demonstrate gross outcomes (faster healing, improved collagen deposition, reduced inflammation), detailed understanding of **molecular targets**, dose-response relationships, long-term effects, and interplay with wound microbiome or immune system lags behind. This limits rational formulation design and prediction of side effects or off-target effects [36].

10. Future Perspectives

As research on herbal agents in wound healing matures, several opportunities and innovations are emerging that could shape the next generation of treatments. Focusing on these areas will help overcome current limitations and advance clinical translation.

10.1. Advanced Biomaterials and Smart Dressings

Combining herbal bioactives with biopolymeric matrices (e.g., chitosan, alginate, gelatin, hyaluronic acid) to create dressings that are biocompatible, moisture-retentive, and capable of controlled release is an active frontier. Such materials may also be engineered to respond to environmental cues (pH, infection markers) for on-demand delivery of actives. Research is progressing on dressings that integrate diagnostics (theranostic systems) for early detection of infection and visual feedback [37].

10.2. Nanotechnology-Enabled Delivery Systems

Nano-formulations such as nanogels, liposomes, solid lipid nanoparticles (SLNs), niosomes, and nano-fibers are increasingly used to improve stability, skin penetration, controlled release, and bioavailability of phytoconstituents. These systems can reduce required dosages, improve therapeutic indices, and mitigate irritation or toxicity associated with some herbal compounds.

10.3. Polyherbal and Synergistic Formulations

Using combinations of herbs (polyherbal formulations) that offer complementary mechanisms (e.g., antimicrobial + anti-inflammatory + antioxidant) may lead to more robust healing, especially in chronic or complex wounds. Rational design of such formulations, with standardization and synergy studies, is needed [38]

10.4. Precision Medicine and Patient-Specific Therapies

Tailoring wound care based on patient-specific factors (age, co-morbidities such as diabetes or vascular disease, nutritional status, microbiome composition) could enhance outcomes. Herbal treatments may be customized in formulation strength, dosage, or delivery vehicle according to wound type (acute vs chronic), location, and patient health. Integration of biomarkers to monitor healing progress is also foreseen.

10.5. Scale-up, Regulatory Pathways, and Standardization

For herbal agents to move from laboratory studies to clinical use, robust quality control, standardization, and regulatory approval are essential. This includes defining marker compounds, validating batch-to-batch consistency, ensuring purity (freedom from contaminants like heavy metals, microbes), and conducting long-term safety studies. Also, regulatory guidelines must accommodate herbal and combination product[39].

10.6. Large-Scale Clinical Trials and Evidence Synthesis

While many small trials and animal studies are promising, there is a need for well-designed randomized controlled trials (RCTs) with adequate sample size, standardized endpoints, long follow-ups, and involving diverse populations. Systematic reviews and meta-analyses aggregating results will help in elucidating which herbal agents are truly effective in human wound care.

10.7. Sustainability, Ethical Harvesting, and Biodiversity Conservation

With increased demand for medicinal plants, sustainable sourcing, ethical harvesting, cultivation, and protection of biodiversity become important. Genetic, environmental, and post-harvest factors influence phytochemical composition, so conservation and agricultural standardization will impact efficacy. Additionally, benefit sharing with traditional medicine holders and communities is ethically necessary [40.]

11. Conclusion

Herbal medicines represent a powerful and sustainable approach to wound management by targeting multiple biological pathways essential for tissue repair. Extensive in-vitro, in-vivo, and clinical studies confirm their ability to accelerate healing through synergistic antioxidant, anti-inflammatory, antimicrobial, and angiogenic mechanisms. However, inconsistency in plant composition, lack of standardization protocols, and limited pharmacokinetic data continue to restrict their regulatory acceptance and large-scale commercialization. Future research must focus on establishing quality control measures, optimizing formulations for stability and bioavailability, and conducting well-designed randomized clinical trials. The integration of herbal bioactives into advanced biomaterials such as hydrogels, nanofibers, and smart dressings—could bridge traditional medicine with modern biomedical engineering. With rigorous scientific validation and interdisciplinary collaboration, herbal wound-healing agents have the potential to evolve from traditional remedies into clinically approved therapeutic systems that meet global healthcare needs.

Compliance with ethical standards

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Disclosure of conflict of interest

The Author declares that there is no conflict of interest.

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