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REVIEW ARTICLE

Collagen-integrated Scaffolds with Phyto-therapeutic Extracts for Augmented Burn Wound Healing: A Systematic Review Highlighting *Musa paradisiaca*

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Abstract

Burns are a major health problem worldwide, affecting millions and causing high economic and health burdens. The traditional treatment options, topical agents, synthetic dressings, and skin grafts fall short in effectively managing the most important features of burn care, such as effective infection control, reduction of scarring, and management of donor site complications. Recent biomaterial advances, especially those in the field of collagen-based scaffolds, have provided encouraging solutions to many challenges of burn wound management by providing structural support and promoting tissue regeneration. This systematic review evaluates the effectiveness of collagen-based scaffolds enhanced with herbal extracts, specifically *Musa paradisiaca* leaf extract, in burn wound healing. A comprehensive analysis of preclinical studies and clinical trials highlights the advantages of these innovative therapies. Collagen-based scaffolds create an ideal matrix for tissue regeneration and structural stability. The incorporation of *M. paradisiaca* extract further enhances therapeutic outcomes due to its bioactive compounds, which exhibit potent anti-inflammatory, antimicrobial, and antioxidant properties. The evidence reviewed here suggests that these combination therapies may accelerate wound healing, reduce infection risks, and minimize scarring compared to conventional treatments. The integration of collagen scaffolds with herbal extracts represents a key milestone in the management of burn wounds and may improve clinical outcomes and the quality of life for patients. Future research should focus on optimizing scaffold formulations, understanding the synergistic effects of herbal extracts, and addressing regulatory and clinical challenges to enable broader clinical applications of these innovative treatments.

Major Findings: Collagen-based scaffolds enhanced with *M. paradisiaca* extract significantly improve burn wound healing by accelerating tissue regeneration, reducing infection risks, and minimizing scarring due to their antimicrobial, anti-inflammatory, and antioxidant properties.

Keywords: Burn Wound Healing, Collagen-based Scaffolds, *M. paradisiaca* Extract, Phyto Therapeutic Scaffolds, Tissue Regeneration

Abbreviations: ECM - Extracellular matrix, EMA - European Medicines Agency, FDA - Food and Drug Administration, HPLC - High-Performance Liquid Chromatography, LDH - Lactate dehydrogenase, MIC - Minimum Inhibitory Concentration, MS - Mass Spectrometry, MTT - 3- (4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide, TCM - Traditional Chinese Medicine

1. Introduction

1.1 Background on Burn Wounds

1.1.1 Epidemiology and Impact

Burn injuries are an important health problem worldwide, with about 11 million injuries every year and these injuries resulting in more than 300,000 deaths. Figure 1 illustrates the depth of burn injury as classified by degree. Table 1 summarizes the country-wise prevalence and mortality rates associated with burn injuries, highlighting significant variations in burn incidence and outcomes across different regions.

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There is a high, rather rough, prevalence in low- and middle-income countries with a predisposition as a cause of unphilosophical cooking methods and limited health and safety measures. Therefore, much of this burden is shouldered by countries that make use of open-flame cooking and kerosene lamps. On the contrary, in high-income countries, the rate of burn injury is lower because of their superior infrastructural facilities and more stringent safety measures. Apart from the acute physical damage, severe burns may also lead to complications like infections, sepsis, and organ failures, which add to further morbidity and mortality. In the long term, sequelae like scarring, contractures, and functional impairments cause considerable and irreversible burden on quality of life, with the need for prolonged rehabilitation. For many victims, such medical complications include post-traumatic stress disorders, depression, and anxiety, usually compounded by visible scars, functional limitations, or other impairments[1,2].

1.1.2 Current Treatment Modalities and Their Limitations

Earlier evolved treatment modalities in the management of burn injuries include topical agents, such as silver sulfadiazine, synthetic dressings, and skin grafting, among others. Topical agents are very popular due to their antimicrobial properties with silver sulfadiazine and promotion of wound healing, but they can delay wound closure, cause toxicity, and increase antimicrobial resistance. In addition, frequent dressing changes, often required with topical treatments, can be painful and further traumatize the wound bed[2-5]. Designed to maintain a moist-heal environment, synthetic dressings include hydrogels, hydrocolloids, and foam dressings to reduce pain while diminishing scarring. These specific dressings are rather costly and also may not fully address deeper tissue damage or infection prevention. Skin replacement continues to be a necessity for the management of deep burns, and while skin grafting, especially autografts using the patient's own skin, is very important, it is not without donor site morbidity, thereby causing further pain and scarring. The necessity of such an approach arises from the fact that allografts, xenografts, or even cultured autografts suffer from the biggest flaw of immune rejection and disease transmission, besides the difficulty in getting suitable donor skin[6]. Recent research with regard to collagen-based scaffolds incorporated with herbal extracts such as *M. paradisiaca* has shown a better alternative, which, if fermented, provides a more effective and natural solution to this problem[11,12].

1.2 Role of Scaffolds in Wound Management

1.2.1 Importance of Scaffolds for Tissue Regeneration

Scaffolds thus form an integral part of current wound management, further leading to tissue regeneration. In a few cases, these structures actually substitute the function of natural extracellular matrix and give temporary support during the process of healing. Scaffolds create conditions for cell migration, proliferation, and differentiation, part of which become the main components in tissue repair. Figure 2 illustrates the sequential stages involved

Table 1. Country-wise prevalence and mortality of burn injuries

Country/Region	Estimated Annual Burn Incidence	Mortality Rate (%)	Key Contributing Factors	References
India	~1,000,000 cases	6–7%	Open-flame cooking, kerosene lamps, and overcrowded housing	3
Bangladesh	~300,000 cases	5–6%	Unsafe stoves, poor housing, and limited emergency facilities	4
Nepal	~55,000 cases	4–5%	Rural exposure, limited burn care infrastructure	5
China	~200,000 cases	3–4%	Industrial and domestic accidents	6
Sub-Saharan Africa	~250,000 cases	8–10%	Open-fire cooking, lack of burn units	7
United States	~500,000 cases	<2%	Industrial and domestic accidents, improved emergency care	8
United Kingdom	~250,000 cases	<1%	Strict safety laws, rapid emergency response	9
Australia	~200,000 cases	<1%	Fire safety awareness, effective burn care systems	10

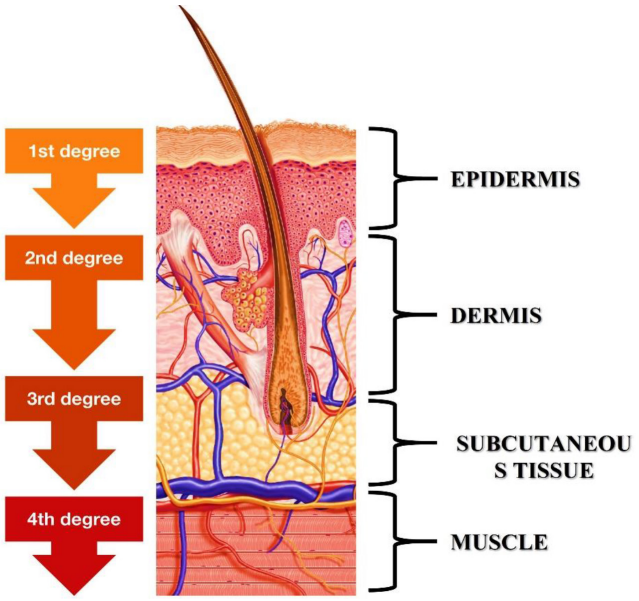


Figure 1. Depth of burn injuries categorized by degree.

in burn wound repair. In cases of severe wounds, such as burns, the natural Extracellular matrix (ECM) is lost or damaged to an extent, and the scaffolds remain an important framework for embedded cells to hold onto, multiply, and regenerate new tissue[13]. Moreover, it could be possible for the scaffolds to be engineered in such a way that they deliver bioactive molecules, such as growth factors or therapeutic agents, directly to the wound, further enhancing healing and decreasing the possible risk of infection. Scaffolds therefore reduce scar formation and promote an organized growth of tissue by helping to restore not only the structure but also the function of the injured area, making them clinically significant in wound management[14].

1.2.2 Overview of Collagen-based Scaffolds

One such natural ECM component and the most abundant human body protein is collagen, which has been used comprehensively in the fabrication of scaffolds because of its excellent biocompatibility, biodegradability, and cell adhesion and growth properties. Collagen-based scaffolds can be produced for various forms that respond to specific wound types and healing requirements mentioned earlier[15,16]. Collagen sponge is porous and, therefore, suitable for deep, wide wounds that need significant tissue regeneration and vascularization. Collagen gels: Holding a soft and hydrophilic milieu, they help wounds that require the retention of moisture and protection from drying.

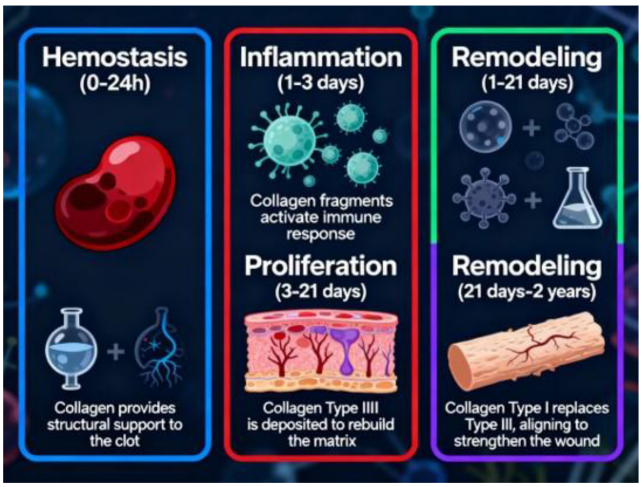


Figure 2. Sequential stages involved in burn wound repair.

Collagen film: It creates a barrier over the wound, thus preventing contamination, retaining a moisture balance, and allowing gas exchange. These scaffolds can also be customized with cross-linking agents to scale mechanical strength up or incorporated with other materials to design their degradation rates and biological activity. It is the plasticity and potent ability of these collagen-based biomedical scaffolds that place these biomaterials at the core of the field of advanced wound care, especially for tissue regeneration to diminish scarring[17]. Table 2 summarizes the key differences between conventional burn wound treatments and the advanced collagen-based approaches used for enhanced healing.

1.3 Herbal Extracts in Wound Healing

1.3.1 Historical and Contemporary Uses

Herbal remedies have been utilized for wound care since ancient times, with various plants serving as primary treatments for injuries and infections. Traditional healing systems such as Ayurveda, Traditional Chinese Medicine (TCM), and Native American medicine frequently employed herbs like *Aloe vera*, Turmeric (*Curcuma longa*), and Honey for their known therapeutic properties[24]. These plants were valued for their ability to cleanse wounds, reduce inflammation, and prevent infection. Over time, modern science has validated many of these traditional uses through rigorous research, leading to their integration into contemporary medical practice. For instance, *Aloe vera* is now a standard ingredient in burn treatments,

Table 2. Comparative analysis of conventional and collagen-based approaches for burn wound healing

Treatment Type	Typical Components / Examples	Mechanism of Action	Healing Time / Efficacy	Advantages	Limitations	References
Conventional Topical Agents	Silver sulfadiazine, povidone-iodine, and antibiotic ointments	Broad-spectrum antimicrobial action, infection control	Moderate efficacy; delayed epithelialization in some cases; 2–3 weeks for partial-thickness burns	Cost-effective, easy to use, strong antibacterial action	Cytotoxic to fibroblasts and keratinocytes; frequent dressing changes; slower healing	18
Autologous Skin Grafting	Split-thickness or full-thickness grafts	Provides immediate tissue coverage and barrier restoration	Effective for deep burns; complete healing in 3–4 weeks, depending on graft take	Long-term closure restores skin function	Limited donor area; risk of infection and scarring; surgical morbidity	19
Pure Collagen Scaffolds / Dressings	Type I collagen from bovine, porcine, or fish sources	Mimics ECM; promotes fibroblast migration, angiogenesis, and granulation tissue formation	Faster re-epithelialization (1.5–2× faster than silver-based creams)	Biocompatible, promotes natural healing, reduces scarring	Costlier than conventional agents; limited antimicrobial activity	20,21
Nanoparticle-Enriched Collagen Scaffolds	Collagen + ZnO, Cu, or Ag nanoparticles; mesoporous bioactive glass	Sustained antimicrobial activity, angiogenesis stimulation, antioxidant protection	Enhanced wound closure and infection control; faster epithelialization (7–10 days in animal models)	Dual action (healing + infection prevention); non-cytotoxic	Need for long-term safety validation; scaling challenges	22,23
Herbal/ Phytochemical-Loaded Collagen Scaffolds	Collagen + curcumin, *M. paradisiaca*, *Aloe vera*, or polyphenolic extracts	Anti-inflammatory, antioxidant, and collagen remodeling effects	Accelerated wound contraction (20–40% faster closure in preclinical studies)	Promotes natural healing, minimizes oxidative stress, and improves scar texture	Variability in extract standardization; limited human trials	21,23
Stem Cell / Exosome-Integrated Collagen Scaffolds	Collagen seeded with MSCs or exosomes	Enhances cellular signaling, angiogenesis, and tissue regeneration	Rapid granulation and epithelialization; improved structural integrity	Superior regenerative potential	Costly; requires advanced handling; regulatory hurdles	21

and *C. asiatica*, once a staple in traditional medicine, is recognized for its role in collagen synthesis and wound healing. This evolution from ancient practices to scientifically validated treatments underscores the enduring value of herbal remedies in modern wound care[25,26].

1.3.2 Mechanisms of Action

Herbal extracts enhance wound healing through multiple interconnected biological mechanisms, including modulation of inflammation, stimulation of collagen synthesis, antimicrobial action, antioxidant protection, and promotion of angiogenesis. Among the potent anti-inflammatory agents, *Boswellia serrata* contains bioactive boswellic acids—primarily 3-O-acetyl-11-keto-β-boswellic acid (AKBA) and β-boswellic acid—which inhibit 5-lipoxygenase (5-LOX) and cyclooxygenase-2 (COX-2), reducing leukotriene and prostaglandin synthesis that drive inflammatory cascades[27,28]. AKBA also suppresses the nuclear factor-κB (NF-κB) signaling pathway, leading to decreased expression of key inflammatory mediators such as tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6), as well as matrix metalloproteinases (MMP-2

and MMP-9) that delay wound closure[29,30]. This dual inhibition accelerates the resolution of inflammation and supports faster epithelialization of the wound bed.

Similarly, *Curcuma longa* (Curcumin) down-regulates NF-κB, COX-2, and inducible nitric oxide synthase (iNOS), thereby reducing oxidative and inflammatory stress[31]. *C. asiatica* enhances fibroblast proliferation and collagen synthesis through activation of the transforming growth factor-β (TGF-β)/Smad signaling pathway, improving tensile strength and tissue regeneration[32]. Additionally, extracts such as *Azadirachta indica* (*Neem*), *Melaleuca alternifolia* (Tea Tree Oil), and Honey exhibit broad-spectrum antimicrobial activity, effectively preventing bacterial infection and biofilm formation[33]. Flavonoid- and tannin-rich plants such as *M. paradisiaca* offer potent antioxidant protection that minimizes oxidative tissue damage[34], whereas angiogenesis-promoting herbs improve blood flow and nutrient delivery to the wound site.

Collectively, these phytochemical mechanisms, particularly the anti-inflammatory and collagen-stimulating actions of AKBA-rich *Boswellia* and Curcumin, enhance wound repair by suppressing pro-inflammatory mediators, protecting against oxidative stress, and stimulating fibroblast and collagen activity. The result is faster, infection-free, and more organized tissue regeneration, underscoring the therapeutic potential of herbal extracts as effective complementary agents in modern wound management.

2. Collagen Scaffolds for Burn Wound Management

2.1 Properties of Collagen Scaffolds

One of the most promising biomaterials in tissue engineering is collagen scaffolds, considering their high biocompatibility, which allows for satisfactory interactions between scaffolds and host tissues. Biocompatibility is known to enhance the processes of cellular adhesion, proliferation, and differentiation while reducing immunogenic responses. Since collagen belongs to the components of the extracellular matrix, it provides the basis for excellent host tissue incorporation of scaffolds, improving their performance for tissue repair[35]. Furthermore, collagen scaffolds are biodegradable and can enzymatically break down in a controlled manner, synchronized with tissue regeneration. In doing so, the scaffold can provide mechanical support for new tissue formation in a transient nature while being replaced during healing. Table 3 presents a comparative overview of Tilapia fish skin dressings and collagen scaffolds used for burn wound healing. Mechanical features, such as strength and elasticity, are among the most critical attributes of collagen scaffolds. Such properties provide for mechanical support of physiological stresses, accommodative of dynamic movements of surrounding tissue, ensuring effective wound healing and functional restoration[14].

2.2 Fabrication Methods

Collagen scaffolds with different state-of-the-art techniques, namely electrospinning, freeze-drying, and solvent casting, have special advantages in tissue engineering applications. Using a high voltage to fibers ejected from collagen dissolved in a solvent, the electrospinning generates nanofibrous mats, thus creating a structure like the extracellular matrix that supports cell adhesion and proliferation. In freeze-drying, a solution of collagen is frozen, and then the ice is sublimated under vacuum. The result is a porous network, which allows cell infiltration, nutrient exchange, and growth, while maintaining the natural structure of the collagen. Another approach is solvent casting: here, the collagen is extracted in a solvent and then cast in moulds to obtain the scaffolds. The controlled porosity and mechanical properties are a result of the solvent evaporating, leaving behind the scaffold. It presents a very useful technique for creating scaffolds of definite shapes and sizes, deemed suitable for various needs in tissue engineering. Table 4 presents a comparative influence of fabrication methods on collagen scaffold properties and biological outcomes. Meanwhile, each of these techniques was directed at developing collagen scaffolds for effective tissue regeneration: electrospinning for its nanofibers to mimic the ECM, freeze-drying for its porous structures, and solvent casting for its moldable shapes[41-43].

2.3 Clinical Applications and Outcomes

Clinical trials in burn treatment using collagen scaffolds have been quite promising, proving that it really improves the rate of healing and outcomes. *In vitro* studies with collagen scaffolds demonstrated an

Table 3. Comparative overview of Tilapia fish skin dressings and collagen scaffolds for burn wound healing

Parameter	Tilapia Fish Skin Dressing	Collagen-Based Scaffold	References
Source and Composition	Derived from *Oreochromis niloticus* (tilapia); rich in Type I collagen, omega-3 fatty acids, and structural proteins.	Derived from bovine, porcine, or recombinant sources; primarily Type I collagen with controlled purity and structure.	36,37
Biocompatibility	High biocompatibility; supports cell attachment and re-epithelialization; minimal immune response reported in animal and clinical studies.	Excellent biocompatibility; widely validated for medical use; low immunogenicity after purification and crosslinking.	36,38,39
Healing Rate	Promotes rapid epithelialization and reduced inflammation; faster wound closure compared to conventional care.	Allows gradual and guided tissue regeneration; healing speed depends on scaffold porosity and drug incorporation.	37–39
Structural Control	Natural matrix with variable thickness and porosity; limited customization options.	Fully engineered structure with tunable pore size, degradation rate, and mechanical strength.	40
Cost and Availability	Low-cost and easily sourced from aquaculture by-products; suitable for low-resource settings.	Higher production and processing costs; commercially established in clinical-grade forms.	37,40
Sterilization and Standardization	Requires effective decellularization and validated sterilization (EtO or gamma); potential variability between batches.	Standardized processing with consistent physicochemical and biological properties.	37,39
Regulatory and Clinical Status	Emerging biomaterial; early-stage clinical adoption; limited long-term regulatory data.	Clinically approved for multiple wound and tissue repair applications.	36,38
Sustainability and Ethics	Environmentally sustainable, utilizing waste fish skin, a non-mammalian source, avoids ethical concerns.	Mammalian origin may raise ethical or cultural issues; synthetic alternatives are available.	36,37,40

almost twofold increase in the wound healing rate compared to traditional techniques through faster epithelialization and closure. In some clinical trials, a lower infection rate has been noted, and this effect might be due to intrinsic antimicrobial properties of the material of the scaffold or the possibility of incorporating antimicrobial agents[44]. This reduction in infections is very critical to avoid complications and to enhance the overall treatment effect. Besides, collagen-based therapies usually provide higher patient satisfaction due to the associated reduction of pain, reduced frequency of dressing, increased healing rates, reduced infection risks, and enhanced quality of life.

3. Herbal Extracts in Wound Healing

3.1 Mechanisms of Herbal Extracts

3.1.1 Anti-Inflammatory Properties

Herbal extracts are capable of reducing inflammation to a great extent, which is considered a critical factor in wound healing. Figure 3 illustrates the mechanism of *M. paradisiaca* extract in burn wound healing. This happens because of their action via inhibition of the production of pro-inflammatory cytokines and enzymes[46]. Pro-inflammatory cytokines, such as tumor necrosis factor-alpha TNF-α, interleukin-1 IL-1, and interleukin-6 IL-6, participate in the inflammatory process and lead to tissue damage, delaying the healing process[52,53]. Herbal extracts suppress these cytokines and, hence, are capable of modulating inflammatory responses and promoting healing. For instance, (*Curcuma longa* turmeric) contains curcumin, which has been shown to inhibit NF-κB, one of the inducers of inflammation, consequently resulting in decreased amounts of inflammatory cytokines. Similarly, *Glycyrrhiza glabra* (licorice) contains glycyrrhizin, which is known to decrease the production of inflammatory promoters like IL-6 and TNF-α. Therefore, extracts from these plants modulate inflammation, hence limiting tissue damage and providing a better environment for wound healing[54].

3.1.2 Antimicrobial Properties

Some of the important properties in the herbal extracts include antimicrobial ones, which are useful in infection control in the process of wound management. These

Table 4. Comparative influence of fabrication methods on collagen scaffold properties and biological outcomes

Fabrication Method	Key Structural Features	Physical Properties	Biological Outcomes in Wound Repair	References
Electrospinning	Produces nanofibrous mats resembling natural extracellular matrix (ECM)	High tensile strength, moderate porosity, tunable fiber diameter, and slower degradation	Promotes fibroblast adhesion, cell alignment, and organized collagen deposition; supports controlled mechanical stability for tensile load-bearing tissues	45–47
Freeze-Drying	Forms a highly porous 3D sponge-like network through ice sublimation	High porosity, low density, moderate tensile strength, rapid degradation rate	Enhances nutrient and oxygen diffusion, promotes fibroblast and keratinocyte infiltration, accelerates angiogenesis, and tissue regeneration	17,41,48
Solvent Casting	Creates dense and uniform films or sheets with controlled porosity	Moderate porosity and mechanical strength; slower degradation	Provides sustained support, suitable for gradual tissue remodeling and drug release; maintains moisture balance over the wound bed	49–51

extracts very often display activity against a range of common wound pathogens, including bacteria, fungi, and viruses. Through effects of antimicrobial action, cell membranes in microbiota are disrupted, their enzymes inhibited, or metabolism interfered with. For example, garlic, which contains potent allicin, has been shown to have broad-spectrum activity as an antibacterial and antifungal agent. The other example is tea tree oil, which contains terpinen-4-ol, for instance, that can act on numerous bacterial and fungal pathogens. Formulating wound products using such agents avoids and controls infections, hence contributing to a positive outcome in managing burn wounds[50,55].

3.1.3 Antioxidant Effects

Herbal extracts go a long way in the fight against pro-oxidant factors, key contributors to tissue damage and delayed wound healing. Oxidative stress is simply the result of an upset balance between the generation of free radicals and a system that can neutralize the radicals through antioxidants. In turn, free radicals can cause cell damage, impair healing, and increase scarring. Herbal extracts containing antioxidant activities scavenge reactive oxygen species and protect against oxidative damage in the tissues. For example, *Rosa damascena* has flavonoids and polyphenols, which are good antioxidants. Similarly, *Vaccinium macrocarpon*, that is, cranberry, contains proanthocyanidins that can decrease oxidative stress and increase the wound healing process more rapidly. These extracts, if incorporated into wound management strategies, could improve tissue repair and really hasten the process of healing, thus solving a major barrier toward effective burn wound treatment[56,57].

3.2 Common Herbal Extracts

Some of the most common herbal extracts include *Aloe vera*, turmeric, green tea, and banana leaf, which have been associated with large benefits toward wound healing, thanks to their active compounds and mechanisms. For instance, *Aloe vera* contains polysaccharides such as acemannan, a compound that enhances cell proliferation and collagen synthesis; glycoproteins decrease inflammation, pain, and improve moisture balance in order to expedite healing. Turmeric, containing the active compound curcumin, exerts anti-inflammatory and antioxidant effects by down-regulating the expression of pro-inflammatory cytokines and enhancing collagen deposition. Green tea extract, rich in epigallocatechin gallate, gives strong antioxidant and antimicrobial properties that reduce oxidative stress and accelerate cell proliferation and tissue regeneration. Flavonoids, tannins, and saponins are the major constituents of *M. paradisiaca*, a banana leaf extract with anti-inflammatory, antioxidant, and antimicrobial activity that improves wound healing by increasing fibroblast proliferation and collagen synthesis. There is clinical evidence that these herbal extracts are effective in improving outcomes in wound care and, therefore, are of value in enhancing burn management and overall wound healing[34,58,59].

4. *Musa paradisiaca* Leaf Extract for Burn Wound Management

4.1 Botanical Characteristics

Musa paradisiaca is a plantain plant characterized by large, broad leaves and elongated fruits. It is native

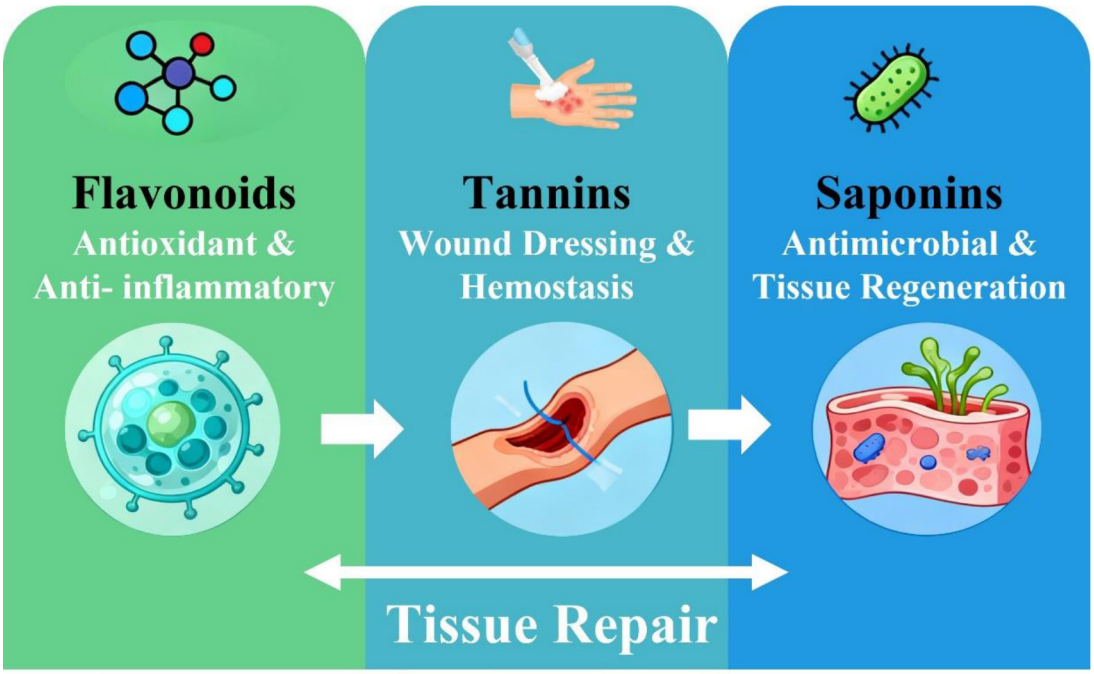


Figure 3. Mechanism of *M. paradisiaca* extract in burn wound healing.

in Southeast Asia but has spread to the greater part of the tropics and subtropics, including Africa, the Caribbean, and Latin America. It has leaves of extraordinary dimension and texture that have been applied since ancient times in traditional medicine. The leaves of plantains are used in several cultures, notably those of the Pacific Islands and parts of Africa, for dressings of wounds, burns, and other skin lesions. These folk applications are supported by folklore and anecdotal evidence that display a historical recognition of the therapeutic potential of the plant. Such geographic distribution and cultural importance underline it as a candidate for modern burn wound management[60–62].

4.2 Bioactive Compounds and Mechanisms

Several bioactive compounds are responsible for the therapeutic effects of *M. paradisiaca* leaves. Flavonoids like quercetin, kaempferol, and rutin possess powerful antioxidant activity and combat oxidative stress by neutralizing free radicals. That would be an action relevant to reducing cellular damage and leading to effective wound healing. Another class of compounds with astringent and antimicrobial properties is tannins, which would further help in reducing inflammation, preventing infection, and promoting tissue regeneration[63]. Additive effects in enhancing antimicrobial activity are provided by saponins and, hence, support the healing process. Recent studies confirm their roles in accelerating wound closure and improving tissue repair, underlining the importance of these compounds in the therapeutic profile of *M. paradisiaca*[64].

4.3 Preparation and Incorporation

The extraction of bioactive compounds from the leaves of *M. paradisiaca* involves different methods to ensure the efficiency and constant activity of the active ingredients. Solvent extraction is one among them, and in it, ethanol and methanol are the solvents used for bioactive compound dissolution in the aqueous solutions[61]. The concentration and purification procedures are normally added for the desired substance isolation by this method. Another successful extractive process is maceration, whereby the leaves are allowed to stay in a solvent for some time, resulting in a satisfactory extraction of compounds. Distillation to purify and isolate essential oils and volatile compounds. Compounds isolated are then incorporated into collagen scaffolds in different methods, including direct immersion of the scaffolds into an extract solution and freeze-drying of the same

scaffolds[49]. Cross-linking agents are used to stabilize the structure of the collagen matrix, and they also function to control the release of the bioactive entities in such a way that it ensures their therapeutic effects for a sustained period[17].

4.4 Efficacy in Burn Wound Healing

Studies conducted on the efficacy of *M. paradisiaca* leaf extract-loaded scaffolds show very encouraging results. Trials have been done in animal models, and on the basis of these preclinical studies, an enhanced process of healing of burn wounds with faster wound closure, enhanced tissue regeneration, and reduced scar formation has been noted[65]. Clinical trials support such findings and suggest that *M. paradisiaca*-loaded scaffolds bring added benefits over conventional treatments to accelerate healing and improve general care outcomes. Comparative studies indicate that *M. paradisiaca* extract does relatively better than other herbal extracts, like those from *Aloe vera* or *Calendula officinalis*, regarding healing efficacy, antimicrobial activity, and reduction of scarring[66].

4.5 Synergistic Effects

Possible synergistic effects while using an agent like the extract of leaves of *M. paradisiaca* could be taken into consideration when agents like *Aloe vera*, known to have soothing and anti-inflammatory effects, or *C. asiatica*, which increases collagen synthesis and strengthens it, were added[26]. Such combinations could offer a much more wholesome approach to wound care through the multiplication of the bioactive compound's effects, leading to advanced healing outcomes and quick recovery[46].

4.6 Safety Profile and Toxicity

Safety profiles for the extract of leaves of *M. paradisiaca* indicate that it is generally very good. Prior research has proven that the extract is well-tolerated and there are minimal adverse effects reported[67]. The majority of problems are minor, like slight skin irritation in a small percentage of cases. Full safety assessments were performed on the extract of *M. paradisiaca* through studies, which included toxicity studies, evaluation for long-term use, and all of which came back negative for significant risks from its use in burn wound management. Research in this direction is underway to firmly reestablish its safety and efficacy for different formulations and populations of patients[68].

4.7 Comparative Efficacy

Comparative investigations between *M. paradisiaca* and other established herbal extracts, such as *Aloe vera*, *Calendula officinalis*, and *C. asiatica,* have demonstrated that *M. paradisiaca* exhibits superior wound healing outcomes in both preclinical and limited clinical studies. In a rat excision wound model, *M. paradisiaca* leaf extract achieved approximately 96–98% wound closure within 14 days, significantly higher than *Aloe vera* (88–92%) and *C. officinalis* (85–89%) under comparable experimental conditions[65,66]. Histological analysis revealed denser collagen fiber deposition, thicker epithelial layers, and enhanced angiogenesis in the *M. paradisiaca*-treated groups, indicating a more efficient tissue remodeling process[68].

Similarly, *C. asiatica*, known for stimulating fibroblast proliferation and collagen synthesis, demonstrated 90–93% wound closure, which was slightly lower and slower compared to *M. paradisiaca*[25]. The superior performance of *M. paradisiaca* is attributed to its high concentration of flavonoids (quercetin, kaempferol, rutin), tannins, and saponins, which work synergistically to enhance fibroblast activity, collagen deposition, angiogenesis, and antioxidant defense mechanisms[63]. Additionally, its potent antimicrobial properties contribute to reduced infection rates and improved epithelialization compared to other phyto-therapeutic extracts[26].

Collectively, these quantitative comparisons substantiate that *M. paradisiaca*-based formulations promote faster wound closure, increased collagen density, and better epithelial regeneration, outperforming many commonly used herbal extracts. These findings reinforce the potential of *M. paradisiaca* as a superior bioactive component in collagen-integrated scaffolds for burn wound management and tissue regeneration[14].

5. Methodological Approaches in Evaluating Herbal Extract-loaded Scaffolds

5.1 *In Vitro* Evaluation Techniques

In vitro evaluation plays a central role in determining the biocompatibility and therapeutic suitability of

collagen–herbal composite scaffolds for burn wound healing. Standard cytocompatibility assays such as MTT, XTT, and LDH leakage tests are widely used to assess cellular responses, including proliferation, metabolic activity, and membrane integrity. For example, curcumin-loaded collagen matrices have demonstrated a clear dose-dependent cytocompatibility profile, with fibroblast viability consistently above 90% at concentrations ≤20 µM, while higher concentrations (≥40 µM) begin to exhibit mild cytotoxicity due to cellular oxidative stress[58]. Likewise, glycyrrhizin bioactive constituent from *Glycyrrhiza glabra,* has shown an IC_{50} value of approximately 120 µg/mL in fibroblast models, indicating a broad safety margin for its incorporation into scaffold formulations[26]. Such quantitative cytotoxicity metrics allow researchers to establish safe therapeutic windows for herbal components before proceeding to animal studies or clinical applications.

In addition to cytocompatibility, antimicrobial evaluation provides essential insight into the infection-control potential of herbal-loaded collagen dressings. Dose–response approaches, such as Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC) assays, are typically employed against key burn wound pathogens, including *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Escherichia coli*. Curcumin and quercetin incorporated into collagen or chitosan scaffolds have shown MIC values in the range of 64–128 µg/mL against *S. aureus* and *E. coli*, demonstrating moderate but clinically meaningful antimicrobial activity[58,69]. Furthermore, extracts from *M. paradisiaca,* a commonly studied herbal agent, have been reported to exhibit an MIC of 100 µg/mL against *S. aureus*[70], supporting their use in infection-preventive biomaterials. Quantifying antimicrobial potency in this manner not only helps to establish effective concentrations but also aids in comparing different herbal compounds and evaluating synergistic effects when used in combination.

Drug Release and diffusion analyses are equally important for understanding the sustained therapeutic performance of herbal-integrated collagen scaffolds. Most herbal-loaded matrices exhibit a biphasic release pattern characterized by an initial burst release (approximately 20–30% of total drug within the first 1–2 hours), followed by a prolonged, controlled-release phase extending up to 48–72 hours[51]. This sustained release often follows Higuchi, Korsmeyer–Peppas, or zero-order kinetics depending on polymer cross-linking, scaffold porosity, and the physicochemical nature of the herbal active[71]. Controlled and predictable release behavior is crucial for maintaining therapeutic concentrations of antioxidants, anti-inflammatory agents, and antimicrobials at the wound site over extended periods. Such quantitative release data help in optimizing scaffold composition, ensuring both biological efficacy and material stability. Collectively, integrating IC_{50}, MIC, and kinetic release data significantly enhances the scientific robustness of *in vitro* evaluations and provides a strong foundation for selecting optimal herbal concentrations for collagen-based burn wound healing scaffolds.

5.2 *In Vivo* Models and Assessments

Animal models: Animal models allow for the testing of herbal extract-loaded scaffolds for performance in a physiologic environment. Valuable information about the efficacy and safety of the scaffolds is derived from these studies. The models commonly used are rats and rabbits, whose processes for wound healing have already been well documented and are known to have similarities with human skin. These models allow one to examine the performance of these scaffolds under *in vivo* conditions on how they are integrated into the wound site and their effects on the process of overall wound healing. The choice of the animal model would depend on things like the size of wounds, duration of study, and objectives of the study[25,72].

Evaluation criteria: Wound Contraction is one of the factors monitored to see how effective the scaffolding will be in facilitating this reduction of wound size over time. It involves histological examinations of tissue samples at the wound site under a microscope to observe cell infiltration, tissue regeneration, and the integration of scaffolds. This would evaluate the extent to which the scaffold supports the growth of new tissue and its integration with the surrounding tissue of the wound.

Tissue Regeneration: The extent of new tissue formation that has occurred and the overall healing process are assessed to provide a comprehensive evaluation of the performance of the scaffold[25,66].

5.3 Analytical Methods for Extract Quantification

Techniques for concentration and stability are vital in ensuring herbal extract-loaded scaffolds are consistent and working to their fullest potential. High-Performance Liquid Chromatography (HPLC) is one of the ways to check the concentration of herbal extracts in the scaffolds through separating the components using interaction with a chromatographic column. This gives an individual the exact measurements regarding the concentration of the extracts in order to ensure it reaches its therapeutic levels. Mass Spectrometry (MS) is a technique coupled with HPLC to provide information regarding the molecular weight and structure of herbal compounds. The combination provides the complete analysis regarding the composition of the extract and confirms its presence in the scaffold. Stability Assessment of the extracts is sampled periodically, and changes in their concentration and efficacy are analyzed to monitor any change with time. This ensures that therapeutic properties inside the extracts will still be present during the intended use period of the scaffold so as to provide an effective and reliable form of treating burn wounds[12,73,74].

6. Regulatory and Clinical Considerations

6.1 Regulatory Guidelines

When herbal extracts are combined with medical devices such as burn wound scaffolds, they come under very strict regulations in regard to safety, efficacy, and appropriate labeling. The guidelines, according to authorities like the FDA in the United States and the EMA in the European Union, set a roadmap that companies have to follow in order to get such products onto the market. As herbal extracts for use in medical devices are categorized by the FDA under the general class of combination products, both drug and device good manufacturing practices apply to them. Pre-market approval procedures include strict evaluation with regard to safety and effectiveness, which is established through clinical trials and laboratory studies. In this respect, one of the major requirements includes a full description of the extract's pharmacological properties, its toxicology assessment, and proof of its therapeutic benefits. Labeling standards clearly state the expectation of clear information relative to composition, possible side effects, and proper use in order to ensure consumer safety. Similarly, the EMA has, in varying but comparable fashion, a regulatory framework wherein the strong clinical data and the stringent quality control standards are the heart of the matter for the approval of herbal extract-based medical devices in Europe[75].

6.2 Challenges in Clinical Translation

Translation of herbal extract-loaded scaffolds from bench to bedside presents several challenges. A major challenge pertains to the standardization of herbal extracts due to vast differences in components and potencies among them. Variability complicates issues of reproducibility and, hence, in establishing uniformity of therapeutic outcome. Table 5 outlines the key translational and practical considerations for herbal extract-loaded collagen scaffolds. Finally, a regulatory approval process burdens the translation by requiring copious amounts of evidence that the herbal component is safe and efficient for the intended medical device application. Herbal extracts included in the scaffold need to undergo rigorous manufacturing practices, sterility, and quality control. Strategies to overcome such barriers include the development of standardized extraction methods, well-designed clinical trials to establish efficacy, and a tight collaboration with regulatory agencies to navigate approval pathways. Critical to clinical translation is the ability to communicate with regulatory bodies and to keep up with changing guidelines[47].

6.3 Case Studies

Successful navigation of the regulatory approval pathway and clinical proof of herbal extract-based products provides insight into development and the impacts of such innovations. Successful outcomes in the case of, for instance, herbal extract-based products, such as the MelaGel burn treatment, during clinical trials include improved wound healing and reduced scar formation. Development of such products normally undergoes rigorous pre-clinical and clinical evaluation for the assessment of their safety and efficacy, followed by careful documentation for filing with various regulatory authorities. These clinical outcomes from case studies often illustrate benefits conferred by herbal-based therapies to patient care, which can include

evidence showing accelerated healing time or reduced complications. Such an impact would be a fact on the patient care in terms of better clinical outcomes and increased acceptance and integration of herbal-based solutions into the standard management regime of burns. The case studies thus prove that herbal extract-loaded scaffolds have enormous potential to provide a variety of natural, effective treatments against conventional treatment options while meeting regulatory and clinical standards[47,76].

7. Innovations in Scaffold Technology

7.1 Advanced Fabrication Techniques

The new developments in scaffold fabrication have changed tissue engineering with the incorporation of quite sophisticated techniques for 3D printing, electrospinning, and bioprinting. One can have control over the architecture of the scaffold and the material distribution within it, hence making complicated and patient-specific structures. As mentioned, technology can produce scaffolds having tailored mechanical and porosity properties that would enhance tissue integration and functionality[80]. For example, researchers have developed 3D-printed scaffolds with graded porosity that mimic natural tissue structures and show improved cell migration and tissue formation. Another key method is electrospinning, which generates nanofiber scaffolds that possess an extremely large surface area-to-volume ratio, promoting cellular adhesion and proliferation. This is very useful in generating the fiber matrix similar to that existing in the ECM, an important concept in tissue regeneration. Recent advances in this electrospinning technique have focused on optimizing electrospinning parameters to control fiber diameter and orientation for improved scaffold performance specific to particular types of tissue. Bioprinting combines living cells with biomaterials to form complex tissue structures[47]. In that way, by depositing both the cells and the biomaterials in a very predefined manner, researchers can replicate the architecture as well as functions of the tissues. Bioprinting currently represents one of the most advanced technologies for the fabrication of multi-cellular structures with vascular networks, which is a milestone in the creation of functional tissue and organ models[45].

7.2 Smart Scaffolds with Controlled Release

Advanced features include stimuli-responsive drug release and real-time monitoring capabilities. Smart scaffolds, in this regard, are designed to release the therapeutic agent at a controlled rate when triggered in response to environmental stimuli such as changes in pH, temperature, or light. Hence, this approach gives efficient delivery of drugs while reducing the side effects by ensuring that the drugs are released only when and where needed. For this purpose, stimuli-responsive systems have been developed, allowing the localization of drug delivery related to infection control or enhanced tissue regeneration[72]. For example, temperature-responsive hydrogels release

Table 5. Translational and practical considerations for herbal extract-loaded collagen scaffolds

Aspect	Description / Key Consideration	Relevance for Clinical Translation	References
Scalability of Production	Translating laboratory formulations into large-scale production requires optimization of extraction, blending, and scaffold fabrication processes to maintain reproducibility and quality.	Ensures batch consistency, cost-effectiveness, and supports GMP manufacturing for clinical application.	1,2
Sterilization Compatibility	Herbal extract-loaded collagen scaffolds must withstand sterilization (e.g., EtO or gamma) without loss of structure or bioactivity.	Guarantees sterility while maintaining the scaffold's biological and mechanical performance.	1,77
Storage Stability	Herbal compounds may degrade due to light, oxygen, or humidity; long-term stability must be validated through accelerated storage tests.	Determines safe shelf life and reliable clinical performance.	78,79
Cost and GMP Feasibility	Manufacturing involves costs for raw materials, sterilization, packaging, and GMP compliance; process standardization minimizes cost variations.	Improves accessibility and supports regulatory approval for clinical and industrial use.	1,77
Regulatory Compliance	Combination products require compliance with both pharmaceutical and device regulations, ensuring safety, efficacy, and traceability.	Essential for market approval and safe clinical translation.	1,77

growth factors or antibiotics after a local inflammation or infection, thereby providing localized treatment without systemic side effects. Embedding sensors or imaging technologies in the scaffolds allows real-time monitoring. These features allow assessment of scaffold performance and tissue regeneration to be performed on a continuous basis. The invention of optical sensors or biosensors as part of scaffolds will help clinicians monitor parameters such as pH, temperature, or biochemical changes *in vitro* in real time, and therefore, intervention can be done in time to improve the outcomes of patients[51,81].

7.3 Integration of Nanotechnology

It has tremendously improved the scaffold properties with the incorporation of nanomaterials in them, improving their drug delivery, mechanical strength, antibacterial activity, etc. Scaffolds are combined with antibacterial nanoparticles like gold or silver to prevent infections during wound healing and tissue regeneration. Nanomaterials increase the efficiency of drug delivery through controlled and sustained release of therapeutic agents. For example, nanocarriers, like liposomes or dendrimers, encapsulate drugs and then release them in a controlled way to enhance the efficiency of treatment while reducing systemic toxicity. Embedding nanostructures into scaffolds improves their mechanical properties, such as tensile strength and elasticity[55,82]. Nanofibers and nanocomposites give scaffolds more durability and, therefore, offer sufficient support for tissue growth that will turn them into structures good for bearing loads and delivering complex tissue engineering tasks. It ranges from advanced fabrication techniques to smart and nanotechnology-aided scaffolds; these innovations in scaffold technology mean a lot with respect to scaffold functionality and scaffold effectiveness in tissue engineering. Especially, these developments presage further effective, personalized, and dynamic solutions for regenerative medicine and burn wound management[14].

8. Patient-centric Outcomes and Quality of Life

8.1 Impact on Wound Healing Rates and Scar Formation

Herbal extract-loaded scaffolds, notably those incorporating *M. paradisiaca* extract, are radical improvements in burn wound management since they enhance wound healing rates significantly while reducing scar formation to near nil. Herbal extracts, like the ones from *M. paradisiaca*, are combined within the scaffold with collagen to provide a biomimetic matrix that enhances tissue repair efficiency. The active compounds of *M. paradisiaca*, such as antioxidants, vitamins, and anti-inflammatory agents, form a very important part of the process of enhancing healing[46]. They act through attenuated oxidative stress and inflammation at the site of the wound, which in turn enhances epithelialization and more efficient collagen synthesis. Such interventions can provide faster closure and better quality of regenerated tissue than conventional treatments. In this respect, these herbal-loaded scaffolds demonstrate quite good efficacy in reducing hypertrophic scarring and keloid formation. Modulation of the inflammatory response and the activity of fibroblasts by herbal extracts ensures that the collagen is deposited in a more organized fashion, significantly improving cosmetic and functional burn injury outcomes. This is contrary to conventional methods, which commonly succumb to long healing times and pronounced scarring due to their inability to address deeper tissue damage and persistent inflammation[14,16].

8.2 Patient Satisfaction and Quality of Life

Patient feedback on herbal extract-loaded scaffolds has raised several benefits that increase treatment satisfaction and improve quality of life. The advanced scaffolds reduce the problem of frequent dressing changes, which can be uncomfortable and distressing, by creating a more stable moisture environment and better infection control. Emollient and anti-inflammatory herbal extracts, like *M. paradisiaca*, to a great extent mitigate pain and discomfort during the healing process. Patients described less discomfort and complications, including infections and too much scarring, and reported being more satisfied with the overall treatment experience[83,84]. Moreover, it has been shown that faster healing and better scar quality provided by these scaffolds allow for quicker return to normal activities and improvement in daily functioning. Further, the reduction in psychological distress and enhancement of self-esteem by means of better aesthetic outcomes and fewer functional

limitations add to the positive effect on the quality of life of patients. In summary, herbal extract-loaded scaffolds will improve clinical outcome measures and offer a more positive and holistic patient experience in the management of burn wounds[85,86].

9. Future Directions and Research Gaps

9.1 Emerging Trends in Scaffold Technology

This has been fast-tracked in recent times due to scaffold technologies for burn wound management, through innovations in material science and fabrication techniques. Some of the new developments include the introduction of advanced materials such as biodegradable polymers, bioactive ceramics, and composite materials that could support tissue regeneration and degrade at a rate that can be modulated. The aims are materials with enhanced biocompatibility that will more closely imitate the natural extracellular matrix and integrate well into native tissue. Techniques like 3D printing and electrospinning make scaffolds with highly precise microstructures, which are customizable and then allow cellular infiltration and tissue formation to take place much more easily, since the environment for wound healing is so much more supportive and organized. In addition, the inclusion of nanotechnology in scaffolds allows for the addition of nanoparticles, thereby endowing the scaffold with targeted drug delivery and enhanced antimicrobial properties against common complications of infection and delayed healing. The introduction of stimuli-responsive scaffolds, which react in the presence of changes in the environment of the wound pH and temperature, for example, is a noteworthy development. This is because active materials would provide real-time responses to attain optimal healing conditions. These trends may vary, greatly improving the effectiveness of scaffolds in the management of burn wounds with their potential to offer more tailored and adaptive solutions[48,87].

9.2 Areas for Further Research

Although scaffold technology has advanced considerably in recent times, a number of major lines of study still remain relatively unexplored, which may act as critical research gaps in optimizing scaffolds for wound management. These involve long-term studies to better understand the safety, efficacy, and biological interactions of a new scaffold material over extended periods. This research shifts the focus to eventual hazards that could emanate with regard to wound healing and patient outcome, including inflammatory responses or long-term toxicity. Research into the performance of scaffolds under different populations, for instance, inter-individual variations with respect to age, associated disorders, and genetics, should be focused on to ensure that the technologies work across different demographics. Other than that, there is also a huge need for refining the formulation of herbal extracts used in these scaffolds[88,89]. These studies include investigating the stability, release profiles, and therapeutic efficacy within the matrix of the scaffold. Knowing how various herbal compounds interact with the material used and hence help in healing could potentially make treatments more effective and individualized. In all, addressing these gaps would be important for the progress in scaffold technology in enhancing burn wound management for better patient care and recovery[90].

10. Conclusion

This review highlights the potential of collagen-based scaffolds infused with herbal extracts, particularly *M. paradisiaca*, in advancing burn wound management. Collagen scaffolds closely mimic the native extracellular matrix, thus providing a template for cellular adhesion, proliferation, and tissue regeneration, which results in accelerated wound closure and good integration with host tissue. When associated with *M. paradisiaca* extracts rich in bioactive compounds that have anti-inflammatory, antimicrobial, and antioxidant properties, such scaffolds have demonstrated considerable enhancements in healing, such as a reduced microbial load, minimized inflammatory responses, reduced scarring, and enhanced wound healing compared to conventional treatments. Clinically, these advanced scaffolds hold much promise, as they hold the potential to offer faster healing, reduced infections, and better outcomes; however, challenges such as cost, clinical validation, and incorporation into established treatment protocols need to be addressed. Therefore, future research ought to focus on large-scale clinical trials, optimization of scaffold formulations to better

modulate their bioactivity and compatibility with herbal extracts, a better understanding of the mechanisms of action of *M. paradisiaca*, and cost-effectiveness analysis that will assure widespread clinical adoption. Such efforts will widen the therapeutic options available in burn wound care and establish evidence-based guidelines on their applications in clinical practice.

11. Author Contribution

To recognize the author's participation, we highlight individual contributions: Deepa S: Guidance for designing the article. Sathesh Kumar K: Guidance for designing the article. Akash R: Literature search, writing the article. Rajesh S: Literature search. All authors have read and agreed to the published version of the manuscript.

12. References

1. Wood FM. Skin regeneration: The complexities of translation into clinical practise. Int J Biochem Cell Biol. 2014; 56:133-140. https://doi.org/10.1016/j.biocel.2014.10.025 PMid:25448410.
2. Lipsky BA, Hoey C. Topical antimicrobial therapy for treating chronic wounds. Clin Infect Dis. 2009; 49(10):1541-1549. https://doi.org/10.1086/644732 PMid:19842981.
3. Gupta JL, *et al.* National programme for prevention of burn injuries. Indian J Plast Surg. 2010; 43(Suppl):S6–S10. https://doi.org/10.4103/0970-0358.70716.
4. Forjuoh SN. Burns in low- and middle-income countries : A review of available literature on descriptive epidemiology, risk factors, treatment, and prevention. Burns: Journal of the International Society for Burn Injuries. 2006; 32(5):529–537. https://doi.org/10.1016/j.burns.2006.04.002.40
5. Atiyeh BS, Gunn SWA, Hayek SN, *et al.* Burn prevention mechanisms and outcomes: pitfalls, failures and successes. Burns: Journal of the International Society for Burn Injuries. 2009; 35(2):181–193. https://doi.org/10.10.1016/j.burns.2008.06.002
6. Wang Y, Beekman J, Hew J, Jackson S, Issler-Fisher AC, Parungao R, *et al.* Burn injury: Challenges and advances in burn wound healing, infection, pain and scarring. Adv Drug Deliv Rev. 2018; 123:3-17. https://doi.org/10.1016/j.addr.2017.09.018 PMid:28941987.
7. Peck MD. Epidemiology of burns throughout the world. Part I: Distribution and risk factors. Burns: Journal of the International Society for Burn Injuries. 2011; 37(7):1087–1100. https://doi.org/10.1016/j.burns.2011.06.005
8. Jeschke MG, van Baar ME, Choudhry MA, Chung KK, Gibran NS, Logsetty S. Burn injury. Nat Rev Dis Prim. 2020; 6(1). https://doi.org/10.1038/s41572-020-0145-5 PMid:32054846 PMCid:PMC7224101.
9. World Health Organization. World report on child injury prevention. Peden M, Oyegbite K, Ozanne-Smith J, Hyder AA, Branche C, Rahman AKMF, Rivara F, Bartolomeos K, editors. Geneva: World Health Organization; 2008. PMID: 26269872.
10. Daunton C, Kothari S, Smith L, Steele D. A history of materials and practices for wound management. Wound Pract Res Aust J Wound Manag. 2012; 20(4):174-186. http://search.informit.com.au/documentSummary;dn=058025628512911;res=IELHEA
11. Bailey-Shaw YA, Williams LAD, Green CE, Rodney S, Smith AM. *In vitro* evaluation of the anti-inflammatory potential of selected *Jamaican* plant extracts using the bovine serum albumin protein denaturation assay. In: Proceedings of the conference. 2017. https://api.semanticscholar.org/CorpusID:201857256
12. Handayani R, Fans K, Mastuti TS, Rosa D. Comparison study of antioxidant activity from three banana leaves extracts. J Teknol dan Ind Pangan. 2021; 32(1):92-97. https://doi.org/10.6066/jtip.2021.32.1.92
13. Xue M, Jackson CJ. Extracellular matrix reorganization during wound healing and its Impact on abnormal scarring. Adv Wound Care. 2015; 4(3):119-136. https://doi.org/10.1089/wound.2013.0485 PMid:25785236 PMCid:PMC4352699.
14. Mogoşanu GD, Grumezescu AM. Natural and synthetic polymers for wounds and burns dressing. Int J Pharm. 2014; 463(2):127-136. https://doi.org/10.1016/j.ijpharm.2013.12.015 PMid:24368109.
15. Berisio R, Vitagliano L, Mazzarella L, Zagari A. Crystal structure of the collagen triple helix model $[(Pro\text{-}Pro\text{-}Gly)_{10}]_3$. Protein Science: A Publication of the Protein Society. 2002; 11(2):262–270. https://doi.org/10.1110/ps.32602
16. Lateef Z, Stuart G, Jones N, Mercer A, Fleming S, Wise L. The cutaneous inflammatory response to thermal burn injury in a murine model. International Journal of Molecular Sciences. 2019; 20(3):538. https://doi.org/103390/ijms20030538
17. Demir A, Cevher E. Biopolymers as wound healing materials: Challenges and new strategies. Biomater Appl Nanomedicine. 2011. https://doi.org/10.5772/25177
18. La Monica F, Di Matteo M, Mazzotta E, *et al.* Collagen-based scaffolds for chronic skin wound treatment. Gels (Basel, Switzerland). 2024; 10(2):137. https://doi.org/10.3390/gels10020137
19. Rodrigues JP, da Silva LP, Martins A, *et al.* Development of collagenous scaffolds for wound healing: characterization and *in vivo* analysis. Journal of Materials Science Materials in Medicine. 2024; 35(1):12. https://doi.org/10.1007/s10856-023-06774-8

20. McGrath M, O'Connell C, Kearney CJ, *et.al.* A biomimetic, bilayered antimicrobial collagen-based scaffold for enhanced healing of complex wound conditions. ACS Applied Materials and Interfaces. 2023; 15(14):17444–17458. https://doi.org/10.1021/acsami.2c18837.
21. Ghasempour A, Rahmani S, Azami M, *et al*. Biomimetic scaffolds loaded with mesenchymal stem cells (MSCs) or MSC-derived exosomes for enhanced wound healing. Stem Cell Research and Therapy. 2024; 15 (1)(1):406. https://doi.org/10.1186/s13287-024-04012-8
22. Altan D, Özarslan AC, Özel C, Tuzlakoğlu K, Sahin YM, Yücel S. Fabrication of electrospun double layered biomimetic collagen–chitosan polymeric membranes with zinc-doped mesoporous bioactive glass additives. Polymers. 2024; 16(14):2066. https://doi.org/10.3390/polym16142066.
23. Moura LIF, Dias AMA, Carvalho E, De Sousa HC. Recent advances on the development of wound dressings for diabetic foot ulcer treatment - A review. Acta Biomater.. 2013; 9(7):7093-7114. https://doi.org/10.1016/j.actbio.2013.03.033 PMid:23542233.
24. Rozana M. Phytotherapy: Harnessing nature's healing power. Journal of Pharmacognosy and Natural Products. 2022; 8:215.
25. Talekar YP, Apte KG, Paygude S V, Tondare PR, Parab PB. Studies on wound healing potential of polyherbal formulation using *in vitro* and *in vivo* assays. J Ayurveda Integr Med. 2017 8(2):73-81. https://doi.org/10.1016/j.jaim.2016.11.007 PMid:28601354 PMCid:PMC5497006.
26. Bahramsoltani R, Farzaei MH, Rahimi R. Medicinal plants and their natural components as future drugs for the treatment of burn wounds: An integrative review. Arch Dermatol Res. 2014; 306(7):601-617. https://doi.org/10.1007/s00403-014-1474-6 PMid:24895176.
27. Ammon HPT. Boswellic acids in chronic inflammatory diseases. Planta Med. 2006; 72(12):1100-1116. https://doi.org/10.1055/s-2006-947227 PMid:17024588.
28. Roy NK, Parama D, Banik K, Bordoloi D, Devi AK, Thakur KK, *et al.* An update on pharmacological potential of boswellic acids against chronic diseases. Int J Mol Sci. 2019; 20(17):4101. https://doi.org/10.3390/ijms20174101
29. Zaid ESA, Mansour SZ, El-sonbaty SM, Moawed FSM, Kandil EI, Haroun RA. Boswellic acid coated zinc nanoparticles attenuate NF-κ B-mediated inflammation in DSS-induced ulcerative colitis in rats. 2023; 37:1-10. https://doi.org/10.1177/03946320221150720 PMid:36600460 PMCid:PMC9830081.
30. Syrovets T, Büchele B, Krauss C, Laumonnier Y, Simmet T. Acetyl-boswellic acids are novel catalytic inhibitors of human topoisomerases I and IIα. Molecular Pharmacology. 2000; 58(1):71–81. https://doi.org/10.1124/mol.58.1.71
31. Liu M, Wang J, Song Z, Pei Y. Regulation mechanism of curcumin mediated inflammatory pathway and its clinical application: a review. Frontiers in Pharmacology. 2025; 16:1642248.
32. Arribas-López E, Zand N, Ojo O, Snowden MJ, Kochhar T. A systematic review of the effect of *Centella asiatica* on wound healing. International Journal of Environmental Research and Public Health. 2022; 19(6):3266.
33. Hammer KA, Carson CF, Riley TV. Antimicrobial activity of essential oils and other plant extracts. J Appl Microbiol. 1999; 86(6):985-990. https://doi.org/10.1046/j.1365-2672.1999.00780.x PMid:10438227.
34. Mathew NS, Negi PS. Traditional uses, phytochemistry and pharmacology of wild banana (*M. acuminata* Colla): A review. J Ethnopharmacol. 2017; 196:124-140. https://doi.org/10.1016/j.jep.2016.12.009 PMid:27988402.
35. Añel RL, Kumar A. Experimental and emerging therapies for sepsis and septic shock. Expert Opin Investig Drugs. 2001; 10(8):1471-1485. https://doi.org/10.1517/13543784.10.8.1471 PMid:11772263.
36. Huang JY, Wong TY, Tu TY, Tang MJ, Lin HH, Hsueh YY. Assessment of tilapia skin collagen for biomedical research applications in comparison with mammalian collagen. Molecules. 2024; 29(2):402.
37. Ibrahim A, Fahmy HM, Abd G, Mahmoud E, Soliman M, Elshahawy AM. New strategies for sterilization and preservation of fresh fish skin grafts. Sci Rep. 2024; p. 1-10. https://doi.org/10.1038/s41598-024-51608-4 PMid:38218988 PMCid:PMC10787751.
38. Lawlley B, Rwiza MJ, Sauli E. Utilizing tilapia fish skin biomaterial for burn wound dressing : A systematic review. Sci African. 2024; 24:e02245. https://doi.org/10.1016/j.sciaf.2024.e02245
39. Lima Júnior EM, de Moraes Filho MO, Costa BA, *et al. Nile tilapia* fish skin-based wound dressing improves pain and treatment-related costs of superficial partial-thickness burns: a phase III randomized controlled trial. Plastic and Reconstructive Surgery. 2021; 147(5):1189–1198. https://doi.org/10.1097/PRS.0000000000007895
40. Yoon J, Yoon D, Lee H, Lee J, Jo S, Kym D, *et al.* Wound healing ability of acellular fish skin and bovine collagen grafts for split-thickness donor sites in burn patients: Characterization of acellular grafts and clinical application. Int J Biol Macromol. 2022; 205:452-461. https://doi.org/10.1016/j.ijbiomac.2022.02.055 PMid:35176324.
41. Amirrah IN, Lokanathan Y, Zulkiflee I, Wee MFMR, Motta A, Fauzi MB. A comprehensive review on collagen type I development of biomaterials for tissue engineering: From biosynthesis to bioscaffold. Biomedicines. 2022; 10(9):1-46. https://doi.org/10.3390/biomedicines10092307 PMid:36140407 PMCid:PMC9496548.
42. Perumal G, Ramasamy B, A MN, Doble M. Nanostructure coated AZ31 magnesium cylindrical mesh cage for potential long bone segmental defect repair applications.

Colloids Surf B Biointerfaces. 2018; 172:690-698. https://doi.org/10.1016/j.colsurfb.2018.09.010 PMid:30243223.
43. Li L, Du Y, Yin Z, Li L, Peng H, Zheng H, Yang A, Li H, Lv G. Preparation and the hemostatic property study of porous gelatin microspheres both *in vitro* and *in vivo*. Colloids Surf B Biointerfaces. 2020; 187:110641. https://doi.org/10.1016/j.colsurfb.2019.110641
44. Sivasamugham LA, Nimalan V, Subramaniam G. Antibacterial effects of *M.* sp. ethanolic leaf extracts against methicillin-resistant and susceptible *Staphylococcus aureus*. South African J Chem Eng. 2021; 35:107-110. https://doi.org/10.1016/j.sajce.2020.09.007
45. Wutticharoenmongkol P, Sanchavanakit N, Pavasant P, Supaphol P. Preparation and characterization of novel bone scaffolds based on electrospun polycaprolactone fibers filled with nanoparticles. Macromol Biosci. 2006; 6(1):70-77. https://doi.org/10.1002/mabi.200500150 PMid:16374772.
46. Jonidi Shariatzadeh F, Currie S, Logsetty S, Spiwak R, Liu S. Enhancing wound healing and minimizing scarring: A comprehensive review of nanofiber technology in wound dressings. Progress in Materials Science. Elsevier Ltd. 2025; 147:101350. https://doi.org/10.1016/j.pmatsci.2024.101350
47. Zhong SP, Zhang YZ, Lim CT. Tissue scaffolds for skin wound healing and dermal reconstruction. Wiley Interdiscip Rev Nanomedicine Nanobiotechnology. 2010; 2(5):510-525. https://doi.org/10.1002/wnan.100 PMid:20607703.
48. Karageorgiou V, Kaplan D. Porosity of 3D biomaterial scaffolds and osteogenesis. Biomaterials. 2005; 26(27):5474-5491. https://doi.org/10.1016/j.biomaterials.2005.02.002 PMid:15860204.
49. Tian Y, Visser JC, Klever JS, Woerdenbag HJ, Frijlink HW, Hinrichs WLJ. Orodispersible films based on blends of trehalose and pullulan for protein delivery. Eur J Pharm Biopharm. 2018; 133:104-111. https://doi.org/10.1016/j.ejpb.2018.09.016 PMid:30273665.
50. Soud SA, Hasoon BA, Abdulwahab AI, Hussein NN, Khwater Maeh R. Synthesis and characterization of plant extracts loaded PVA/PVP blend films and evaluate their biological activities. EurAsian J Biosci Eurasia J Biosci. 2020; 14:2921-2931.
51. Boateng JS, Matthews KH, Stevens HNE, Eccleston GM. Wound healing dressings and drug delivery systems: A review. J Pharm Sci. 2008; 97(8):2892-2923. https://doi.org/10.1002/jps.21210 PMid:17963217.
52. Kotsiafti A, Giannakas K, Christoforou P, Liapis K. Progress toward better treatment of therapy-related AML. Cancers (Basel). 2023; 15(6). https://doi.org/10.3390/cancers15061658 PMid:36980546 PMCid:PMC10046015.
53. Sgambellone S, Febo M, Durante M, Marri S, Villano S, Bereshchenko O, *et al*. Role of histamine H4 receptor in the anti-inflammatory pathway of glucocorticoid-induced leucin zipper (GILZ) in a model of lung fibrosis. Inflamm Res. 2023; 72(10-11):2037-2052. https://doi.org/10.1007/s00011-023-01802-3 PMid:37815550 PMCid:PMC10611623.
54. Zhong S, Yin Y. Regulatory role of the programmed cell death 1 signaling pathway in sepsis induced immunosuppression. Front Immunol. 2023; 14:1-7. https://doi.org/10.3389/fimmu.2023.1183542 PMid:37292207 PMCid:PMC10244656
55. Elangwe CN, Morozkina SN, Olekhnovich RO, Polyakova VO, Krasichkov A, Yablonskiy PK, *et al*. Pullulan-based hydrogels in wound healing and skin tissue engineering applications: A Review. Int J Mol Sci. 2023; 24(5). https://doi.org/10.3390/ijms24054962 PMid:36902394 PMCid:PMC10003054.
56. Mishra AP, Saklani S, Milella L, Tiwari P. Formulation and evaluation of herbal antioxidant face cream of *Nardostachys jatamansi* collected from Indian Himalayan region. Asian Pac J Trop Biomed. 2014; 4(Suppl 2):S679-S682. https://doi.org/10.12980/APJTB.4.2014APJTB-2014-0223
57. Chandrasekar R, Kumar GS. Formulation and evaluation of a poly herbal anti-acne gel. Res J Top Cosmet Sci. 2020; 11(1):5. https://doi.org/10.5958/2321-5844.2020.00002.3
58. Alven S, Nqoro X, Aderibigbe BA. Polymer-based materials loaded with curcumin for wound healing applications. Polymers (Basel). 2020; 12(10):1-25. https://doi.org/10.3390/polym12102286 PMid:33036130 PMCid:PMC7600558.
59. Anand P, Kunnumakkara AB, Newman RA, Aggarwal BB. Bioavailability of curcumin: Problems and promises. Mol Pharm. 2007; 4(6):807-818. https://doi.org/10.1021/mp700113r PMid:17999464.
60. Saro JM, Pascual KB, Daguio JD, Saro JM, Grace M, Valencia A, *et al*. Comparative analysis of ethanolic extracts from banana (*M. paradisiaca*) exocarps as potential sources of antimicrobial properties comparative analysis of ethanolic extracts from banana (*M. paradisiaca*) exocarps as potential sources of antimicrobial properties. Artic Int J Biosci. 2022; 21(1):169-183. https://doi.org/10.12692/ijb/21.1.169-183
61. Kibria AA, Kamrunnessa, Rahman MM, Kar A. Extraction and evaluation of phytochemicals from banana peels (*M. sapientum)* and banana plants *(Musa paradisiaca)*. Malaysian J Halal Res. 2019; 2(1):22-26. https://doi.org/10.2478/mjhr-2019-0005
62. Sivasamugham LA, Nimalan V, Subramaniam G. Antibacterial effects of *M. spp*. ethanolic leaf extracts against methicillin-resistant and susceptible *Staphylococcus aureus*. S Afr J Chem Eng. 2021; 35:107-110. https://doi.org/10.1016/j.sajce.2020.09.007
63. Ghuman S, Ncube B, Finnie JF, McGaw LJ, Mfotie Njoya E, Coopoosamy RM, *et al*. Antioxidant, anti-inflammatory and wound healing properties of medicinal plant extracts used to treat wounds and dermatological disorders. South African J Bot. 2019; 126:232-240. https://doi.org/10.1016/j.sajb.2019.07.013
64. Gavan A, Colobatiu L, Hanganu D, Bogdan C, Olah NK, Achim M, *et al*. Development and evaluation of hydrogel

wound dressings loaded with herbal extracts. Processes. 2022; 10(2). https://doi.org/10.3390/pr10020242

65. Gore MA, Akolekar D. Evaluation of banana leaf dressing for partial thickness burn wounds. Burns. 2003; 29(5):487-492. https://doi.org/10.1016/S0305-4179(03)00050-0 PMid:12880731.
66. Amutha K, Selvakumari U. Wound healing activity of methanolic stem extract of *M. paradisiaca* Linn. (Banana) in Wistar albino rats. Int Wound J. 2016; 13(5):763-767. https://doi.org/10.1111/iwj.12371 PMid:25224162 PMCid:PMC7950173.
67. Herman A, Herman AP. Herbal products for treatment of burn wounds. Journal of Burn Care and Research: Official Publication of the American Burn Association. 2020; 41(3):457–465. https://doi.org/10.1093/jbcr/iraa010
68. Agarwal PK, Singh A, Gaurav K, Goel S, Khanna HD, Goel RK. Evaluation of wound healing activity of extracts of plantain banana (*M. sapientum var. paradisiaca*) in rats. Indian J Exp Biol. 2009; 47(1):32-40.
69. Quideau S, Deffieux D, Douat-Casassus C, Pouységu L. Plant polyphenols: Chemical properties, biological activities, and synthesis. Angew Chemie - Int Ed. 2011; 50(3):586-621. https://doi.org/10.1002/anie.201000044 PMid:21226137.
70. Reddy KR, Madhu C, Mouli J, Chandra B, Reddy B, Mohan J, Joshi P, Sharanya B. Estimation of phytochemical screening, antibacterial and antifungal activity on ethanol extract of *Solanum lycopersicum*, *Pouteria sapota*, *M. acuminata*, and *Beta vulgaris*. Indo American Journal of Pharmaceutical Sciences. 2017; 4(9):2808–2816.
71. Kakkar V, Singh S, Singla D, Kaur IP. Exploring solid lipid nanoparticles to enhance the oral bioavailability of curcumin. Molecular Nutrition and Food Research. 2011; 55(3):495–503. https://doi.org/10.1002/mnfr.201000310
72. Goder D, Eshkol-Yogev I, Matsliah L, Lemberger M, Harlev M, Furer A, *et al*. *In vivo* study of the efficacy of bupivacaine-eluting novel soy protein wound dressings in a rat burn model. Burns. 2022; 48(3):623-632. https://doi.org/10.1016/j.burns.2021.07.006 PMid:34330581.
73. Alharbi NS, Khaled JM, Alanazi K, Kadaikunnan S, Alobaidi AS. Biosynthesis of silver nanoparticles (Ag-NPs) using *Senna alexandrina* grown in Saudi Arabia and their bioactivity against multidrug-resistant pathogens and cancer cells. Saudi Pharm J. 2023; 31(6):911-920. https://doi.org/10.1016/j.jsps.2023.04.015 PMid:37234348 PMCid:PMC10205756.
74. Tanmoy G, Deveswaran R, Apurba S, Kavana K, Monisha R, Bharath S. *In-vitro* investigation of wound healing potential of *M. acuminata* leaf extract. Anal Chem Lett. 2021; 11(3):437-449. https://doi.org/10.1080/22297928.2021.1892521
75. Geckil H, Xu F, Zhang X, Moon S, Demirci U. Engineering hydrogels as extracellular matrix mimics. Nanomedicine (Lond). 2010; 5(3):469-484. https://doi.org/10.2217/nnm.10.12 PMid:20394538 PMCid:PMC2892416.
76. Beheshti A, Shafigh Y, Zangivand AA, Samiee-Rad F, Hassanzadeh G, Shafigh N. Comparison of topical sucralfate and silver sulfadiazine cream in second degree burns in rats. Adv Clin Exp Med. 2013; 22(4):481-487.
77. Amin Z, Afrin M, Meghla NS, Nur A, Rahman M, *et al*. Assessment of antibacterial, anti-inflammatory, and cytotoxic effects of different extracts of *Gynura procumbens* leaf. Curr Ther Res. 2021; 95:100636. https://doi.org/10.1016/j.curtheres.2021.100636 PMid:34367384 PMCid:PMC8326354.
78. Wood FM. Skin regeneration: The complexities of translation into clinical practise. Int J Biochem Cell Biol. 2014; 56:133-140. https://doi.org/10.1016/j.biocel.2014.10.025 PMid:25448410.
79. Lipsky BA, Hoey C. Topical antimicrobial therapy for treating chronic wounds. Clinical Infectious Diseases: An Official Publication of the Infectious Diseases Society of America. 2009; 49(10):1541–1549. https://doi.org/10.1086/644732
80. Wang C, Liu Z, Zhang N, Huang S, Mao R, Wang H, *et al*. Three dimensional fibrous scaffolds as tissue repairing templates during post-operative healing. Mater Des. 2021; 210:110019. https://doi.org/10.1016/j.matdes.2021.110019
81. Seyedian R, Isavi F, Najafiasl M, Zaeri S. Electrospun fibers loaded with *Cordia myxa* L. fruit extract: Fabrication, characterization, biocompatibility and efficacy in wound healing. J Drug Deliv Sci Technol. 2021; 63:102528. https://doi.org/10.1016/j.jddst.2021.102528
82. Vuddanda PR, Montenegro-Nicolini M, Morales JO, Velaga S. Effect of plasticizers on the physico-mechanical properties of pullulan based pharmaceutical oral films. Eur J Pharm Sci. 2017; 96:290-298. https://doi.org/10.1016/j.ejps.2016.09.011 PMid:27629498.
83. Colohan SM. Predicting prognosis in thermal burns with associated inhalational injury: A systematic review of prognostic factors in adult burn victims. J Burn Care Res. 2010; 31(4):529-539. https://doi.org/10.1097/BCR.0b013e3181e4d680 PMid:20523229.
84. Nielson CB, Duethman NC, Howard JM, Moncure M, Wood JG. Burns: Pathophysiology of systemic complications and current management. J Burn Care Res. 2017; 38(1):e469-e481. https://doi.org/10.1097/BCR.0000000000000355 PMid:27183443 PMCid:PMC5214064.
85. Bigliardi P, Langer S, Cruz JJ, Kim SW, Nair H, Srisawasdi G. An asian perspective on povidone iodine in wound healing. Dermatology. 2017; 233(2-3):223-233. https://doi.org/10.1159/000479150 PMid:28848111.
86. Araujo TAT, Almeida MC, Avanzi I, Parisi J, Simon Sales AF, Na Y, *et al*. Collagen membranes for skin wound repair: A systematic review. J Biomater Appl. 2021; 36(1):95-112. https://doi.org/10.1177/0885328220980278 PMid:33349104.

87. Kumar D, Saini N, Pandit V, Ali S. An insight to pullulan: A biopolymer in pharmaceutical approaches. Int J Basic Appl Sci. 2012; 1(3). https://doi.org/10.14419/ijbas.v1i3.101
88. Agarwal T, Tan S-A, Onesto V, Law JX, Agrawal G, Pal S, *et al*. Engineered herbal scaffolds for tissue repair and regeneration: Recent trends and technologies. Biomed Eng Adv. 2021; 2:100015. https://doi.org/10.1016/j.bea.2021.100015
89. Soud S, Hasson BA, Ismail A, Hussein N, Maeh R. Synthesis and characterization of plant extracts loaded PVA/PVP blend films and evaluate their biological activities. Eurasian Journal of Biosciences. 2020; 14:2921–2931.
90. Monafo WW, Freedman B. Topical therapy for burns. Surg Clin North Am. 1987; 67(2):133-145. https://doi.org/10.1016/S0039-6109(16)44137-X PMid:3544263.