"A Review on a Vrana Ropana (Wound Healing): Decoding Ayurvedic knowledge through modern validation."

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Abstract:
The biological process of wound healing is highly coordinated and multifaceted. One of the biggest clinical challenges is still managing chronic and non-healing wounds. Modern treatment procedures have been utilized to treat wounds, but they have drawbacks. It is necessary to investigate alternative approaches to wound care in order to overcome limitations. Ayurveda is one of the ancient medicinal systems that have given elaborate knowledge on wound healing based on the principle of Vrana Chikitsa. Many medicinal plants used in the treatment of wounds in the traditional system of Vrana Ropana. The molecular mechanism behind the wound healing process is better understood with the help of these contemporary scientific validation technologies. This review aims to critically examine the scientific basis of classical Ayurvedic wound-healing practices by integrating traditional knowledge with contemporary biomedical evidence. The combination of Indigenous Knowledge Systems and scientific study provides an excellent way of generating safe, efficacious, cost-effective, and sustainable wound healing formulations.

Introduction:
The body's first line of defence is the skin, which protects it from externally harmful substances including infections, minor injuries, and environmental harm. Any kind of physical disturbance like this initiates a very well-coordinated healing process that aims to preserve tissue integrity (Tavakoli & Klar, 2020). Wounds are classified on the basis of pathophysiology and consequences: Acute and Chronic Wounds. Acute wounds, which heal in a predictable amount of time, and chronic wounds, which do not go through the normal healing phases because of underlying conditions like obesity, diabetes, infection or old age (Nizam et al., 2025). Impaired wound healing represents growing clinical and economic burden. Approximately 10.5 million Americans, or one in six Medicare users, are thought to have chronic wounds, with problems ranging from pressure ulcers (PUs) to surgery site infections (SSIs). Medicare alone pays an estimated $22.5 billion a year for wound care treatment a staggering amount that doesn't take into consideration indirect expenses like diminished quality of life or reduced productivity(Sen, 2025). Millions of individuals worldwide suffer from chronic wounds, and a significant portion of the population has non-healing wounds that need ongoing treatment. Every year, almost 6.5 million people in the US alone suffer from chronic wounds(Sen, 2023). Diabetic foot ulcers (DFUs) are especially common, impacting 15–34% of individuals with diabetes at some point in their lifetimes(McDermott et al., 2023). Modern wound management strategies includes use of antibiotics, biomaterials, stem cell therapy, inclusion of growth factors, tissue engineering and many more have therapeutic potential but

also have limitations like cytotoxicity, high cost, ethical issues and antibiotic resistance continue to prevent widespread use(Sewwandi et al., 2023).

These problems illustrate an urgent need to explore alternative approaches. One possible solution to these issues may lie in the ayurvedic approach to managing wounds by offering a sustainable, holistic view of wound care that emphasizes natural healing, tissue regeneration and minimal side effect. The oldest know documentation medical systems is Ayurveda, which provides a systematic and holistic understanding of vrana chikitsa. “Vrana” is a Sanskrit term for wound according to Ayurveda. In Ayurveda wound is roughly categorized into Nija (endogenous, created by Dosha vitiation) and Agantuja (external, caused by trauma). Sushruta provides a complete list of 60 measures (Shashti Upakrama) for the treatment of wound, which include debridement (Shodhana), cleaning (Parisheka), suturing (methods such as Gophanika and Tunnasevani), herbal formulation administration, bandaging (Vrana Bandhana), and protection (union/scar formation)(Khattra, 2024). The medicinal plants with katu, tikta, and kaṣāya rasa, has different property which encourage the wound healing includes antimicrobial activity, reduced inflammation, and enhance tissue repair(Rath et al., 2014).

However, in present scientific era, therapeutic approaches require experimental evidence, data of underlying molecular mechanisms and most important reproducibility rather than depending merely on observations and tradition based knowledge. While the traditional Indian system of medicine called Ayurveda is known to have vast repository of ancient wisdom enriched through centuries of observation, clinical practice, and experiential healing, many of its concepts remained scientifically unexplored for a long period of time.

In Ayurveda wound healing is known as Vrana Ropana, can be considered an integrated practice encompassing plant-based medication, tissue regeneration, reduction of inflammation, infection control, and physiological balance restoration. There is a large number of medicinal plants and formulations used for successful wound management in the ancient texts of Ayurveda; nevertheless, their recognition in contemporary medical science needs scientific proof.

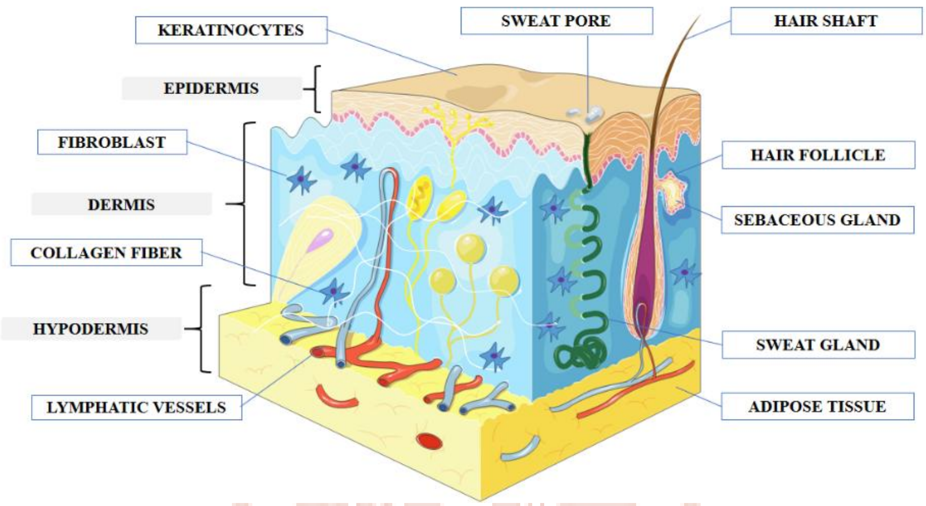
The emergence of new developments in phytochemistry, molecular biology, cell culture, omics science, bioinformatics, and computational approaches has led to the possibility of scientific validation of these traditional medicinal systems. Herbal plants which were used for wound management in ancient time have strong antioxidant, anti-inflammatory, antibacterial, angiogenic, collagen-stimulating, and extracellular matrix regeneration properties. Furthermore, modern scientific approaches such as in vitro and in vivo experiments transcriptomics, proteomics, metabolomics, molecular docking, and network pharmacology as well as molecular level studies are helping unravel the biochemical components and pathways responsible for tissue repair.

Therefore, the combination of Indigenous Knowledge Systems and biomedical science may prove a promising approach towards developing wound-healing therapeutics that are safe, sustainable, inexpensive, and biologically effective. In this context, present review seeks to critically analyse ancient Ayurvedic beliefs of wound healing and the medicinal plants linked with Vrana Ropaṇa. The study also emphasizes phytochemical ingredients, molecular processes, in vitro assessments, omics-based investigations, and computational research that together demonstrate the scientific significance of ancient Indian medical knowledge and its potential for worldwide therapeutic applications.

Biology of wound healing:

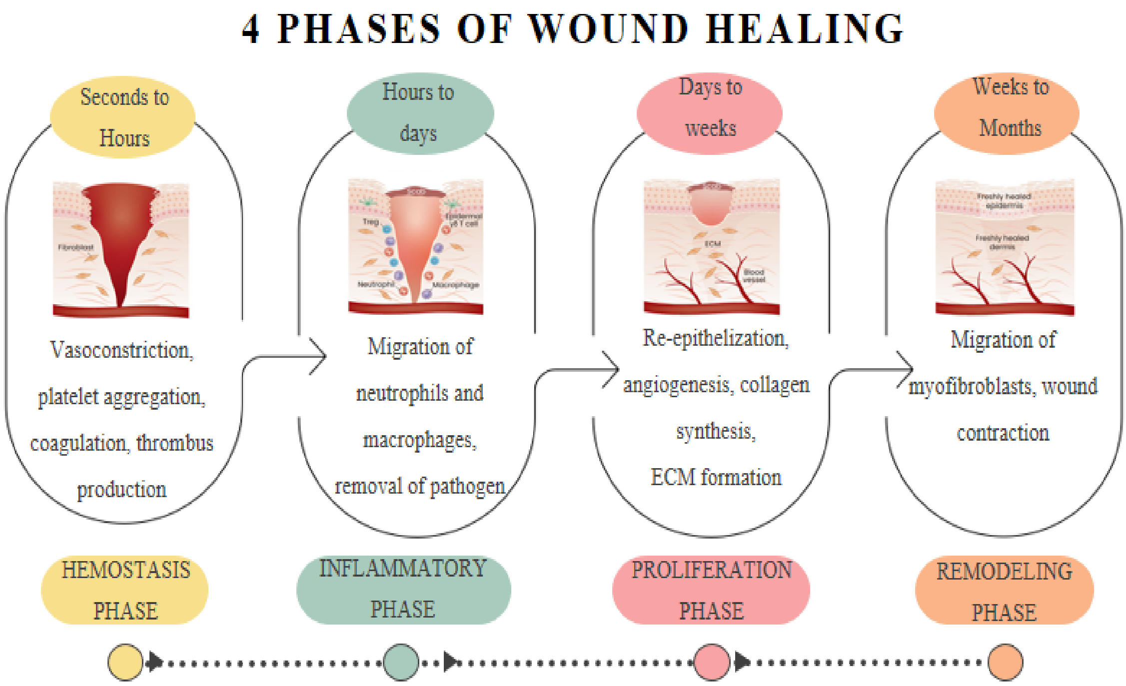
Skin is the largest organ of the body in terms of its surface area. This layer protects inside tissues against mechanical injury, microbial infections, UV radiation, and severe temperatures(Rodrigues et al., 2018). Mammalian skin consists of two layers: the epidermis and dermis, which sit above the hypodermis and deeper fascia [figure 1]. The epidermis is made up of keratinocytes and has hair follicles, as well as sweat and sebaceous glands. These tentacles reach into the dermis. Fibroblasts play a crucial role in wound healing by depositing collagen matrix. The dermis has a network of cutaneous vessels that expand during healing and extend into the underlying hypodermis, which is rich in adipose tissue.(Peña & Martin, 2024). There are several factors that lead to wounds. Wound healing is a dynamic process that happens in phases over the course of several weeks or months. The initial phase of hemostasis begins shortly after injury and lasts minutes to hours. [figure 2] It involves vasoconstriction, platelet aggregation, and clot formation via both intrinsic and extrinsic coagulation pathways, which stop the bleeding.

There will be an inflammatory phase, followed by 1 to 4 days infiltrated by neutrophils and monocytes for white blood cells, which initiate the release of cytokines and growth factors by clearing debris, preventing infection and leading to the fibroblast-activated phase; from days 4 to 21, is the proliferative phase, consisting of fibroblast-driven deposition of collagen as well as angiogenesis, where new cells in reepithelialisation of the skin help restore the intact(Wallace et al., 2023).



[Figure 1: Human skin anatomy; Source: Adapted from BioIcons (https://bioicons.com/**)]**

This whole process of wound healing is thus dynamic and closely regulated. Therefore, any distortion in these stages can lead to delayed healing or chronic wounds along with excessive scar formation, therefore underlining the importance of adequate therapeutic strategies aimed at optimizing tissue regeneration.



[Figure2: Phases of wound Healing; source: Adapted from
https://doi.org/10.14348/molcells.2023.0071**]**

Phases of Wound Healing

a. The Beginning of Wound Healing: Hemostasis

The blood and lymph from the injured blood vessels and lymphatics flood the area and clean the wound surface right after formation of wound. Immediately after that, the formation of the vasoactive mediators like catecholamine, serotonin, bradykinin, and histamine initiates vasoconstriction of the injured blood vessels, reducing the amount of blood leakage. Vasoconstriction persists for about 5 to 10 minutes. After that, there is vasodilation of the blood vessels, and the cells along with fluid leak out from the blood vessels into the extravascular area (Hosgood, 2006). As the blood starts to flow into the wound site, platelets interact and bind to the wall of the damaged blood vessel along with the collagen in the extracellular matrix. This results in the secretion of various inflammatory substances by platelets, thereby causing aggregation of platelets. This sets off both the intrinsic and extrinsic pathways for blood clot formation, leading to clotting of blood at the site(Verhamme & Hoylaerts, 2009). Several growth factors and cytokines such as tissue factor (TF), platelet derived growth factor (PDGF), fibroblast growth factor (FGF), tumour necrosis alpha (TNFa) and interleukin-1 (IL-1), Transforming growth factor-beta (TGF-b) are activated to regulate tissue repair and regeneration. The release of platelet factors is strongest within an hour of platelet activation. However, even when platelets are activated, their release of factors continues for up to seven days. In other words, the process is continuous and influences wound healing (Senzel et al., 2009).

b. The Defensive and Cleaning Phase: Inflammation

This process facilitates the attraction of the cells that digest non-living tissue, foreign substances, and bacteria, signalling the start of the next stage. Phagocytosis plays an important role in further wound healing since wound infections that lack a balanced bacterial environment cannot heal (Sorg & Sorg, 2023). Recruitment of inflammatory cells at the wound site happens in response to stimuli at the wound site. In an acute wound, cells within the host undergo necrosis, releasing various components which act as danger signals (such as uric acid, DNA, RNA, extracellular matrix proteins). These molecules are known as damage associated molecular patterns(Kono & Rock, 2008). If there is contamination of the wound by any type of pathogen, then along with pathogen-associated molecular patterns (PAMPs), the wound microenvironment will also contain these danger signals. The pattern recognition receptors such as toll-like receptors will recognize these danger signals; therefore, they will be activated. Later, they will express various genes coding for chemical mediators (Kaisho & Akira, 2006). Neutrophils are inflammatory cells that are abundantly present in a new injury and their role is primarily to clear out the waste and prevent any infections. The recruitment of neutrophils is done through several factors such as IL-8 or CXCL8 discussed above and neutrophils have more than 30 receptors that control their recruitment and activation process (Futosi et al., 2013). However, a deficiency in the monocyte and tissue macrophage will lead to drastic changes in wound healing, such as inadequate debridement, insufficient fibroblast proliferation, improper angiogenesis, and poor fibrosis. More growth factors (such as transforming growth factor-α, heparin binding epidermal growth factor, and basic fibroblast growth factor) are released by the polymorph nuclear leukocytes and macrophages, contributing to the process of inflammation. The collagen fibers in the wound can be seen in the incision margin of the wound; however, they are vertically arranged without spanning across the incision site. The proliferation of epithelial cells leads to the development of a thickened epidermis covering the wound (Enoch & Leaper, 2008).

c. The Tissue Regeneration Phase: Proliferation

Proliferative stage begins on day 3 and continues for 2-4 weeks following wounding. Proliferative stage is associated with fibroblast migration and the development of granulation tissue. As the proliferative stage advances, the initial provisional fibrin/fibronectin matrix is replaced by new granulation tissue that develops in response to injury. The epithelialization of the wound marks the end of the proliferative stage (Enoch & Leaper, 2008). Vascular regeneration is crucial in the proliferative stage. Formation of new vessels is known as angiogenesis and is accomplished in two stages: vessel sprouting and vessel anastomosis (Fantin et al., 2010). In addition to secreting VEGF, which aids vessel sprouting, macrophages secrete two transmembrane proteins known to facilitate angiogenesis. The role of these macrophages in wound repair is essential, and in studies with macrophage deficiency, angiogenesis was found to be hampered(Brancato & Albina, 2011).

Fibroblast actively proliferate and synthesize collagen, fibronectin, proteoglycans and glycosaminoglycan which are components of extracellular matrix. This ECM components provide structural support for cell adhesion, migration and tissue regeneration. In tissue restoration deposition of collagen plays a major role at wound site. Keratinocytes migrate and proliferate from the wound edges which lead the restoration of the epidermal barrier and wound closure. Tissue regeneration, extracellular matrix remodelling and cellular proliferation regulate by growth factors such as transforming growth factor-beta (TGF-β), epidermal growth factor (EGF), and fibroblast growth factors (FGF)(Enoch & Leaper, 2008).

d. The Strengthening and Restoration Phase: Remodeling

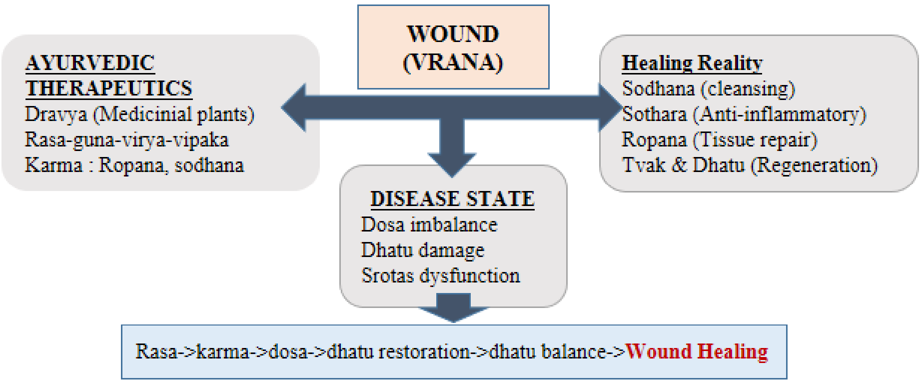
The last stage of healing is to be the full epithelisation of the wound. However, this process may take months or even years. Re-epithelization, ECM remodelling, neovasculature regression and scar maturation occur during this phase(Peña & Martin, 2024). Granulation tissue that consists of collagen type III will be replaced with more potent collagen type I fibers, enhancing the strength of the tissue structure. Myofibroblasts regulate the process of ECM remodeling by producing matrix metalloproteinases (MMPs) and their tissue inhibitors, TIMPS, which must be regulated appropriately in order to have effective tissue remodeling and avoid chronic wound development. Afterward, myofibroblasts become apoptotic cells, and macrophages will phagocytize any dead cells and debris within the wound site, producing avascular and acellular mature scar tissue. An increase in inflammatory response in this stage may lead to the development of hypertrophic scars and keloids. IL-6 cytokine plays a significant role in the process of fibrosis, collagen production, and scar remodeling (Sorg & Sorg, 2023).

Ayurvedic perspective of wound healing:

Management of wounds has a long-standing history across various culture. Wound management is mentioned in Rigveda written between 1500 and 1200 BC(Rawekar et al., 2025). The oldest know documentation medical systems is Ayurveda, which provides a systematic and holistic understanding of vrana chikitsa. Ayurveda offers a comprehensive, holistic, and evidence-based framework for wound care, encapsulated in the concept of Vrana Chikitsa. The Sanskrit term "Vrana" denotes the disruption or destruction of normal tissue architecture, which may result from endogenous or exogenous factors [Figure 3].

In Ayurveda wound is roughly categorized into Nija (endogenous, created by Dosha vitiation) and Agantuja (external, caused by trauma). Sushruta provides a complete list of 60 measures (Shashti Upakrama) for the treatment of wound, which include debridement (Shodhana), cleaning (Parisheka), suturing (methods such as Gophanika and Tunnasevani), herbal formulation administration, bandaging (Vrana Bandhana), and protection (union/scar formation)(Khattra, 2024). These principles remarkably parallel modern concepts of wound bed preparation, infection control, tissue remodeling, and regenerative healing.

Extensive research on wound healing in Ayurveda has been reported over the last century, especially on the topics of Vrana and Vrana Śodhana and Vrana Ropaṇa, with the purpose of providing scientific backing to classical postulates in the modern scientific setting (Sheoran et al., 2019). Numerous scholars have emphasized the significance of Vrana Śodhana and Vrana Ropaṇa dravyas in managing chronic wounds. Gandhi connected Ayurveda with contemporary theories of wound-healing to highlight the significance of cleansing and healing formulations in healing chronic wounds(Gandhi, 2024). Ayurvedic wound classifications, therapeutic approaches, and formulations used in wound management have been documented in systematic reviews (Khattra, 2024).



[Figure 3: Concept of *Vrana*]

According to ayurvedic principles, the action of drug can either be due to its Dravyaprabhava (particular impact) or Gunaprabhava (effect based on Rasa, Guna, Veerya, and Vipaka). The Dravyaprabhava refers to the specific properties of a medicine inherited from its panchmahabhoot structure. Conversely, Gunaprabhava explains pharmacological activities using pharmacodynamics qualities such as Rasa, Guna, Veerya, and Vipaka. Dravyaprabhava is unique to the drug and may not be explained by its pharmacodynamics properties. Therefore, if we want to use drugs properly, we must understand both their dravyprabhava and gunaprabhava which help us to use drugs rationally and safely based on their effects as described in Ayurveda (Kumar et al., 2021).

The concept of Ayurveda applies to medicinal plants listed in *Suśruta Saṁhitā* under Vrana-shodhan, Vrana-Ropana, and Vrana-Shodhana-Ropana. Acharya Sushruta has listed 153 plants for Vrana ropana in his *Suśruta Saṁhitā*, which can be used for injuries and wounds. In the Vrana-Shodhana category, the most common plants are of Katu, Tikta, and Kashaya Rasa. Tikta and Katu Rasa include Krimighana, which has antibacterial and antifungal properties. To treat chronic wounds, Katu Rasadravya (medicinal herbs) can be utilized initially for Vrana-Shodhana. Katu Rasa also possesses anti-inflammatory properties (Shothahara)(Wankhede et al., 2023). Tikta and Kashaya Rasa Dravyas have moisture-reducing properties that can reduce excessive exudate. They also have the ability to dry, which promotes wound healing and reduces inflammation, which can cause delayed healing. Tikta and Kashaya Rasa rely heavily on Sheeta Veerya, which has Stambhana (haemostasis) properties and plays a crucial role in clotting during the inflammatory phase. The majority of plants come from Arkadi Gana, known for their Krimighana and Vrana-Shodhana properties, which aid in wound healing and infection prevention(Raina et al., 2021).

A large portion of the published literature consists of formulation-based studies. The dual Šodhana and Ropaṇa actions of Pañcavalkala formulations have been examined (Dhurve & Dudhamal, 2020). Classical Ayurvedic texts have also documented Aragvadhādi Gaṇa's ability to heal wounds (Ghodela et al., 2017). Management of wound by Clinical trial in Manjiṣṭhādi Ghṛta showed significant reduction in parameters like granulation and epithelialization (Baria et al., 2011). These facts further endorse the efficacy of Ayurvedic wound healing practices. Durvādi Taila in the healing of episiotomy wounds (Shokhanda et al., 2025). Efficacy of Durvādi Taila in wound healing (Mathew, 2018). A comparative clinical trial of Vranarakṣasā Taila and Madhu in cases of Duṣṭa Vrana, Jalaukāvacaraṇa and Śodhana Ropaṇa Lepa in the management of Duṣṭa Vrana (Verma & Swapna, 2020).

Ayurvedic wound-healing principles constitute a comprehensive therapeutic system that encompasses wound cleansing, infection control, inflammation modulation, tissue regeneration, and scar management. The increasing scientific validation of classical formulations and medicinal plants underscores the translational potential of Ayurvedic knowledge in developing novel wound-healing therapeutics. The integration of traditional Vrana Chikitsa concepts with modern molecular biology, pharmacology, and biotechnology may offer new opportunities for evidence-based regenerative medicine and advanced wound-care research.

Medicinal Plants Used in Vrana Ropana:

Ayurveda uses medicinal plants with cleaning and healing properties extensively for wound management [Table 1]. In Sushrut Samhita, Acharya Susruta mentions many herbal formulations. These plants are applied in different forms like decoctions, oils, pastes, powders, and for fumigation. The blend of traditional Ayurvedic wisdom and modern scientific evidence shows how significant these plants are for effective wound repair and tissue regeneration.

[Table 1: list of medicinal plants used for *Vrana Ropana* in ancient time]

Sr. No	Plant name (sanskrit name)	Plant name (scientific name)	Family	Part used	Activity	References
1	Eranda (एरण्ड)	*Ricinus communis*	Euphorbiaceae	Leaves	Anti-inflammatory, anti-bacterial	(Susruta, 1963),(Jena & Gupta, 2012)
2	**Haridra** (हरिद्रा)	*Curcuma longa*	**Zingiberaceae**	**Rhizome**	Anti-Inflammatory, Antimicrobial	(Susruta, 1963),(Akbik et al., 2014)

					Antioxidant, Tissue Regeneration	
3	**Yashtimadhu** (यष्टीमधु)	*Glycyrrhiza glabra*	Fabaceae	Roots rhizomes	Anti-Inflammatory, Antimicrobial Antioxidant ,Collagen Production and Repair	(Susruta, 1963),(Assar et al., 2021)
4	**Balu (बलु)**	*Sida cordifolia*	***Malvaceae***	Leaves	Enhanced Healing, **Tissue Strength,** Anti-Inflammatory, Antioxidant	(Susruta, 1963),(Pawar et al., 2013)
5	**Padma** (पद्म)	*Nelumbium speciosum*	Nelumbonaceae	Leaves, flowers, and seeds	Anti-Inflammatory, Antimicrobial Antioxidant, Tissue Regeneration	(Susruta, 1963),(Lee et al., 2015), (Sahu et al., 2025)
6	**Shatavari** (शतावरी)	*Asparagus racemosus*	Asparagaceae	Root and seed	Antioxidant, anti-inflammatory, and immunomodulatory effects	(Susruta, 1963),(Kodancha et al., 2011)
7	Utpala	*Nymphaea stellata*	Nymphaeaceae	**Flowers, leaves,** and **rhizomes**	Antioxidant, anti-inflammatory, and immune-modulatory effects	(Susruta, 1963),(Antonisamy et al., 2014)
8	**Nagakesara** (नागकेसर)	*Messua ferrea*	Calophyllaceae	**Seed kernels** and the **flower or seed oils**	Anti-Inflammatory, Antimicrobial	(Susruta, 1963),(Asif et al., 2017)

					Antioxidant, Tissue Regeneration	
9	**Chandanam** (चन्दनम्)	*Santalum album*	Santalaceae	**Heart-wood** and the **essential oil** extract	Antioxidant, anti-inflammatory, and immune-modulatory effects	(Susruta, 1963),(Saneja et al., 2009)
10	Guggulu (गुग्गुलु)	*Commiphora mukul Engl.*	Burseraceae	Tem bark exudate	Angiogenesis, antioxidant, anti-inflammatory	(Susruta, 1963),(Malayeri et al., 2025)
11	**Shalmali** (शाल्मली)	*Salmalia malabarica*	Malvaceae	Bark, resin (Mocharasa), and leaves	Antibacterial, astringent, and anti-inflammatory properties	(Susruta, 1963)
12	**Vatavriksha** (वटवृक्ष)	*Ficus benghalensis*	Moraceae	**Milky latex**, **stem bark**, **aerial roots**, and **leaves**	Accelerate tissue repair, boost collagen production, and reduce inflammation	(Susruta, 1963),(Garg & Paliwal, 2011)
13	Priyangu	*Callicarpa macrophylla*	Lamiaceae	**Bark** and **leaves**	Enhance wound contraction, increase tensile strength, and speed up tissue epithelialization	(Susruta, 1963)
14	**Dhataki** (धातकी)	*Woodfordia fruticosa*	Lythraceae	**Flowers**	Reducing inflammation, preventing infection, and promoting collagen synthesis	(Susruta, 1963),(Raghuwanshi et al., 2017)
15	**Udumbara** (औदुम्बर or उदुम्बर)	*Ficus racemosa*	Moraceae	**Stem bark and leaves**	Accelerate wound closure, enhance cell migration,	(Susruta, 1963),(Murti & Kumar, 2012)

					and stimulate collagen synthesis	

Integrating Indigenous Knowledge Systems (IKS) with Modern Validation Approaches:

Indigenous knowledge systems are a goldmine for healthcare practices. These repositories were built by wise people over many years, observing and connecting with nature. Ayurveda is a special part that offers a big picture of health, diseases, and recovery. In old texts, vrana chikitsa, or wound healing, is described in great detail. various ways of wound management are mentioned in Ancient Ayurvedic books. Although these methods have been passed down for ages, to get accepted widely today, they need scientific validation.

The integration of traditional knowledge with modern scientific validation offers an opportunity to bridge this gap. Modern biomedical science provides experimental tools which has potential of evaluating the traditional knowledge's efficacy, safety and mechanisms of action. Modern phytochemical analysis methods will assist in identifying a bioactive molecule found in medicinal plants that is important for wound healing. Flavonoids, phenolic acids, terpenoids, alkaloids, and polysaccharides are examples of bioactive substances found in medicinal plants that have tissue-regenerating, antibacterial, anti-inflammatory, and antioxidant activities. These biological processes closely align with the therapeutic goals outlined in Ayurvedic wound care. For instance, the Ayurvedic idea of Vrana Ropana is linked to increased fibroblast proliferation, collagen production, angiogenesis, and tissue remodelling, whereas Vrana Shodhana is connected with antibacterial and wound-cleansing properties.

The increased interest in traditional medicinal systems has emphasized the need for scientific approaches to assess their therapeutic claims. While the Ayurvedic literature gives detailed accounts of wound treatment and healing procedures, current biological research provides instruments for examining their efficacy, safety, and underlying processes. The combination of these methodologies has made it easier to scientifically validate various therapeutic plants and formulations used in Vrana Ropana.

Phytochemical analysis is the primary approaches for the validation which help to identify and characterise the bioactive constituents present in medicinal plants. There are many advanced analytical techniques such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), and nuclear magnetic resonance (NMR) spectroscopy have been widely used to identify compounds responsible for wound-healing activity. Numerous phytochemicals, including flavonoids, phenolic compounds, terpenoids, alkaloids, and polysaccharides, have been associated with antioxidant, anti-inflammatory, antimicrobial, and regenerative properties.

The primary approach for evaluating the wound healing ability of medicinal plant extracts is in- vitro investigations, which comprise several cell-based assays utilizing fibroblasts and keratinocytes to examine biological processes such as cell proliferation, migration, collagen formation, and angiogenesis. Scratch tests are used to investigate wound closure, whereas cytotoxicity assays give a safety profile for drugs.

Successful in vitro investigations are followed by in vivo research that use animal models to assess the efficacy of herbal extracts. The most common experimental systems are excision, incision, and burn wound models. Therapeutic efficacy is determined by measuring parameters such as wound contraction rate, epithelialization time, tensile strength, collagen content, and histological alterations. These studies give important evidence for the capacity of medicinal herbs to enhance tissue repair and speed up wound healing.

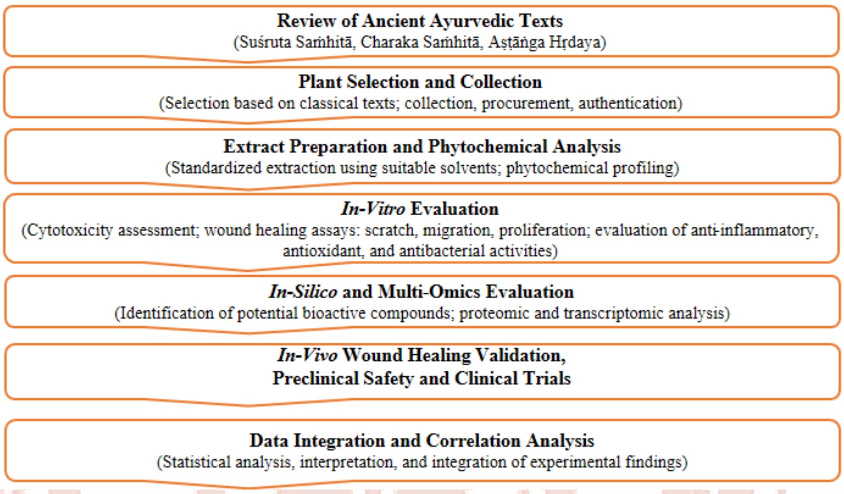
To understand wound healing mechanisms at molecular level different techniques are employed such as quantitative polymerase chain reaction (qPCR), Western blotting, immunohistochemistry, and enzyme-linked immunosorbent assays (ELISA) enable the investigation of genes, proteins, and signaling molecules involved in tissue regeneration. These methods help identify the influence of herbal compounds on critical wound-healing mediators including vascular endothelial growth factor (VEGF), transforming growth factor-beta (TGF-β), platelet-derived growth factor (PDGF), matrix metalloproteinases (MMPs), and inflammatory cytokines.

Multiomics approaches offer a more comprehensive understanding of the biological impacts of conventional drugs. Transcriptomics analyses gene expression patterns linked with wound repair, whereas proteomics investigates changes in protein expression and signalling pathways. Metabolomics helps identify bioactive metabolites and biomarkers involved in healing processes. Together, these technologies offer systems-level insights into the intricate relationships that underpin the therapeutic benefits of Ayurvedic medicinal herbs.

In recent years, in silico studies have grown in relevance for evaluating therapeutic effectiveness. Molecular docking studies aid in the prediction of phytochemical interactions with molecular targets involved in inflammation, oxidative stress, angiogenesis, and extracellular matrix remodeling. Network pharmacology facilitates the investigation of multi-target and multi-component interactions, providing a scientific foundation for comprehending the holistic nature of Ayurvedic formulations.

Clinical trials are the final stage of the contemporary scientific validation process. Clinical trials are used to study the effectiveness, safety, dosing, and therapeutic results of Ayurvedic therapies in humans. Several herbal formulations have shown promise in experimental research, but bigger randomized controlled trials are needed to help them integrate into evidence-based wound treatment procedures.

Collectively, these modern scientific validation methodologies give a solid scientific foundation for exploring ancient Ayurvedic knowledge. Researchers can use phytochemical characterization, experimental studies, molecular investigations, omics technologies, computational tools, and clinical evidence to evaluate the therapeutic potential of Vrana Ropana practices and facilitate their translation into contemporary healthcare applications [Figure 4].



[Figure 4: Summarized plan of scientific validation of ancient Ayurvedic knowledge]

Challenges and Limitations:

Despite the expanding amount of data confirming the wound-healing capabilities of Ayurvedic medicinal plants and formulations, a number of obstacles remain to prevent their widespread adoption and incorporation into mainstream treatment. Addressing these constraints is critical for transforming traditional knowledge into scientifically verified, clinically effective treatment approaches. One of the most significant issues is a lack of standardization of herbal medications. The chemical makeup of medicinal plants varies greatly depending on geographic location, meteorological conditions, harvesting season, farming procedures, and extraction processes. Such variability frequently results in variations in the concentration of bioactive chemicals, making it difficult to replicate experimental findings and assure consistent treatment results.

The availability of high-quality clinical evidence is restricted. Many published research is limited to in vitro investigations or animal models, with few well-designed human clinical trials. Small sample numbers, insufficient controls, short research durations, and differences in treatment procedures frequently decrease the quality and generalizability of clinical findings. As a result, translating good laboratory findings into ordinary clinical practice remains difficult. Another point of issue is the complexity of Ayurvedic formulas. Many traditional medicines include many herbs and substances that may work together through various biological mechanisms. While this multi-component approach is regarded as one of Ayurveda's strengths, it also hampers scientific inquiry, quality control, and determining the specific components responsible for therapeutic results.

Another area that requires more attention is safety assessments. Although medicinal plants are typically thought to be safe owing to their natural origin, improper dose, infection, adulteration, herb-drug interactions, and long-term usage can all result in negative consequences. Comprehensive toxicological investigations are so required to determine safety profiles and optimum treatment doses. Furthermore, integrating Indigenous Knowledge Systems into current biomedical research necessitates multidisciplinary collaboration among Ayurvedic practitioners, pharmacologists, molecular biologists, clinicians, and data scientists. Such joint efforts remain restricted, leaving gaps between ancient wisdom and modern scientific understanding.

Future Perspectives:

The growing worldwide burden of acute and chronic wounds, along with the limits of standard treatment options, has rekindled interest in traditional medical systems as potential sources of novel therapeutic treatments. Ayurveda, with its rich understanding of Vrana Chikitsa and medicinal herbs, provides a solid platform for developing next-generation wound-healing treatments. However, fulfilling this promise necessitates a multidisciplinary strategy that blends traditional knowledge with breakthroughs in current biomedical research. Future research should prioritize the systematic scientific validation of Ayurvedic therapeutic herbs and formulations via well-designed experimental and clinical trials. While some plants have shown promise wound-healing effects in laboratory studies, many remain understudied. Comprehensive studies addressing effectiveness, safety, dose optimization, and mechanisms of action are required to develop better evidence for clinical use.

It is anticipated that the use of omics technologies, such as proteomics, metabolomics, transcriptomic, and genomes, would greatly advance our knowledge of the molecular underpinnings of Ayurvedic wound-healing treatments. By identifying important genes, proteins, metabolites, and signalling pathways involved in tissue healing, these methods can offer mechanistic insights into conventional treatment techniques. Finding new biomarkers and therapeutic targets for wound care may be made easier with the use of this knowledge. Advances in computational biology and artificial intelligence are also likely to play an important role in future research. Molecular docking, network pharmacology, machine learning, and bioinformatics methods can anticipate molecular targets, uncover intricate relationships between phytochemicals and biological processes, and speed up the identification of bioactive substances.

The multi-component and multi-target character of Ayurvedic medicines presents new prospects for scientific investigation thanks to these technologies. The creation of sophisticated herbal-based wound care systems is another exciting field. The stability, bioavailability, and therapeutic efficacy of hydrogels, nanofibers, nanoparticles, films, scaffolds, and smart wound dressings may all be enhanced by the addition of plant-derived bioactive chemicals. These methods combine the benefits of contemporary biomaterials and tissue engineering technology with the regeneration potential of traditional medicinal herbs. Standardization and quality control of herbal formulations should be prioritized in future research. Reproducibility will be enhanced and consistent therapeutic results will be guaranteed by establishing proven processes for plant identification, culture, extraction, phytochemical characterization, and formulation creation. For Ayurvedic goods to be more widely acknowledged in international healthcare systems, they must meet internationally recognized quality criteria.

Large-scale randomized controlled clinical studies continue to be a top goal. To assess the efficacy of Ayurvedic treatments in a variety of patient demographics and to justify their inclusion in evidence-based wound care recommendations, strong clinical data is required. To do this, cooperative research combining physicians, pharmacologists, molecular biologists, and Ayurvedic specialists will be essential. Additionally, combining Indigenous Knowledge Systems with modern scientific methods may help create sustainable and reasonably priced healthcare solutions, especially in environments with low resources where access to cutting-edge wound care treatments may be limited. A vast and mostly unexplored resource, traditional medicinal plants have the potential to enhance current therapeutic choices and broaden the scope of accessible therapies.

The area of wound healing is anticipated to change in the upcoming years due to the convergence of contemporary biotechnology, computational sciences, regenerative medicine, and conventional medical expertise. The area of wound healing is anticipated to change in the upcoming years due to the convergence of contemporary biotechnology, computational sciences, regenerative medicine, and conventional medical expertise. It could be feasible to create innovative, evidence-based treatments that are not only safe and effective but also affordable and ecologically sustainable by bridging the gap between traditional knowledge and modern research. In addition to advancing wound care research worldwide, such initiatives will bolster the scientific legitimacy of Ayurvedic wound treatment.

Conclusion:

Wound healing is a multifaceted biological process that encompasses hemostasis, inflammation, proliferation, and tissue remodeling. Despite notable advancements in contemporary wound care, the rising incidence of chronic wounds, along with treatment-related limitations and escalating healthcare costs, necessitates the exploration of safe, effective, and cost-efficient therapeutic alternatives. Within this framework, Ayurveda provides a substantial body of knowledge on wound management through the concept of Vrana Chikitsa, which includes wound cleansing, infection control, tissue regeneration, and the restoration of physiological balance. This review underscores the significant alignment between classical Ayurvedic principles and modern insights into wound healing. Numerous medicinal plants traditionally utilized in Vrana Ropana have undergone scientific validation through phytochemical analyses, in vitro assays, in vivo studies, and emerging molecular methodologies. These investigations reveal that many Ayurvedic herbs exhibit antioxidant, anti-inflammatory, antimicrobial, angiogenic, collagen-stimulating, and extracellular matrix regenerative properties, which collectively enhance wound repair.

Recent advancements in phytochemistry, molecular biology, omics technologies, bioinformatics, molecular docking, and network pharmacology have significantly enhanced our understanding of the mechanisms that underpin the therapeutic effects of traditional remedies. These methodologies facilitate the integration of ancient empirical knowledge with evidence-based medicine by identifying bioactive compounds, molecular targets, and signalling pathways involved in tissue regeneration. However, challenges such as limited clinical evidence, lack of standardization, variability in herbal formulations, and insufficient mechanistic studies continue to impede the wider acceptance of Ayurvedic wound-healing therapies. Overcoming these obstacles through interdisciplinary research, stringent quality control measures, and well-designed clinical trials is essential for their successful incorporation into modern healthcare systems. The integration of Indigenous Knowledge Systems with contemporary biomedical science offers a promising pathway for the development of innovative wound-healing therapeutics. The scientific validation of Ayurvedic Vrana Ropana enhances the credibility of traditional medical knowledge and provides opportunities to discover sustainable, cost-effective, and biologically effective wound management strategies.

Ongoing research in this area has the potential to significantly advance global wound care and regenerative medicine.

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