CODEN: WJAPAC Impact Factor: 3.87 ISSN: 3049-3013

World Journal of Advance Pharmaceutical Sciences

Volume 2, Issue 2. Page: 9-16 Review Article www.wjaps.com

RECENT DEVELOPMENT IN THE PHYTOCHEMICAL BASED NANO DRUG DELIVERY SYSTEM FOR WOUND HEALING AND SKIN REGENERATION

***Ashirwad Sawale, Paras Raut, Shivani Kale and Aman Upaganlawar**

Department of Pharmacology, SNJBs Shirman Sureshdada Jain College of Pharmacy, Chandwad, Nashik, India.

How to cite this Article Ashirwad Sawale, Paras Raut, Shivani Kale and Aman Upaganlawar (2025). RECENT DEVELOPMENT IN THE PHYTOCHEMICAL BASED NANO DRUG DELIVERY SYSTEM FOR WOUND HEALING AND SKIN REGENERATION. World Journal of Advance Pharmaceutical Sciences, 2(2), 9-16.

Article Info

Article Received: 10 May 2025,

Article Revised: 30 May 2025,

Article Accepted: 20 June 2025.

DOI: https://doi.org/10.5281/zenodo.15755988

***Corresponding author:**

***Ashirwad Sawale**

Department of Pharmacology, SNJBs Shirman Sureshdada Jain College of Pharmacy, Chandwad, Nashik, India.

ABSTRACT

Effective and rapid wound healing requires advanced therapeutic strategies capable of maintaining a moist wound environment, minimizing infection, and promoting tissue regeneration. Among emerging technologies, phytoconstituent-based nanodrug delivery systems have demonstrated promising potential in enhancing wound healing. These nanoscale formulations offer targeted and sustained release of bioactive compounds, enabling accelerated tissue repair while minimizing adverse effects. Nanomedicine provides a more focused and efficient therapeutic approach, addressing the limitations of conventional dosage forms by improving site-specific delivery and bioavailability of therapeutic agents. Recent research has highlighted various nanocarrier systems such as dendrimers, hydrogels, liposomes, micelles, nanoparticles, and nanosomes that significantly enhance wound healing outcomes. These nanotechnologies not only improve the clinical relevance of treatment strategies but also offer superior therapeutic benefits, particularly in managing chronic and diabetic wounds. This review summarizes recent advancements in nanomedicine and emphasizes its expanding role in modern wound care through innovative drug delivery platforms tailored for improved healing efficacy.

KEYWORDS: Inflammation, Wound Healing, Nanomedicine, Liposomes Niosomes.

INTRODUCTION

Wound

A wound is an injury or condition that damages the structure or integrity of the skin and can be brought on by surgery, pathological illnesses like diabetes or vascular diseases, or external pressures like cuts, burns, or pressure.[1]

Fig. 1: Skin injury.

Types of wounds

There are mainly divided into two types and they are below,

Table No. 1: Types of Wounds.

Chronic Wound	Acute Wound
1. Venous/Vascular ulcers	I. Abrasion
2. Diabetic ulcers	II. Avulsion
3. Pressure ulcers	III. Cut wound
4. Ischemic wound	IV. Laceration
	V. Velocity wound
	VI. Radiation Wound

Wound healing process

The wound healing response is the process by which skin has evolved a quick and effective mechanism to mend breaks in its barrier.[2] A vast range of cells and biochemical components are involved in physiological process of wound healing. Tissue recovery is eventually aided by the activation of many enzyme pathways during the healing process. Throughout the procedure, damaged tissues are restored and replaced. The series of interconnected and overlapping procedures required for the healing phases that help to replace and restore damaged tissue. Bleeding, inflammation, movement, proliferation and remodelling phase.[3,4]

There are four main phases in wound healing they are describing in below;

1. Hemostasis
2. Inflammtion
3. Proliferation
4. Remodelling/Maturation

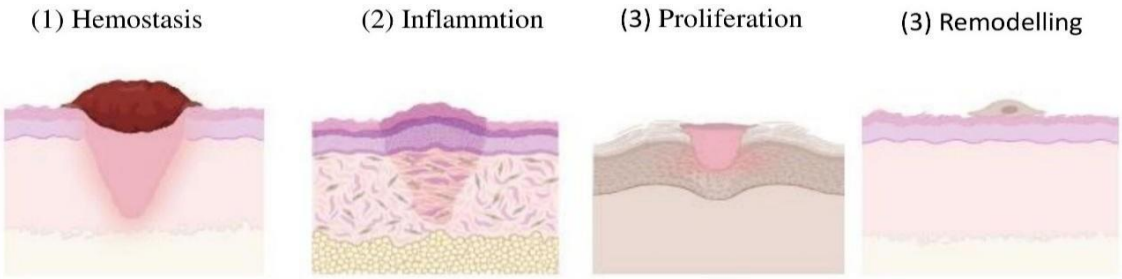

Fig. 2: Schematic representation of the different phases of wound healing.

1. Hemostasis

The sympathetic nervous system causes vasoconstriction at this stage to prevent drainage, which is followed by the start of clotting.[5] Hemostasis, the initial phase of healing, began with the damage to halt the bleeding. The body starts the blood coagulation and crisis repair frameworks at this time and builds a dam to contain the waste.[6] Damage-related tissue cells release chemokine's, growth factors, and alarm signals that help blood flow select resistant cells and stimulate the expansion of tissue-inhabitant population, resulting in safe cell collection at the injury site.[7]

2. Inflammation

Phase 1 in this category deals with coagulation, while Phase 2, often known as the defensive or inflammatory phase, prepares the wound site for the growth of the most recent tissue by killing bacteria and removing away debris.[8] Phase 2 involves the entry of neutrophils, a kind of white blood cell, into the wound to eradicate bacteria & clear the debris. White blood cells (WBC) leave behind macrophage cells, which continue to clear debris. To facilitate wound tissue repair that is responsible for growth and protein supplementation, these cells move toward the systemic cell. This stage, which lasts for 4 to 6 days and is classified as chronic inflammation, is frequently accompanied by erythema, heat, swelling, and pain.[9]

3. Proliferation

When the wound is completely healed, the wound enters its third phase, when the major targets for the wound are the filling and covering. The granulation arrangement, which allows skin cells to migrate on top of this tissue during the re-epithelialization process, is a representation of the proliferation stage.

This organisation comprises newly developed veins, safe cells, and fibroblasts. The first three proliferative stages (epithelialisation) are wound filling, wound region reduction, and the formation of a thin coating on the wound. The anatomical arrangements of the skin of different species facilitate quick healing. The proliferative stage usually lasts between four and twenty-four days.[10,11]

4. Remodelling/Maturation

At this stage of development, freshly formed tissue gradually develops strength and adaptability. Collagen fibres start to rearrange at this time, causing the tissue to regenerate and become more durable (though maximum strength is only 80% of pre-injury strength) Depending on the type of wound, the maturation stage might span from around 21 days to 2 Years.[12]

Skin regeneration process

The process involves replacing and regenerating skin damaged tissues.[7] The healing process involves a series of interconnected and overlapping stages that work together to restore damaged tissue and re-establish tissue function. The intricate dynamic self-healing mechanism of the skin (or other organ tissues), which usually consists of three stages, is influenced by the extracellular matrix, many repair cells, and interactions between these

elements following an injury.[13] Hemostasis and inflammation form up the initial phase.

Vasoconstriction, platelet aggregation, and fibrin clot formation occur after skin damage and contribute to wound haemostasis. Inflammation starts with the formation of fibrin clots and the degranulation of aggregated platelets, which releases chemokines.[14] White blood cells like neutrophils and macrophages are drawn into the wound from the circulation by these chemokines.[15]

The inflammatory response progressively lessens as the healing process goes on, and inflammatory cells undergo apoptosis. During the inflammatory response, tissue fragments and foreign microbes are eliminated. Cell division and proliferation constitute the second stage. Cell migration and proliferation are initiated and maintained during the inflammatory stage by migratory epithelial and dermal cells, residual inflammatory cells, and other growth factors.[16]

The basement membrane is broken down by vascular endothelial cells at this stage, which are mediated by fibroblast growth factor 2 (FGF-2), platelet-derived growth factor (PDGF), and vascular endothelial growth factor (VEGF).[17]

Following their migration to the wound, the cells divide, create intercellular connections, and ultimately develop into blood vessels.[18] Simultaneous fibroblast proliferation within the wound results in production of granulation tissue and extracellular matrix with observable neovascularisation. During the healing process, growth factors and cytokines are crucial signalling molecules that encourage dynamic communication and reciprocal interaction between cells and the extracellular matrix surrounding them.[19]

Tissue remodelling is the last phase of wound healing, during which the newly created tissue is strengthened and reorganised, frequently leading to the creation of scar tissue.[20] The newly formed granulation tissue is restored to form scar tissue.[21] The extracellular matrix, which is mainly made up of collagen, fibronectin, and hyaluronic acid, eventually takes the place of the matrix that was momentarily produced in the stage above. It mainly contains collagen I. After fibroblasts and myofibroblasts migrate and the granulation tissue matrix is rebuilt, wound contraction occurs. Finally, fibroblasts go through apoptosis to produce scar tissue with a tensile strength comparable to that of healthy skin tissue and a very low cell count.

PHYTO-THERAPEUTICS in THE MANAGEMENT of WOUND

Herbal medicines are widely utilised since they are effective and have no negative side effects.[21] Plant and other secondary metabolites can control inflammation by influencing the growth factors, cytokines & cells that aid in wound healing. This enhances epithelialisation, angiogenesis, and fibroplasias.[22,23]

Numerous clinical studies on the effects of herbal products are available, despite difficulties in the identification and purity of the active components.[24] We briefly examine a few phytomedicines that show promise for reducing inflammation during wound healing.[25]They some plants leaves contain mucilaginous gel, which has been utilised for centuries for its anti-inflammatory and wound-healing properties.[26] Increased fibroblast and keratinocyte proliferation, along with a decrease in prostaglandin, reactive oxygen species, and cytokine production, are the foundations of the mechanism of action for wound healing.[27,28]

Phytochemical-based nanodrug delivery methods for skin regeneration and wound healing

Some examples of the plant extracts that have been used are *Cassia roxburghi, Drosera binata, Carrica papaya L., Propolis,* and *Bryonia laciniosa L*. These extracts have been used to produce the green-synthesized AgNPs and to formulate appropriate wound medications.[20] Due to their inherent antibacterial and antimicrobial qualities, the majority of these extracts can be used to treat wounds.[29] Antimicrobial substances contribute significantly to the reduction of microbial colonisation and subsequent growth, which speeds up the healing of wounds.[30] This demonstrates the importance of their inclusion in wound care.

Apart from the advantages of herbal-based chemicals in the healing process,[31] controlling their delivery to the injured side and increasing their chemical activity can be achieved by nanosizing these therapies or combining them into nanoparticles.[32] For instance, by increasing the antibacterial impact, accelerating the creation of granular tissues, and raising collagen synthesis, Nano sizing the curcumin particles created a well-regulated and sustained delivery mechanism and increased their wound healing activity Since, curcumin is a well-known powerful antioxidant molecule derived from herbs, it can be Nano sized without significantly affecting its intrinsic antioxidant effect.[33] Li et al, Reported that, compared to curcumin that had not been changed, nanocurcumin added to alginate hydrogels had a <1% drop in its antioxidant activity (native form). By lowering the Superoxide Dismutase (SOD) level, the addition of curcumin to wound dressings greatly reduced the wound's oxidative stress.[34]

The treatment chronic wounds significantly affect global social and economic conditions.[35] The primary causes of this increasing prevalence of chronic wounds seem to be healthcare costs, an ageing population, physical trauma, and co-morbidities of diabetes and obesity.[36] Chronic wound conditions made it impossible to regenerate functioning epidermis, which delayed the predicted closure of the wound opening. When skin integrity is not restored, skin pathology changes, resulting in chronic

ulceration or no healing, which delays the healing process.[37]

Numerous traditional medicines have been studied for their potential to cure cutaneous wounds. It is recognised that some phytochemicals like phenolic compounds, flavonoids, tannins, alkaloids & some fatty acids may have the ability to heal wounds.[38]

Nonetheless, the delivery of plant-based treatments might be enhanced by lowering nanotechnology platform. Enhancing patient adherence, preventing problems, and speeding up wound healing are the main goals of novel delivery systems for bioactive chemicals sourced from plants. This session focusses on how nanotechnology- based delivery systems, including nanofibers, vesicular structures, nanoparticles, nanoemulsions, and nanogels, have the potential to revolutionise the use of natural wound healing treatments.

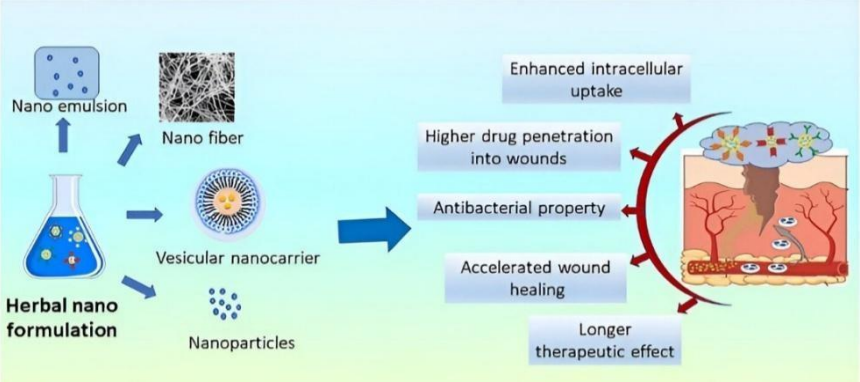

Fig. 3: advanced drug delivery systems containing herbal components for wound healing.

Officinal L. is widely used to treat wounds. When used for severe skin injuries, it gave good results. The polyphenolic compound curcumin, also known as 1, 7-bis (4-hydroxy-3-methoxyphenyl)-1, 6-heptadiene-3, 5-dione, is the primary active ingredient in turmeric. The plant Curcumin longa L. is the source of it. Several benefits, including as anti-inflammatory, antibacterial, and antioxidant qualities, make curcumin a popular active ingredient for wound healing.[39]

Curcumin has been employed in numerous in-vivo animal models to treat epidermal injuries.[40] Because it produces TGF1, which causes an increase in blood vessels & cell granulation, re-epithelisation takes place in the early phases and improves coagulation synthesis. Essential oils like cinnamon, lemongrass, and peppermint have been proposed by as potential antibacterial agents. These Nano fibrous dressings made of electro spun cellulose were found to inhibit Escherichia coli growth and use less oil. These dressings proved to be safe to use and did not show any cytotoxic effects.[41]

Dendrimers

Dendrimers are homogeneous, monodispersed, nanoscale (1-10 nm) polymer macromolecule systems that can be used for both therapeutic and diagnostic reasons.[42] Phenyl acetylene subunits were utilized to make dendrimers. Furthermore, functional groups on the surface of dendrimers may have antibacterial properties.

Dendrimers stimulate re-epithelialization and quicker wound healing, segregate contaminated tissues, delay the healing process, and prolong the inflammatory response.[43] Bacterial structural disturbance would result from the interaction of positively & negatively charged groups found on dendrimers and on cell wall of bacteria.

According to a different study, Dendrimer nanoparticles (NPs) can be planned to carry and encapsulate various therapeutic chemicals, increasing their effectiveness and enabling targeted release. Silver demonstrated anti-inflammatory and anti-microbial effects that worked in concert.[44] These characteristics were also demonstrated to prevent inflammation & enhance healing activity.

Nanohydrogels

Nanohydrogels have a three-dimensional structure, a polymeric network that may absorb excess aqueous fluid from wounds, and are hydrophilic.[45] Their permeable network allows them to absorb moisture, which keeps the wound wet & promotes healing by preserving the right amount of oxygen.

They have a soft consistency and are quite porous, making them very useful in tissue regeneration.[46] It is regarded as an appropriate material for wound dressing since it produces a cooling impact on the targeted area without adhering. When combined with hydrogel NPs, polymers like chitosan, polyethylene glycol, polyvinyl alcohol, dextrin & antibiotics aid in healing of tissue burn wounds.

According to a study, scarring was kept to a minimum and tetracycline hydrochloride hydrogel demonstrates an antibacterial action for both gram-negative and positive bacteria. Gelatine-based hydrogels that carry basic Fibroblast Protein (FP) stimulate healing without scarring, according to a recent study. Nanohydrogels are widely

used today due to their efficiency, compatibility, and good effects on skin regeneration.[46]

Liposomes

One of the best nano-carriers for topical medication administration is liposomes, which are bilayer vesicles made of amphiphilic substances like phospholipids. They are skin-compatible, biodegradable, and non-toxic. They can also hold hydrophobic substances in the bilayer and hydrophilic drugs (like growth hormones) in the inner water cavity. Because of its numerous advantages, liposomes have developed into a flexible instrument for wound care & skin renewal with encouraging therapeutic results. Transferosomes, a novel type of deformable liposome, often contain phospholipids together with an edge activator such sodium cholate, sodium deoxycholate, or Tween-80 to increase their flexibility and delivery capabilities. offering a novel viewpoint on the use of topical medications. When used topically, these special carriers show extra benefits beyond the benefits of traditional liposomes. High flexibility is provided by the edge activator's presence.[47] Permits them to move across the surface of flexible liposomes stratum corneum and the healthy epidermis. Nevertheless, there are some drawbacks to using liposomes, including the potential for rapid and sometimes unavoidable drug leakage. The lack of stability and repeatability in liposomes remains a major obstacle to their application in clinical research.

Polymeric nanoparticals (PNPs)

Biocompatible colloidal systems known as polymeric nanoparticles are getting popular in the fields of biomedicine and bioengineering.[48] By incorporating or conjugating drugs with polymeric systems, they are shielded from enzymatic degradation by wound proteases.[49] This enables controlled release of the therapeutic agents, reducing the need for frequent administration. Nanoparticles will aid in the efficient distribution of biomolecules such as genes, growth hormones, and antibacterial medications. Nowadays, most polymeric nanoparticles are made from mixtures of polylactic co-glycolic acid (PLGA), alginate, gelatine, chitosan, and other polymer combinations.[50]

Metallic nanoparticles

The antimicrobial, antibacterial & anti-inflammatory qualities of metal-based nanoparticles make them widely used. The most prevalent metallic nanoparticles are those based on gold and silver. Medical applications for metal-based nanoparticles are numerous. The creation of metallic nanoparticles frequently uses herbal plants because they have superior therapeutic effects and fewer side effects than conventional dosage forms.[51]

The majority of herbal extracts, such as black tea leaf, eucommiaulmoides, aeravalanats, and hippophaerhamnoides, have been mixed with metallic nanoparticles. Olive leaf, Averrhoabilimbi, Salicornia, Abelmoschusesculentus, and Cladophorafascicularis. Cissusarnotiana, Ipomoea carnea, and Geranium.[52] Due to their antimicrobial, antibacterial & anti-inflammatory qualities, silver nanoparticles are used extensively.

The bioactivity & solubility of silver particles in the wounded area are influenced by their size; the smaller the particles, the more strongly they will interact with the skin. Silver nanoparticles have vesicle sizes ranging from 1-100 nm. By producing a greater concentration of oxygen free radicals than silver ions alone, studies have demonstrated that mixing reduced grapheme oxide nanovesicles with silver-silver chloride nanoparticles can improve wound healing.[53] These particles have a positive impact on the antibacterial activity against both Gram-positive & Gram-negative bacteria, according to in-vivo studies conducted on mice.[54] They can therefore hasten the healing of wounds.

Lipids nanoparticles

In efforts to get around liposomes drawbacks, lipid nanoparticles such as solid lipid nanoparticles (SLNs) and Nano-structured lipid carriers (NLCs) were developed.[55] Lipid nanoparticles are often produced using lipid molecules or physiological lipids, and their creation does not require the use of any potentially harmful organic solvents.[56] Their non-toxic, nanoscale structure allows for sustained drug release and adaptable administration methods. Due to the availability of a market product containing Q10 (Nano Repair Q108, Dr. Rimpler), Lipid nanoparticles have shown promising yet incomplete success in topical drug and cosmetic applications.[57]

A recent investigation showed that dual-loaded SLNs containing LL37 (antibacterial) and serpin A1 (elastase inhibitor) act synergistically to promote faster wound recovery.[58] SLNs promoted wound healing in fibroblast and keratinocyte cells. Additionally, compared to the groups treated with L137 and Al, it increased the efficacy of antibacterial drugs against S. aureus and E. coli.[59]

Skin regeneration and wound healing using a nano-drug delivery system

The potential of phytochemical-based nano-DDSs to enhance drug therapeutic efficacy is enormous due to their capacity to prevent drug degradation and sustain drug release. Phytochemical-based nanoscale drug delivery systems (nano-DDSs) for skin regeneration and wound healing have become increasingly popular as a result of recent developments. These systems efficiently deliver medicinal substances to their intended locations. These systems consist of dendrimers, lipid nanoparticles, polymeric nanoparticles, inorganic/metallic nanoparticles, liposomes, and nanohydrogels.[60]

- ✓ Some of the Phytochemical based nano-DDSs is listed in below table.

Table No. 2: Current studies on the delivery of nanomedicines for wound healing and skin regeneration.

Formulation	Drugs	Administration	Outcome
Nano particle	Eucalyptus is essential oil	Twice daily topical therapy for 15 days	In vivo on Sprague Dawley rats induce re-ephilizatio wound healing
Deformable liposomes	Curcumin	Once a day for 18 days; topical treatment.	Induce fibrosis, angiogenesis, re-epithelialization, and wound contraction; shorten the inflammatory process and prevent infection
Nanoparticles	Thrombin	Topical medicine	Improved skin tensile strength, quicker healing, and fewer surgical problems
Nanoparticles	Silver	Daily topically with dressing	Through the decrease of wound infection and the control of fibrogenic cytokines, rapid healing and enhanced aesthetic appearance were obtained
Nanoparticles	Cerium oxide	Thirteen days for once daily topical therapy	created a favourable environment for restoration by lowering oxidative stress at the wound site and safeguarding regenerating tissue.

NEED OF THE STUDY

Nanosystems are a great option for applying the wound healing process because of their physiochemical properties. The wound therapy process using nanotechnology systems has a higher therapeutic impact than traditional therapy for wound healing. The nanotechnology eliminates the drawbacks of conventional dosage forms and users in a new era for the advancement of biocompatible, site-specific, growing drug loading capacity, non-toxic, improvised drug delivery action, and cost- effective technology in the wound care industry. With the help of this review paper, we are able to learn more about different nano drug delivery system and the wound- care applications of this system. For researchers and clinicians who are working to improve technology and offer affordable wound care, the information in this paper will be valuable.

FUTURE SCOPE

This review study's main goal was to describe the advantages of using nanosystems to promote wound healing. Nano systems are ideally suited for the application of the wound healing process due to their distinct physiochemical properties. Nanotechnological systems' wound therapy process has a higher therapeutic impact than standard therapy for wound healing. Due to their greater therapeutic effects & less adverse effects, research has been done on natural & herbal chemicals all over the world. It is necessary to create a more effective way to deliver drugs to the intended location at a dosage that doesn't alter the way the illness is currently being treated. The biggest issue with nano-vehicles is their toxicity because they could have negative consequences on people. Therefore, this needs to be fixed right away in order to advance wound healing therapy in clinical trials. One of the issues is that non-material mediated wound healing pathways are rather less understood in in vivo models. In-vitro studies or single purpose microorganisms are primarily used in research of non-material wound healing processes. The in-vivo wound healing application is required for the comprehensive studies that use both Gram- positive & Gram-negative bacterial strains. Therefore, improving and enhancing should be the main focus.[61] Recent experiments on the effects of phytochemicals on wound healing & skin regeneration have shown the potential clinical utility of plant-based compounds. To fully understand the exact mechanism and potential targets of phytochemicals in skin regeneration, more research is required.[61] Human research and clinical trials are necessary to fully understand how phytochemicals affect skin regeneration and wound healing.[61]

CONCLUSION

Phytochemicals such as curcumin, picroliv, and arnebin-1 show promising potential in promoting wound healing by stimulating angiogenesis and tissue regeneration. These natural compounds offer an affordable and effective therapeutic option for cutaneous wound management. They act through specific molecular pathways to modulate inflammation, re-epithelialization, and extracellular matrix remodelling. While their benefits in skin repair are well-supported by preclinical studies, further randomized controlled trials are needed to validate their clinical efficacy and safety for therapeutic use.

REFERENCE

1. Sen CK. Human wound and its burden: updated 2022 compendium of estimates. Adv Wound Care, 2023; 12(12): 657-70.
2. Eming SA, Martin P, Tomic-Canic M. Wound repair and regeneration: mechanisms, signalling, and translation. Sci Transl Med., 2014; 6(265): 265sr6.
3. Kumar V, Abbas AK, Aster JC. Robbins & Cotran Pathologic Basis of Disease-General Pathology, Vol 1: First Bangladesh Edition-E-Book. Elsevier Health Sciences, 2017.
4. Wang H, Yang Y, Liu J, Qian L. Direct cell reprogramming: approaches, mechanisms and progress. Nat Rev Mol Cell Biol., 2021; 22(6):

410-24.
5. Li D, Peng H, Qu LE, Sommar P, Wang A, Chu T, et al. miR-19a/b and miR-20a promote wound healing by regulating the inflammatory response of keratinocytes. J Invest Dermatol, 2021; 141(3): 659-71.
6. Guenin-Mace L, Konieczny P, Naik S. Immune-epithelial cross talk in regeneration and repair. Annu Rev Immunol, 2023; 41: 207-28.
7. Saifullah Q, Sharma A. Current trends on innovative technologies in topical wound care for advanced healing and management. Curr Drug Res Rev., 2024; 16(3): 319-32.
8. Shukla SK, Sharma AK, Gupta V, Ashavarddhan MH. Pharmacological control of inflammation in wound healing. J Tissue Viability, 2019; 28(4): 218-22.
9. Landén NX, Li D, Ståhle M. Transition from inflammation to proliferation: a critical step during wound healing. Cell Mol Life Sci., 2016; 73: 3861-85.
10. Sorg H, Tilkorn DJ, Hager S, Hauser J, Mirastschijski U. Skin wound healing: an update on the current knowledge and concepts. Eur Surg Res., 2017; 58(1-2): 81-95.
11. Čoma M, Fröhlichová L, Urban L, Zajíček R, Urban T, Szabo P, et al. Molecular changes underlying hypertrophic scarring following burns involve specific deregulations at all wound healing stages. Int J Mol Sci., 2021; 22(2): 897.
12. Geng X, et al. Molecular mechanisms of angiogenesis in wound healing. Front Cell Dev Biol., 2023; 11: 1057682.
13. Johnson KE, Wilgus TA. Vascular endothelial growth factor and angiogenesis in the regulation of cutaneous wound repair. Adv Wound Care, 2021; 10(5): 221-34.
14. Dreifke MB, et al. Growth factor-mediated interactions in wound healing. Nat Rev Mol Cell Biol., 2022; 23(8): 539-54.
15. Pakshir P, et al. The myofibroblast at a glance. J Cell Sci., 2020; 133(13): jcs227900.
16. Ricard-Blum S, Vallet L. Fragments generated upon extracellular matrix remodeling: Biological regulators and potential drugs. Matrix Biol., 2021; 100-101: 170-88.
17. Aziz ZAA, et al. Herbal Medicines for Wound Healing: A Systematic Review of Randomized Controlled Trials. Phytother Res., 2021; 35(7): 3502-19.
18. Gantwerker EA, Hom DB. Skin: Histology and Physiology of Wound Healing. Facial Plast Surg Clin North Am., 2020; 28(1): 1–10.
19. Mazumder K, et al. Plant-Derived Bioactive Compounds in Wound Healing: Modulation of Growth Factors and Cytokines. Phytother Res., 2021; 35(5): 2307–24.
20. World Health Organization. WHO Traditional Medicine Strategy 2023–2025. Geneva: WHO, 2023.
21. Nejatzadeh-Barandozi F. Traditional and Modern Applications of Mucilaginous Plants in Dermatology. J Ethnopharmacol, 2023; 302(Pt A): 115857.
22. Saeedi-Boroujeni A, et al. Anti-Inflammatory Potential of Hibiscus rosa-sinensis Mucilage. Int Immunopharmacol, 2021; 99: 107939.
23. Saeedi-Boroujeni A, et al. Anti-Inflammatory Potential of Hibiscus rosa-sinensis Mucilage. Int Immunopharmacol, 2021; 99: 107939.
24. Pirbalouti AG, et al. Malva sylvestris Mucilage: Cytokine Regulation in Chronic Wounds. Phytomedicine, 2022; 104: 154318.
25. Valsalam S, et al. Biosynthesis of silver and gold nanoparticles using Musa acuminata colla flower and its pharmaceutical activity. J Photochem Photobiol B., 2022; 234: 112542.
26. Salem SS, et al. Bactericidal and in-vivo wound healing activities of silver nanoparticles synthesized from C. roxburghii leaf extract. Colloids Surf B Biointerfaces, 2022; 210: 112246.
27. Gouda S, et al. Advanced AgNP-based wound dressings: Current status and future perspectives. J Drug Deliv Sci Technol, 2023; 79: 104052.
28. Aziz ZAA, et al. Herbal Medicines for Wound Healing: A Systematic Review. Front Pharmacol, 2022; 13: 843127.
29. Jeevanandam J, et al. Nanoformulation of Herbal Compounds for Wound Healing. Pharmaceutics, 2021; 13(11): 1823.
30. Krausz AE, et al. Antioxidant Properties of Nanocurcumin. Nanomedicine, 2020; 15(20): 1959-77.
31. Chen Y, et al. Nanocurcumin Reduces Oxidative Stress in Wounds. Biomater Sci., 2023; 11: 2562-78.
32. Sen CK, et al. Human Wound and Its Burden: Updated 2022 Compendium. Adv Wound Care., 2022; 11(5): 281-92.
33. Frykberg RG, Banks J. Challenges in Treatment of Chronic Wounds. Adv Wound Care., 2021; 10(9): 1-15.
34. Theocharidis G, et al. Single-Cell Transcriptomics Uncovers Dysfunctional Cellular Programs in Non- Healing Wounds. Nature, 2022; 610(7931): 373-80.
35. Maver T, et al. Phytochemicals in Wound Healing: Molecular Mechanisms. Biomed Pharmacother, 2023; 158: 114182.
36. Gopinath V, et al. Curcumin-Loaded Nanofibrous Matrix for Wound Healing. Mater Sci Eng C., 2022; 134: 112584.
37. Krausz AE, et al. Curcumin-Encapsulated Nanoparticles for Wound Healing. Nanomedicine, 2020; 15(20): 1959-77.
38. Liakos I, et al. Cellulose-Based Dressings with Essential Oils. ACS Appl Mater Interfaces, 2021; 13(3): 3382- 92.
39. Abbasi E, et al. Dendrimers: Synthesis, Applications, and Properties. Nanoscale Res Lett., 2020; 15: 1-23.

40. Palmerston Mendes L, et al. Dendrimer Nanosystems for Wound Healing Applications. J Control Release, 2023; 341: 1-18.
41. Wang Y, et al. Silver-Dendrimer Nanocomposites for Wound Healing. ACS Appl Mater Interfaces, 2023; 15(1): 1-15.
42. Li J, Mooney DJ. Designing hydrogels for controlled drug delivery. Nat Rev Mater., 2021; 6: 1-17.
43. Wang Y, et al. Porous hydrogels for tissue engineering. Adv Mater., 2023; 35(2): 2106942.
44. Chen G, et al. Multifunctional hydrogels for burn wound healing. Chem Eng J., 2023; 451: 138487.
45. Gupta R, et al. Transfersomes: A Revolutionary Approach for Transdermal Drug Delivery. J Drug Deliv Sci Technol., 2023; 79: 103987.
46. Mitchell MJ, et al. Engineering precision nanoparticles for drug delivery. Nat Rev Drug Discov., 2021; 20: 101- 24.
47. Anselmo AC, Mitragotri S. Nanoparticles in the clinic: An update. Bioeng Transl Med., 2021; 6(2): e10143.
48. Kumari A, et al. Biodegradable polymeric nanoparticles for therapeutic applications. Mater Today Chem., 2022; 24: 100821.
49. Ovais M, et al. Phyto-therapeutic and nanomedicinal approaches for wound healing. Int J Pharm., 2020; 588: 119741.
50. Fahmy HM, et al. Plant-mediated synthesis of metallic nanoparticles for wound healing applications. Mater Today Chem., 2021; 20: 100429.
51. Chen J, et al. Graphene oxide-silver nanocomposites for accelerated wound healing. ACS Appl Mater Interfaces, 2022; 14(5): 6261-73.
52. Li Y, et al. Broad-spectrum antibacterial activity of silver-graphene nanocomposites. Biomater Sci., 2023; 11: 1024-36.
53. Poonia N, et al. Solid lipid nanoparticles and nanostructured lipid carriers: A review of recent advances. J Drug Deliv Sci Technol., 2022; 68: 103105.
54. Beltrán-Gracia E, et al. Lipid-based nanoparticles for dermal drug delivery: Advances and challenges. Pharmaceutics, 2021; 13(8): 1196.
55. Müller RH, et al. Industrial status of lipid nanoparticles for skin applications. Eur J Pharm Biopharm, 2021; 163: 198-208.
56. Chen X, et al. Co-delivery of LL37 and serpin A1 via solid lipid nanoparticles enhances diabetic wound healing. Acta Biomater, 2022; 140: 206-18.
57. Zhang L, et al. Synergistic antibacterial therapy using peptide-loaded lipid nanoparticles for chronic wound infections. Biomaterials, 2023; 294: 121982.
58. Chen G, et al. Comprehensive review of phytochemical-loaded nanocarriers for wound healing. Chem Eng J., 2023; 451: 138487.
59. Mitchell MJ, et al. Engineering precision nanoparticles for drug delivery. Nat Rev Drug Discov., 2021; 20: 101- 24.
60. Theocharidis G, et al. Single-cell transcriptomics uncovers dysfunctional cellular programs in non-healing wounds. Nature., 2022; 610(7931): 373-80.
61. Sen CK, et al. Human wound and its burden: Updated 2022 compendium. Adv Wound Care., 2022; 11(5): 281- 92.