REVIEW ARTICLE

Green-Synthesized Zinc Oxide Nanoparticles and Emerging Frontiers in Pharmacological Applications

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Abstract

The application of phyto-formulated nanoparticles (PNPs) in wound treatment has emerged as a promising area in biomedical research. PNPs, obtained from different medicinal plants, exhibit excellent biocompatibility, reduced toxicity, and notable therapeutic properties, making them suitable candidates for enhancing wound repair. This review explores the current trends in the formulation and biomedical applications of PNPs for antibacterial potential and wound healing. Through green synthesis approaches, PNPs acquire unique physicochemical features, including specific size, morphology, and surface properties, which play a significant role in improving wound healing efficiency. Moreover, PNPs are enriched with various bioactive phytochemicals such as flavonoids, polyphenols, and essential oils that contribute antioxidant, anti-inflammatory, antimicrobial, and pro-angiogenic activities necessary for tissue regeneration and rapid wound closure. In addition, the biodegradable nature of PNPs supports safer biomedical applications by minimizing possible toxic effects. This review further discusses the mechanisms through which PNPs influence cellular events involved in wound healing, including migration, cell proliferation, differentiation, and extracellular matrix remodeling. The synergistic use of PNPs with conventional wound dressings and therapeutic agents is also emphasized, highlighting their importance in the development of advanced wound management systems, good health, and well-being. Overall, the incorporation of PNPs into wound healing therapies provides an effective and sustainable strategy for improved wound care and supports the advancement of safer and more efficient next-generation therapeutic approaches.

Key words: Antibacterial activity, good health and well-being, therapeutic medicinal plants, wound healing efficacy

INTRODUCTION

The currently available wound healing therapies, techniques, and treatment products are often inadequate in completely restoring the structural integrity and normal physiological function of the skin, which has intensified research efforts in wound management strategies.[1] An ideal wound healing approach should facilitate rapid tissue repair, minimize scar formation, prevent microbial infections, enhance the healing energy, and preserve an optimal moist environment at the wound site.[2] Recent developments in nanotechnology have created new opportunities for wound care applications by the utilization of nanomaterials that exhibit potential antimicrobial and therapeutic characteristics.[3] Conventional wound treatment methods mainly rely on antiseptics and antibacterial agents, while several techniques have been developed for the amalgamation of organic and inorganic nanoparticles (NPs).[4] Nevertheless, physical and chemical synthesis methods are often associated with high cost,

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increased processing time, and environmental concerns. In contrast, plant-mediated synthesis has emerged as a simple, eco-friendly, economical, and sustainable alternative for nanoparticle production.[5]

Secondary metabolites and phytoconstituents present in plant extracts play a significant role in reduction, stabilization, capping, and chelation processes during nanoparticle synthesis, thereby replacing toxic chemical agents with safer biological substitutes.[6] The integumentary system, comprising the skin and its associated structures such as hair follicles, glands, and nails, is recognized as the largest organ system in the human body.[7] It acts as a defensive barrier against physical, chemical, biological, and ultraviolet (UV) radiation-induced damage because of its multifunctional protective nature.[8] Structurally, the skin consists mainly of the epidermis and dermis, which originate from different embryonic layers, namely the ectoderm and mesoderm, respectively.[9]

In recent years, nanomaterial-embedded wound dressings have gained extensive importance in healthcare applications for managing different forms of tissue injury and skin damage.[10] Wounds can severely affect the good health and well-being of patients and are generally defined as disruptions in the integrity of the skin caused by internal or external factors.[11] Conditions such as burns, surgical injuries, trauma, diabetes, and chronic diseases further increase the demand for effective wound management therapies.[12] The wound healing mechanism is a complex but highly coordinated biological process involving four major phases, including hemostasis, inflammation, propagation, and remodeling.[13] Owing to their diverse pharmacological properties, green-synthesized NPs derived from medicinal plants have recently attracted substantial attention in wound healing research.[14] Among these, herbal formulations and zinc oxide nanoparticles (ZnONPs) are widely preferred because of their affordability, enhanced bioavailability, therapeutic effectiveness, and reduced adverse effects compared with conventional treatment methods.[15] This review, therefore, focuses on the emerging trends and recent developments in phyto-based nanomedicines for wound healing applications.

ZnONPs

NPs synthesized using plant extracts demonstrate enhanced stability and exhibit a broad diversity of shapes and particle sizes when compared with NPs produced through other biological routes. Among different metal oxide NPs, ZnONPs have received extensive research attention because of their unique physicochemical characteristics and wide-ranging biomedical applications.[16] ZnONPs are particularly recognized for their strong antimicrobial activity, compatibility with skin tissues, UV-protective ability, and significant effectiveness in wound healing potential.[17] Sellappan *et al*. on phyto-formulated ZnONPs have revealed their eco-friendly, non-toxic, and non-allergenic nature, with fewer adverse effects than chemically synthesized NPs.[18] In addition, ZnONPs have shown remarkable potential in skin-related therapies by accelerating wound repair, controlling inflammation, and supporting tissue regeneration processes.[19] The use of medicinal phyto extracts as reducing and stabilizing agents during ZnONP formulation provides several advantages over conventional physical and chemical methods, which often involve toxic reagents and complex procedures.[20] The widespread preference for ZnONPs is mainly due to their affordability, photocatalytic efficiency, UV shielding properties, large surface area, and multifunctional applications in medicine, agriculture, environmental remediation, and antimicrobial therapies.[21] Several medicinal plants, including *Vitex trifolia, Pongamia pinnata, Punica granatum, Ficus benghalensis, Hibiscus subdariffa, Couroupita guianensis* Aubl*,* and *Trifolium pratense*, have been effectively utilized for the extracellular biosynthesis of ZnONPs.[22] An important feature of ZnONPs is their capability to induce cellular damage through the generation of reactive oxygen species (ROS) and the release of zinc ions (Zn^{2+}), which contribute to their cytotoxic and antimicrobial properties.[23] Furthermore, zinc is an essential micronutrient required for several physiological functions in the human body. Green synthesized ZnONPs enhance wound healing through multiple biological mechanisms, including infection control, stimulation of cellular proliferation and migration, free radical scavenging, regulation of inflammatory responses, and promotion of rapid tissue regeneration and wound contraction.[24] Their excellent biodegradability and biocompatibility are largely associated with the controlled dissolution of Zn^{2+}.[25] However, the biomedical application of chemically synthesized ZnONPs remains limited because of the hazardous chemicals involved during synthesis.[26] Therefore, increasing attention is being directed toward environmentally sustainable and green approaches for ZnONP production.

GREEN SYNTHESIS OF ZnONPs

In recent years, considerable attention has been directed toward the application of phyto extracts for the environmentally friendly formulation of ZnONPs through green synthesis approaches. Various biomolecules exist in phyto extracts, including amino acids, proteins, alkaloids, polysaccharides, and enzymes, which act as natural reducing and stabilizing agents, thereby facilitating nanoparticle formation while improving the safety, sustainability, and eco-compatibility of the formulation process when compared with conventional physical and chemical methods. Due to their favorable properties, such as biocompatibility, reduced toxicity, and cost-effectiveness, ZnONPs have emerged as significant materials for various biomedical applications.[27] These NPs possess significant biological activities and have been widely investigated for their anticancer, antioxidant, antibacterial, anti-inflammatory, and wound healing potential.[28] Green synthesis of ZnONPs can be achieved using different plant parts such as leaves, stems, roots, bark, fruits, rhizomes, seeds, and flowers, which are rich in phytochemicals, including ursolic acid, lupeol, sitosterol, leucocyanidin, oleanolic acid, proanthocyanidins, rutin, kaempferol, and quercetin glycosides, as well as anthocyanins that contribute to the reduction and stabilization of NPs.[29] In comparison with traditional physico-chemical methods, plant-mediated synthesis provides several benefits, particularly by reducing the use of toxic chemicals that may adversely affect both human health and the environment.[30] Phytoconstituents present in medicinal plants, therefore, play a vital role in the biosynthesis of metal and metal oxide NPs through green synthetic routes.[31] Figure 1 presents the schematic representation of the green synthesis procedure adopted for ZnONP preparation, illustrating the stepwise methodology involved. Briefly, 1 mM zinc acetate solution is prepared in 50 mL of deionized water and continuously stirred for 1 h, followed by the gradual addition of sodium hydroxide solution and plant extract. After incubation, the development of a yellow coloration in the reaction mixture confirms the formation of ZnONPs. The obtained suspension is subsequently centrifuged to separate the precipitate, which is collected, dried, and preserved for further investigations. The synthesized ZnONPs are then characterized using different analytical techniques, including UV-visible spectroscopy, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy, transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy, and X-ray diffraction analysis,[32] as summarized in Table 1.

ANTIBACTERIAL ACTIVITY OF GREEN SYNTHESIZED ZnONPs

Plant-mediated zinc oxide (ZnO) nanostructures exhibit remarkable antibacterial properties mainly through the production of ROS when they come into contact with microbial cells. These reactive molecules trigger oxidative damage within bacteria, causing membrane lipid destruction, protein alteration, and impairment of genetic material, eventually resulting in bacterial cell death. In addition, these nano-sized particles can enter bacterial cells and disturb essential intracellular activities and organelle functions. Such multiple antibacterial mechanisms indicate the strong therapeutic potential of biologically fabricated ZnO nanomaterials against pathogenic microorganisms. Figure 2 depicts the antibacterial mechanism associated with biosynthesized ZnO nanostructures.[17] Jayaseelan *et al*.[34] explored the fabrication of ZnO nanomaterials using *Tinospora cordifolia* extract and reported excellent antibacterial efficacy against several pathogens. The synthesized nanostructures showed maximum inhibitory activity against *Bacillus cereus* (19 mm), while *Pseudomonas aeruginosa* and *Escherichia coli* exhibited inhibition zones of 18 mm each. Similarly, Kaningini *et al*.[35] developed zinc-based nanostructures utilizing *Magnolia officinalis* extracts and investigated their antimicrobial potential, where *E. coli* and *Staphylococcus aureus* displayed greater sensitivity toward the prepared nanoformulation. Kirubakaran *et al*.[32] prepared ZnO nanomaterials from *Salvia coccinea* leaf extract, and the resulting particles demonstrated considerable inhibitory action towards both gram-positive and gram-negative bacterial species. Al-Askar *et al*.[36] employed *Pluchea indica* leaf extract for the biosynthesis of zinc-derived nanostructures and evaluated their antimicrobial performance against different pathogens. Their investigation showed notable inhibitory effects, particularly against *Bacillus subtilis* (24.26 mm), followed by *E. coli* (21.83 mm) and *S. aureus* (20.67 mm) at 1000 µg/mL concentration. Likewise, Dappula *et al*.[37] formulated ZnO nanomaterials using aqueous extracts of the whole plant of *Andrographis alata*, and the obtained particles revealed strong antibacterial potential against several clinically important bacterial strains. Table 2 summarizes the antimicrobial efficiency of

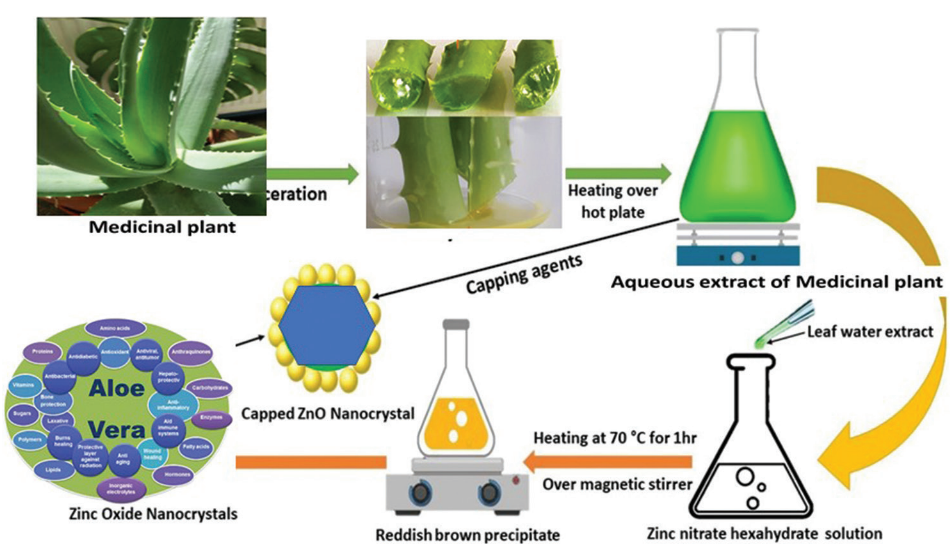

Figure 1: Green synthesis of zinc oxide nanoparticles[33]

Table 1: Characterization of green-synthesized zinc oxide nanoparticles

S. No.	Plants	Instruments	Shape	Parts taken for extraction	References
1.	*Gossypium* (cotton)	13 (XRD)	Spherical	leaves	[54]
2.	*Murraya koenigii*	>100 nm (FE-SEM)	Hexagonal	leaves	[55]
3.	*Aloe vera* (Liliaceae)	25–65 (SEM and TEM	Spherical	Freeze dried leaf peel	[56]
4.	*Plectranthus amboinicus*	50–180 (SEM)	Rod s	Leaf extract	[57]
5.	*Nephelium lappaceum* L.	50.95 (XRD)	Needle	Fruit peels	[58]
6.	*Punica granatum*	32.98 nm and 81.84 nm in TEM	Spherical and hexagonal	Fruit peel	[59]
7.	*Cocus nucifera*	20–80 (TEM), 21.2 (XRD)	Spherical	Coconut water	[60]
8.	*Tamarindus indica*	19–37 nm (XRD, TEM)	Rough, hexagonal	Fruit peel	[61]
9.	*Trifolium pratense*	60–70 (XRD)	Spherical	Flower	[62]
10.	*Rosa canina* (Rosaceae)	21–243 nm (XRD)	Spherical	Fruit extract	[63]

SEM: Scanning electron microscopy, TEM: Transmission electron microscopy, XRD: X-ray diffraction

Table 2: Antibacterial activity of green-synthesized zinc oxide nanoparticles against multidrug-resistant pathogens

S. No.	Name of the plants	Plant parts	Antibacterial and wound healing activity	References
1.	*Tinospora cordifolia*	Leaf	*B. cereus* at 19 mm, followed by *P. aeruginosa* and *E. coli* at 18mm	[34]
2.	*Magnolia officinalis*	Leaf	*E. coli* and *S. aureus*	[35]
3.	*Salvia coccinea*	Leaf	Gram-positive and gram-negative pathogenic bacteria	[32]
4.	*Pluchea indica*	Leaf	*Bacillus subtilis* (24.26 mm), followed by *S. aureus* (20.67 mm) and *E. coli* (21.83 mm)	[36]
5.	*Andrographis alata*	Whole plants	Potent antibacterial activity	[37]
6.	*Calendula officinalis*	Flower	Exhibited partial cell migration and achieved a percent wound closure of 69.1%,	[42]
7.	*Catharanthus roseus*	Leaf	Exhibited increased swelling characteristics, along with sustained drug release (57%) and speed up wound healing	[43]
8.	*Coccinia indica*	Seed	Highest wound contraction observed at 98.37±1.45%	[44]
9.	*Plantago ovata*	Husk	Promoted full-thickness wound repair	[45]
10.	*Nigella sativa*	Seeds	Significant wound closure rates of 93.00±0.43%	[46]

B. cereus: *Bacillus cereus*, *S. aureus*: *Staphylococcus aureus*, *E. coli: Escherichia coli*, *P. aeruginosa*: *Pseudomonas aeruginosa*

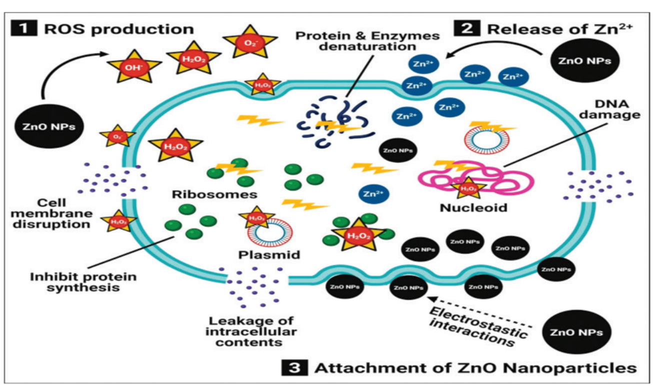

Figure 2: Antibacterial activity of green-synthesized zinc oxide nanoparticles[64]

biologically synthesized zinc-based nanostructures against multidrug-resistant microorganisms. Altogether, these reports demonstrate that medicinal plant-assisted zinc nanomaterials could serve as promising alternatives for the effective management of bacterial infections.[51,64]

MECHANISM OF WOUND HEALING IN PLANT EXTRACT MEDIATED ZnONPs

The wound healing activity promoted by plant-assisted ZnO nanostructures involves multiple interconnected biological processes. Initially, these zinc-based nanomaterials exhibit strong antimicrobial activity, which helps in controlling microbial invasion at the wound region and minimizes the possibility of secondary infections and related complications.[38] In addition, biologically synthesized ZnO nanomaterials enhance cellular proliferation and support the migration of keratinocytes and fibroblasts, thereby accelerating tissue formation and re-epithelialization during the healing process.[39] Owing to their free radical scavenging ability, these nanostructures also reduce oxidative stress and inflammatory responses, creating a favorable physiological environment for rapid tissue repair.[40] Moreover, zinc-derived NPs influence the expression of several growth factors and inflammatory mediators associated with wound healing pathways, particularly transforming growth factor-beta and vascular endothelial growth factor, which are essential for angiogenesis, collagen formation, and tissue remodeling.[41] Collectively, plant-fabricated ZnO nanomaterials contribute to wound recovery by preventing infections, stimulating cellular regeneration, modulating inflammation, and coordinating the complex biochemical events involved in tissue restoration and regeneration.[42] Figure 3 illustrates the wound healing mechanism mediated by medicinal plant-derived ZnO nanostructures.

WOUND HEALING ACTIVITY OF GREEN SYNTHESIZED ZnONPs

Biologically synthesized ZnO nanomaterials possess remarkable wound healing properties by stimulating cellular proliferation, enhancing cell migration, supporting tissue remodeling, preventing microbial infections, and reducing inflammatory responses, thereby making them attractive candidates for wound care applications. Table 2 summarizes the wound healing efficacy of plant-derived zinc-based nanostructures against multidrug-resistant pathogens. Aydin Acar *et al*.[16] reported the preparation of zinc-derived nanostructures using *Calendula officinalis* flower extract through an eco-friendly method. Their findings demonstrated that the prepared *C. officinalis*-mediated nanomaterials promoted enhanced cell migration and achieved 69.1% wound closure, which was comparatively higher than the untreated control group, showing 64.8% closure. Sellappan *et al*.[43] developed keratin–sodium alginate wound dressing matrices incorporated with biosynthesized ZnO nanomaterials using herbal extracts from *Catharanthus roseus* leaves and *Matricaria recutita* flowers. Enzymatic degradation studies revealed that the fabricated dressing maintained structural stability, exhibited superior swelling capacity, and enabled sustained drug release of approximately 57% over 144 h, thereby facilitating faster wound repair. Senthikumar *et al*.[44] synthesized gelatin-loaded zinc nanocomposites (GN/ZnONCs) using *Coccinia indica* seed extract through a plant-assisted preparative technique. The wound healing assessment of enriched GN/ZnONCs showed substantial tissue regeneration, with maximum wound contraction reaching 98.37 ± 1.45%, indicating their effectiveness in promoting new cell and tissue formation. Azam *et al*.[45] fabricated ZnO-based nanomaterials using psyllium gel obtained from *Plantago ovata* as both reducing and stabilizing agents. *In vivo* analysis in mice confirmed excellent compatibility of the prepared PG-mediated nanostructures and demonstrated accelerated wound recovery. The nanocomposite dressing significantly lowered matrix metalloproteinase-1 (MMP-1) and MMP-2 expression while enhancing collagen type I, collagen type III, and fibronectin messenger RNA levels, thereby supporting efficient full-thickness wound repair. Halarnekar *et al*.[46] prepared chitosan-coated zinc nanocomposites (NS-CS/ZnONCs) utilizing aqueous seed extracts of *Nigella sativa*. Both NS-ZnONPs and NS-CS/ZnONCs exhibited remarkable wound closure percentages of 93.00 ± 0.43% and 95.67 ± 0.43%, respectively, on the 15th day at a dosage of 14 mg/wound, which was comparable to the standard treatment group (93.42 ± 0.58%). Furthermore, hydroxyproline estimation confirmed significantly elevated collagen turnover in NS-ZnONPs (60.70 ± 1.44 mg/g tissue)

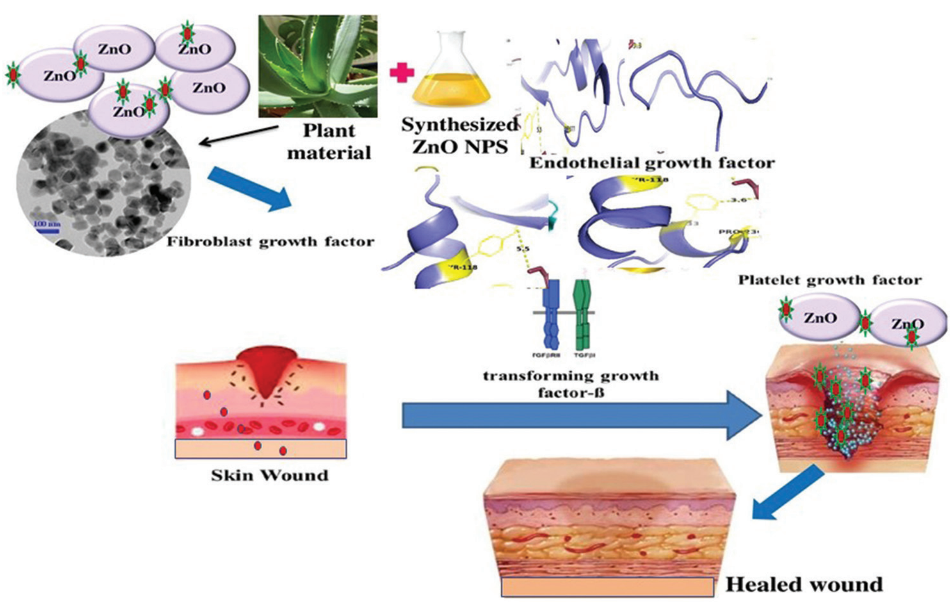

Figure 3: Mechanism of wound healing in plant extract-mediated zinc oxide nanoparticles

and NS-CS/ZnONCs (66.10 ± 1.23 mg/g tissue) treated groups compared with the control (47.7 ± 0.81 mg/g tissue). Collectively, these findings demonstrate the immense therapeutic potential of plant-assisted ZnO nanostructures as multifunctional materials for efficient wound management and enhanced tissue regeneration.

THERAPEUTIC MEDICINAL PLANTS IN WOUND HEALING

Therapeutically important medicinal plants have gained considerable attention because of their valuable contribution toward tissue repair and skin regeneration. *Achillea millefolium* has traditionally been employed in herbal medicine for managing bleeding disorders, skin injuries, digestive disturbances, influenza, and common cold symptoms.[47] Its therapeutic efficiency is mainly associated with the abundance of flavonoids, which contribute to strong free radical scavenging and inflammation-controlling activities. In addition, extracts obtained from *Achillea* species exhibit considerable antimicrobial potential together with antioxidant and tyrosinase-suppressing properties, suggesting their usefulness in dermatological and cosmetic preparations designed for skin care applications.[48] Members of the Aloe genus are widely recognized for multiple medicinal functions, including detoxification support and management of disorders such as constipation and herpes infections. Among them, *Aloe vera* has been extensively utilized in traditional wound care practices and has demonstrated beneficial effects in the treatment of burns, postoperative wounds, chronic ulcers, and pressure sores. Hydrogel formulations prepared from *A. vera* have been reported to improve angiogenic responses, minimize edema, stimulate wound contraction, and shorten healing duration considerably.[49] Curcumin, a naturally occurring polyphenolic constituent isolated from *Curcuma longa* L., has been valued for centuries for its skin regenerative ability. Experimental findings indicate that topical curcumin application enhances epithelial restoration and collagen deposition by encouraging granulation tissue development. Furthermore, curcumin administration suppresses inflammatory mediators, including tumor necrosis factor-alpha (TNF-α) and MMP-9, while modulating cytokine expression to accelerate tissue recovery in wound models.[50] Herbal preparations derived from *Althaea officinalis* have also been historically used to alleviate inflammatory conditions and support wound repair. Studies involving *A. officinalis*-associated zinc-derived nanomaterials demonstrated lowered expression of inflammatory cytokines such as interleukin (IL-1β), IL-6, and TNF-α together with enhanced IL-10 production in comparison with untreated groups, thereby indicating improved anti-inflammatory performance through nanoparticle self-assembly approaches.[24] *C. officinalis* is another medicinal herb possessing a broad range of biological properties, including antioxidant, antimicrobial, antiviral, hepatoprotective, immunomodulatory, antiulcer, anticancer, anti-acne, and wound healing activities. Investigations involving *C. officinalis*-derived zinc nanostructures revealed superior tissue repair efficiency, with wound closure rates reaching 69.1%, which exceeded those observed in the control group (64.8%).[16] *Matricaria chamomilla* is well known for its antiseptic, antibacterial, anti-inflammatory, and antispasmodic characteristics, and formulations containing chamomile extracts have shown enhanced burn wound recovery by improving cellular proliferation and biocompatibility.[52] Likewise, essential oils isolated from *Eucalyptus globulus* leaves are extensively appreciated for their antimicrobial and antiseptic activities. Recent evidence suggests that ethanol extracts formulated from *Eucalyptus alba* leaves dried below 30°C promote better cellular growth and improved wound repair outcomes.[53] Altogether, the incorporation of medicinal plant-derived bioactive compounds into wound dressings and topical therapeutic systems may provide an efficient strategy for enhancing tissue regeneration and improving clinical wound management.

CHALLENGES AND FUTURE PROSPECTIVE

The amalgamation of plant-derived zinc-based nanomaterials into wound healing applications offers both significant opportunities and several existing limitations that must be addressed in future research. One of the major concerns involves developing economical and large-scale production strategies while maintaining consistency in nanoparticle quality and biological performance.[66-67] In addition, possible nanotoxicological effects, long-term safety issues, and variations in stability under different wound conditions remain important challenges that require careful investigation. Regulatory approval and standardization processes also represent critical barriers that must be overcome before these materials can be successfully introduced into clinical practice. Nevertheless, plant-assisted zinc nanostructures continue to show remarkable promise in advanced wound management applications. Improved understanding of the interactions between phytochemical constituents and zinc-based nanomaterials may facilitate the design of tailored therapeutic systems suitable for different wound types and healing stages. Furthermore, advanced delivery platforms such as hydrogel matrices, nanocarriers, and bioengineered scaffolds may improve site-specific delivery, controlled drug release, and prolonged therapeutic activity, thereby enhancing wound repair efficiency. The development of highly biocompatible coatings and supportive scaffold materials may additionally provide an ideal microenvironment for tissue regeneration and faster recovery. Therefore, extensive future investigations focusing on biosafety, therapeutic efficacy, biodegradability, and long-term clinical performance are essential for the successful translation of plant-mediated zinc nanomaterials into effective and sustainable wound healing therapeutics.

CONCLUSION

The application of plant-assisted zinc-based nanomaterials has arisen as a promising and advanced strategy for improving wound healing therapies. The distinctive physicochemical and biological properties of zinc-derived nanostructures, particularly their selective antimicrobial action and tissue regenerative potential, make them valuable candidates for effective wound management and infection control. The involvement of phytochemical constituents during nanoparticle fabrication not only supports environmentally sustainable synthesis but also enhances the biological efficiency and microbial targeting ability of these nanomaterials. Beyond conventional wound care applications, plant-mediated zinc nanostructures have also shown potential in areas including targeted drug delivery, cosmetic formulations, biomedical engineering, and the food sector. Recent developments further indicate their ability to accelerate skin regeneration, prolong therapeutic activity, and improve healing efficiency in chronic and ulcerative wounds. Nevertheless, certain limitations still require attention, including the lack of standardized evaluation protocols, concerns regarding biodegradability and bioabsorption, and restrictions associated with commercialization and patent regulations. Therefore, overcoming these scientific and regulatory challenges through extensive research and clinical authentication will be essential for fully utilizing the therapeutics of plant-derived zinc nanomaterials in wound repair and skin rejuvenation therapies, ultimately benefiting patients through safer and more effective treatment strategies.

ETHICAL APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

CONSENT OF PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The dataset generated and/or analysed during the current study are available from the corresponding author, upon reasonable request.

AUTHORS' CONTRIBUTIONS

K. Abirami: Writing–original draft, data curation. M. Maghimaa: Conceptualization, writing–original draft, data curation, visualization, formal analysis, writing–review and editing. Gulipalli Pallavi: Data curation, formal analysis.

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