INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

OPEN ACCESS

Review Article

# Nanomedicine In Healing Chronic Wound

**Khedkar Divya*, Narhire Prerna, Shaikh Mustakin, Salve Sonal, Wadhave Amol**

*SDMVM Diploma in Pharmacy Institute, Chh Sambhajinagar 431001*

ARTICLE INFO

Published: 14 Aug 2025

Keywords:
Nanomedicine; Chronic wounds; Targeted drug delivery; Antimicrobial nanoparticles; Tissue regeneration; Wound healing

DOI:
10.5281/zenodo.16875202

## ABSTRACT

Chronic wounds, such as diabetic foot ulcers, pressure sores, and venous leg ulcers, represent a significant global healthcare burden due to their prolonged healing times, high risk of infection, and resistance to conventional therapies. Nanomedicine offers a promising frontier in wound management by enabling targeted drug delivery, antimicrobial action, and enhanced tissue regeneration at the nanoscale. This review explores recent advances in the application of nanotechnology for chronic wound healing, including the development of nanoparticle-based dressings, nanocarriers for controlled release of bioactive agents, and nanosystems that mimic the extracellular matrix to support cellular proliferation and angiogenesis. We highlight the mechanisms by which nanomaterials—such as silver, gold, silica, and polymeric nanoparticles—promote wound repair, reduce inflammation, and combat multidrug-resistant pathogens. Furthermore, the review discusses current challenges in clinical translation, including biocompatibility, scalability, and regulatory hurdles, while outlining future perspectives on integrating nanomedicine with smart biosensors and personalized wound care strategies. Overall, nanotechnology holds transformative potential to overcome the limitations of traditional wound therapies and accelerate healing in chronic, non-healing wounds.

## INTRODUCTION

The application of nanotechnology in chronic wound care represents a paradigm shift in therapeutic approaches, promising enhanced precision and efficacy. As we embark on this exploration, we delve into the fundamental aspects of introducing nanotechnology to wound care.

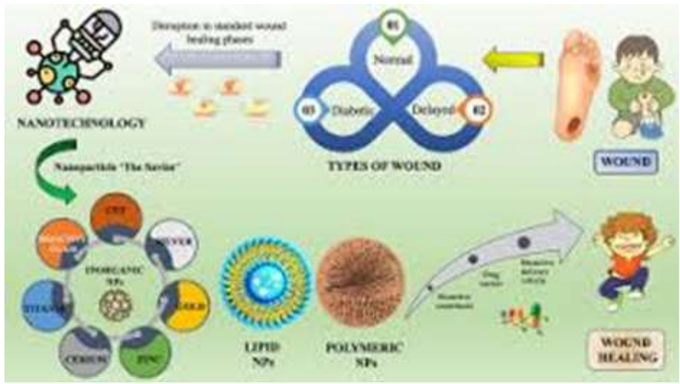
1. Overview of Chronic Wounds :- Chronic wounds, characterized by delayed healing and persistent inflammation, present a substantialburden on patients and healthcare systems (Anderson etal., 2016). These wounds often accompany conditions like diabetes, vascular diseases, and aging,

***Corresponding Author:** Khedkar Divya
**Address:** *SDMVM Diploma in Pharmacy Institute, Chh Sambhajinagar 431001*
**Email** : salvesonal09@gmail.com

**Relevant conflicts of interest/financial disclosures**: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

demanding novel interventions to address their intricate nature.[1]

2. Evolution of Therapeutic Approaches:- Traditional wound care approaches, while effective for acute wounds, fall short in managing the complexities of chronic wounds. The evolution of therapeutic strategies reflects a growing recognition of the need for precision and targeted interventions in chronic wound management (Jones et al., 2018).[2]



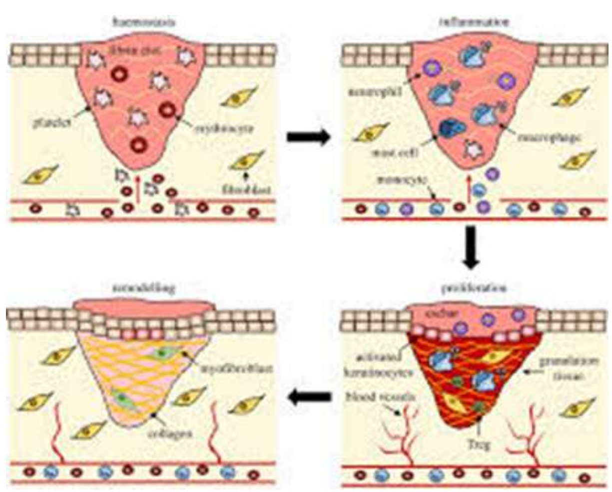

**Showing Nano technology in wound care**

This shift in focus towards nanotechnology in wound care is driven by the unique properties of nanoparticles, which allow for tailored interventions at the molecular and cellular levels. By understanding the distinct characteristics of chronic wounds and the limitations of conventional approaches, the stage is set for the exploration of nanotechnology's transformative role.[3]

This introductory section lays the foundation for a deeper exploration of how nanotechnology can address the specific challenges posed by chronic wounds. As we proceed to subsequent sections, we will unravel the mechanisms, types of nanoparticles, clinical applications, challenges, and future directions in the integration of nanotechnology into chronic wound care.

## TYPES OF NANOPARTICLES AND MECHANISMS IN WOUND HEALING:-

Understanding the diverse types of nanoparticles and their mechanisms in wound healing is pivotal in harnessing the full potential of nanotechnology for chronic wounds.



**Showing mechanism of wound healing**

i. Lipid-Based Nanoparticles: Enhancing Drug Solubility and Stability: Lipid-based nanoparticles offer a promising avenue for improving the solubility and stability of therapeutic agents, crucial for sustained and effective wound healing (Williams et al., 2017). These nanoparticles, often incorporating liposomes or lipidbased carriers, facilitate the encapsulation and controlled release of therapeutic cargos within the wound microenvironment. [4]
ii. Polymeric Nanoparticles: Controlled Release for Prolonged Therapeutic Effects: Polymeric nanoparticles provide a platform for controlled drug release, ensuring prolonged therapeutic effects (Gupta et al., 2019). By leveraging the unique properties of polymers, these nanoparticles enable a sustained release of therapeutic agents, optimizing their presence in the wound site over time. [5]
iii. Inorganic Nanoparticles: Unique Properties for Tailored Interactions: Inorganic nanoparticles, such as metallic or metal oxide nanoparticles, exhibit unique properties like high surface area and tunable reactivity (Chen et al., 2018). These properties enable tailored interactions within the wound microenvironment, influencing cellular responses and fostering an environment conducive to healing. [6] By exploring the mechanisms of these distinct types of nanoparticles, we gain insights into how nanotechnology can be precisely tailored to address the complexities of chronic wounds. The subsequent sections will further delve into the clinical applications, opportunities, challenges, and future directions in the integration of nanotechnology into chronic wound care.

## CLINICAL APPLICATIONS AND FORMULATIONS

The translational potential of nanotechnology in chronic wound care is exemplified through its clinical applications and formulations, showcasing real-world efficacy and success stories.


**Showing clinical application**

i. **Real-world Efficacy:** Case Studies and Clinical Trials: Clinical validation of nanotechnology in chronic wound healing is evident in compelling case studies and rigorous clinical trials. The application of nanomaterials has demonstrated notable success in promoting wound healing while maintaining safety standards (Rodriguez et al., 2020). [7]

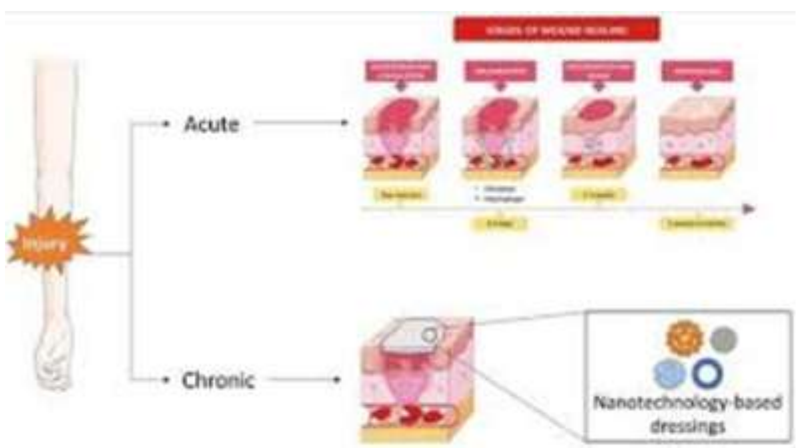
These real-world applications underscore the transformative impact of nanotechnology, offering targeted and efficient solutions for chronic wound management.

ii. **Success Stories in Promoting Wound Healing:** Within the landscape of chronic wound care, success stories emerge from the application of nanotechnology in promoting wound healing. Notable advancements in wound closure, tissue regeneration, and reduced healing times reflect the tangible benefits of nanoparticle-based therapies (Williams et al., 2017). [8] These success stories not only validate the efficacy of nanotechnology but also inspire further exploration into its diverse formulations and applications for chronic wound healing.As we proceed, we will delve into the opportunities presented by nanotechnology in chronic wound care, exploring targeted drug delivery precision and enhanced cellular uptake as key avenues for advancing therapeutic interventions.

This targeted approach holds significant promise, particularly in conditions like diabetic foot ulcers where localized therapy is paramount.

## OPPORTUNITIES IN NANOMEDICINE FOR CHRONIC WOUNDS:-

Exploring the vast landscape of opportunities in nano-medicine for chronic wounds reveals two distinct yet interlinked avenues: targeted drug delivery and enhanced cellular uptake.




**showing Nano-medicine for Acute and Chronic Wounds**

1. **Targeted Drug Delivery: Precision in Therapeutic Administration:-**

Nanoparticles provide a precise platform for targeted drug delivery, addressing the specific challenges posed by chronic wounds (Shi et al., 2020). By engineering nanoparticles for site-specific recognition, therapeutic agents can be delivered precisely to the affected areas, minimizing systemic exposure and maximizing therapeutic impact. [9] This targeted approach holds significant promise, particularly in conditions like diabetic foot ulcers where localized therapy is paramount.

2. **Enhanced Cellular Uptake: Overcoming Cellular Barriers:-**

Chronic wounds often exhibit impaired cellular functions, hindering the natural healing process (Chen et al., 2018). Nanoparticles, with their small size and high surface area, facilitate enhanced cellular uptake, ensuring a more efficient delivery of therapeutic agents to key cells involved in wound repair[10].. This enhanced cellular uptake addresses a critical aspect of chronic wounds, promoting the activation of cellular processes necessary for an accelerated healing response. By capitalizing on these opportunities, nanomedicine not only offers precision in therapeutic administration but also navigates the cellular intricacies of chronic wounds. The subsequent sections will delve into the challenges associated with integrating nanotechnology into chronic wound care and propose future directions for overcoming these hurdles.

**Nanotechnology in wound management :-**

Nanotechnology in wound management represents a paradigm shift from conventional wound dressings to a more active, dynamic, and targeted approach to healing. Chronic wounds, which are often stalled in the inflammatory phase, require interventions that can effectively address a multitude of pathological factors simultaneously. Nanomaterials, with their unique properties such as a high surface area-to-volume ratio, customizable surface chemistry, and ability to interact with biological systems at a molecular level, are exceptionally well-suited for this purpose. The integration of nanotechnology into wound care involves several key strategies, each designed to overcome specific barriers to healing.

**1. Targeted Drug Delivery and Bioactive Release:**

One of the most significant advantages of nanotechnology is its ability to serve as a precise drug delivery system. Nanocarriers, such as liposomes, polymeric nanoparticles, and dendrimers, can be engineered to encapsulate and protect a variety of therapeutic agents, including antibiotics, growth factors, anti-inflammatory drugs, and gene-based therapies. This allows for the sustained and controlled release of these agents directly at the wound site, minimizing systemic exposure and potential side effects. For example, nanoparticles can deliver antibiotics directly to a bacterial biofilm, where the concentration of the drug is high enough to eradicate the infection while sparing healthy tissues. Similarly, the localized delivery of growth factors like VEGF or PDGF can promote angiogenesis and cell proliferation, which are often impaired in chronic wounds.

**2. Antimicrobial and Anti-biofilm Strategies:**

Chronic wound infections, particularly those caused by biofilms, are a major impediment to healing. Nanomaterials offer a powerful arsenal against these pathogens. Silver, gold, and zinc oxide nanoparticles, for instance, possess intrinsic antimicrobial properties that can disrupt bacterial cell membranes and inhibit their growth. These nanoparticles can be incorporated into wound dressings or hydrogels to provide a continuous and broad-spectrum antimicrobial effect. Furthermore, some nanomaterials are specifically designed to penetrate and disrupt the protective matrix of biofilms, making the encapsulated bacteria more susceptible to antibiotics and the body's immune response.

**3. Bioactive Scaffolds for Tissue Regeneration:**

Beyond simple drug delivery, nanotechnology is revolutionizing the development of wound dressings. Electrospun nanofiber scaffolds are particularly promising in this regard. Their intricate structure closely mimics the extracellular matrix (ECM) of native skin, providing an ideal environment for cell adhesion, migration, and proliferation. These scaffolds can be fabricated from biocompatible polymers and loaded with bioactive molecules to actively promote tissue regeneration. They can provide mechanical support, absorb wound exudate, and create a moist environment that is conducive to healing. By mimicking the natural tissue architecture, these scaffolds can guide the formation of new tissue, leading to enhanced re-epithelialization and reduced scar formation.

**4. Modulating the Wound Microenvironment:**

Nanomaterials can also actively modulate the chronic wound microenvironment to shift it from a non-healing state to a healing one. For example, cerium oxide nanoparticles and other antioxidant nanomaterials can neutralize the excessive reactive oxygen species (ROS) that contribute to chronic inflammation and cellular damage. Additionally, some nanomaterials have shown the ability to modulate the inflammatory response by regulating the activity of key cells like macrophages, promoting a switch from a pro-inflammatory to a pro-healing phenotype. This targeted manipulation of the biological processes within the wound bed is a major advantage that nanotechnology offers over traditional treatments.

In summary, nanotechnology provides a versatile and multifaceted platform for addressing the complex pathophysiology of chronic wounds. By combining targeted drug delivery, potent antimicrobial activity, tissue engineering principles, and microenvironment modulation, nanomedicine holds the potential to significantly accelerate healing, reduce complications, and improve the quality of life for patients with chronic wounds.

**Types of nanoparticle and mechanism in wound healing:-**

Nanoparticles, due to their unique physicochemical properties, are categorized into several types, each with distinct advantages and mechanisms of action in promoting chronic wound healing.

**Types of Nanoparticles in Wound Healing**

**1. Metal and Metal Oxide Nanoparticles:**

- These are some of the most widely used nanoparticles in wound care due to their inherent antimicrobial properties.
- **Silver Nanoparticles (AgNPs):** Silver has been used as a broad-spectrum antimicrobial agent for centuries. AgNPs are highly effective against a wide range of bacteria, including antibiotic-resistant strains. They are often incorporated into wound dressings to prevent and treat wound infections.
- **Zinc Oxide Nanoparticles (ZnO NPs):** These nanoparticles also exhibit strong antimicrobial activity and have been shown to promote cell proliferation, angiogenesis (formation of new blood vessels), and collagen synthesis, which are all crucial steps in wound healing.
- **Gold Nanoparticles (AuNPs):** AuNPs are highly biocompatible and can be functionalized with various therapeutic agents. They are used for targeted drug delivery, as well as for their anti-inflammatory properties and ability to scavenge reactive oxygen species (ROS).
- **Copper Nanoparticles (CuNPs):** Copper is an essential trace element for various enzymes involved in tissue repair. CuNPs possess both antimicrobial and pro-angiogenic properties, accelerating wound closure.
- **Cerium Oxide Nanoparticles ($CeO_2$ NPs):** Known as "nanoceria," these nanoparticles have potent antioxidant properties, which are

critical for mitigating the chronic inflammation associated with non-healing wounds. They can mimic the activity of antioxidant enzymes, scavenging ROS and promoting a shift from a pro-inflammatory to a pro-healing environment.

**2. Polymeric Nanoparticles:**

- These nanoparticles are particularly valuable as smart delivery systems for a variety of therapeutic agents.
- **Chitosan Nanoparticles:** Chitosan is a natural, biodegradable, and biocompatible polymer with intrinsic hemostatic (blood-clotting) and antimicrobial properties. Chitosan nanoparticles can be used to deliver growth factors and antibiotics, and they also form a protective barrier over the wound.
- **Poly(lactic-co-glycolic acid) (PLGA) Nanoparticles:** PLGA is a well-known biodegradable and biocompatible synthetic polymer. PLGA nanoparticles are excellent carriers for controlled and sustained release of drugs, growth factors, and other bioactive molecules, ensuring a prolonged therapeutic effect at the wound site.
- **Dendrimers:** These are highly branched, tree-like nanoparticles with a well-defined structure. Their multiple surface groups allow for the attachment of various therapeutic agents, making them highly versatile for targeted drug and gene delivery.

**3. Carbon-Based Nanomaterials:**

- These materials offer unique structural and electronic properties that can be harnessed for wound healing.
- **Carbon Quantum Dots (CQDs):** These are tiny, zero-dimensional carbon materials that have shown promise in wound healing due to their antibacterial and anti-biofilm efficacy. They can also reduce inflammation and promote tissue repair.
- **Graphene Oxide:** This single-atom-thick sheet of carbon can be used in wound dressings to provide structural support, prevent bacterial growth, and modulate cellular responses, such as fibroblast proliferation and angiogenesis.

**4. Nanocomposites and Hydrogels:**

- These systems combine different types of nanoparticles or nanomaterials to create a synergistic effect.
- **Nanofiber Scaffolds:** Created through techniques like electrospinning, these scaffolds mimic the natural extracellular matrix (ECM), providing a structural framework for cells to migrate and proliferate. They can be loaded with therapeutic nanoparticles to create a "smart" dressing.
- **Nanoparticle-Loaded Hydrogels:** Hydrogels are polymer networks that can absorb large amounts of water, creating a moist environment conducive to healing. By incorporating various nanoparticles, these hydrogels can gain additional functionalities like antimicrobial activity, antioxidant properties, and sustained drug release.

**Mechanisms of Action in Wound Healing**

The mechanisms by which these nanoparticles promote wound healing are multifaceted and often work in synergy to address the various complexities of chronic wounds:

**Antimicrobial and Anti-biofilm Activity:** Many nanoparticles, particularly those made of silver, zinc oxide, and copper, directly kill bacteria by disrupting their cell membranes, producing reactive oxygen species (ROS), or interfering with their metabolic processes. Theycan also penetrate and disrupt the protective matrix of biofilms, making them a potent tool against chronic wound infections.

**Modulation of Inflammation:** Chronic wounds are stuck in a prolonged inflammatory phase. Nanoparticles can help by scavenging excessive ROS, which reduces oxidative stress and cellular damage. They can also modulate the activity of immune cells like macrophages, encouraging them to switch from a pro-inflammatory (M1) phenotype to a pro-healing (M2) phenotype.

**Promotion of Angiogenesis and Re-epithelialization:** Nanoparticles can stimulate the production of growth factors like VEGF, which is essential for the formation of new blood vessels. A sufficient blood supply is vital for delivering oxygen and nutrients to the wound site. Additionally, nanoparticles can promote the migration and proliferation of keratinocytes and fibroblasts, which are the key cells involved in re-epithelialization and the production of new tissue.

**Controlled Drug and Gene Delivery:** Nanocarriers can encapsulate therapeutic agents, such as growth factors, antibiotics, and anti-inflammatory drugs, and release them in a controlled, sustained manner. This localized delivery enhances the therapeutic efficacy, minimizes systemic side effects, and ensures that the agents are active at the wound site for an extended period.

**Biomimetic Scaffolding:** Nanofiber scaffolds and hydrogels can be designed to mimic the structural and biochemical cues of the natural ECM. This provides a supportive environment for cells to attach, proliferate, and differentiate, thereby promoting tissue regeneration and reducing scar formation.

## Challenges and limitations in nanotechnology integration :-

Nanotechnology holds immense promise for revolutionizing various fields, from medicine and electronics to energy and consumer products. However, its widespread integration is met with a range of significant challenges and limitations. These issues are not only technical but also span across economic, social, and ethical domains.

Here's a breakdown of the key challenges and limitations in nanotechnology integration:

### Technical and Scientific Challenges

#### Fabrication and Scalability:

- **Complexity:** The design and engineering of nanoparticles are highly complex, requiring precise control over their size, shape, and composition. Small variations can drastically alter their properties.
- **Reproducibility:** Manufacturing processes often lack the reproducibility needed for consistent product quality. Scaling up production from the lab to a commercial scale is a major hurdle.
- **High Costs:** The specialized equipment and intricate processes involved in creating nanomaterials are often expensive, limiting their commercial viability.

#### Characterization and Measurement:

- **Detection:** Nanomaterials are so small that they can be difficult to detect and characterize using conventional methods. New, more sophisticated techniques are required to accurately measure their properties.
- **Inconsistent Techniques:** A lack of standardized characterization techniques

makes it difficult to compare results across different studies and laboratories.

**Performance and Stability:**

- **Chemical Stability:** Many nanomaterials can be chemically unstable, leading to issues like corrosion or degradation.
- **Aggregation:** Nanoparticles often have a tendency to clump together (aggregate) in a solution, which can reduce their effectiveness and alter their intended properties.
- **Drug Delivery Barriers:** In nanomedicine, a major challenge is for nanoparticles to overcome biological barriers like the blood-brain barrier or the dense stroma of tumors to reach their intended target.

**Health, Safety, and Environmental (HSE) Concerns**

- **Toxicity:** The unique properties of nanomaterials, such as their high surface-area-to-volume ratio, can lead to unknown or unpredictable toxic effects on biological systems.
- **Bioaccumulation:** There are concerns that nanoparticles could accumulate in organs and tissues, with potential long-term health consequences.
- **Environmental Impact:** The release of nanomaterials into the environment could have unforeseen ecological effects, and more research is needed to understand and mitigate these risks.

**Risk Assessment and Regulation:**

- **Lack of Data:** There is a significant lack of comprehensive data on the long-term health and environmental impacts of many nanomaterials, making it difficult to establish effective risk assessments and regulations.
- **Regulatory Framework:** The current regulatory frameworks are not always well-equipped to handle the unique nature of nanomaterials, which exist at the intersection of different fields.

**Economic and Societal Challenges**

**Cost and Commercialization:**

- **Manufacturing Costs:** The high cost of production and the need for expensive equipment can be a barrier to entry for many companies.
- **Market Uncertainty:** The lack of standardized regulations and long-term safety data can create uncertainty for businesses and investors.

**Ethical and Social Issues:**

- **Public Perception:** There is often a general lack of public knowledge about nanotechnology and its applications, which can lead to distrust and resistance.
- **The high cost of nanotechnology:-**based solutions could lead to disparities in access, particularly in fields like healthcare and agriculture.

**Educational and Workforce Gaps:**

- **Interdisciplinary Training:** Nanotechnology is a highly interdisciplinary field, requiring expertise in physics, chemistry, biology, and engineering. There is a need for educational programs and a workforce that can bridge these different disciplines.
- **Lack of Teacher Training:** A lack of systematic training for educators in this field can hinder the development of a new generation of nanoscientists.

In conclusion, while nanotechnology offers transformative potential, its successful integration hinges on overcoming these multifaceted challenges. Addressing these issues will require continued research, collaboration between different sectors, the development of robust regulatory frameworks, and public engagement to ensure responsible and sustainable innovation.

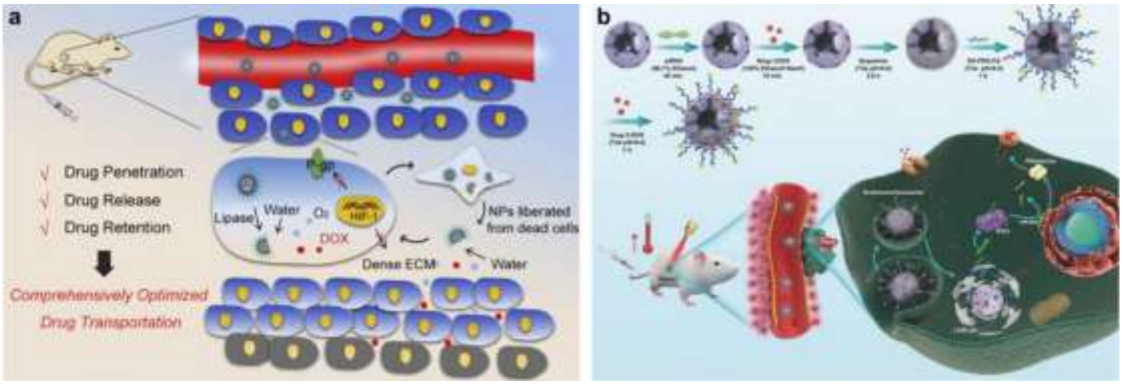

**Nanomedicine-enable chemotherapy and derived synergistic cancer therapy**

## Nanomedicine-enhanced chemotherapy

As the first-line treatment strategy against cancer, chemotherapy has made tremendous achievements in suppressing tumor proliferation, preventing metastasis, and prolonging patients' lives [20]. Commonly used chemodrugs such as doxorubicin (DOX), paclitaxel (PTX), docetaxel (Dtxl), and cisplatin (DDP), etc., can effectively destroy cancer cells after being taken up by tumor cells. However, the therapeutic effectiveness of these chemical drugs is always severely compromised by rapid clearance and non-specific distribution, resulting in inevitable systemic toxicity. Additionally, tumor cells will gradually develop a strong resistance pathway against chemotherapy drugs during long-term administration, known as MDR, which is one of the primary reasons for chemotherapy failure. Nowadays, nanomaterial-enabled chemotherapy aims to elevate the efficacy of conventional cancer chemotherapy regimens through diverse strategies.

## Targeted delivery of chemotherapy drugs

The enhanced tumor vascular permeability and inhibition of lymphatic drainage allow nanomedicines to enter the interstitial space of the tumor and then be retained, which is the typical EPR effect that achieves passive enrichment of therapeutic agents in the tumor [21]. Numerous studies have been reported in this area. For example, most recently, Li et al. developed a novel cationic dendrimer-decorated nanogels (NGs-G2) to reduce the detrimental retention of chemotherapeutics in the liver while increasing their accumulation in tumors (Fig. 1a) [22]. After modification by the G2 dendrimer, the overall charging NGs-G2 of is turned from neutral into positive, and it exhibits overall charging properties of positively charged corona and neutral core. This unique architecture and charge conversion confers NGs-G2 with highly desired biodistribution of reduced liver accumulation, increased tumor uptake, and facilitated drug release, leading to greatly enhanced anti-tumor therapeutic efficacy with no significant side effects (Fig. 1b). In addition, to further amplify the interactions between nanomedicines and cancer cells, Ma et al. fabricated a novel cancer chemotherapy nanomedicine by self-assembly of the mussel-derived tumor-targeting peptide with a pH-sensitive antitumor drug (Fig. 1c) [23]. In particular, this tumor-targeting peptide RGD enhances the enrichment of chemotherapeutic agents in tumor tissue by binding to αvβ3 integrins overexpressed on tumor cell membranes, making the self-assembled nanoparticles tumor-targeting**.**




**Schematic illustration of DOX-CaO2/MnO2-MS NPs for largely promoted drug transport. B. Schematic diagram of the synthesis process of M-R@D-PDA-PEG-FA-D and the combination of photothermal chemotherapy and gene targeting for the treatment of tumors**

**Schematic illustration of DOX-**CaO2/MnO2-MS NPs for largely promoted drug transport. B. Schematic diagram of the synthesis process of M-R@D-PDA-PEG-FA-D and the combination of photothermal chemotherapy and gene targeting for the treatment of tumors

## Opportunities and Challenge:-

Nanomedicine is emerging as a powerful tool with significant potential to revolutionize the treatment of chronic wounds. Chronic wounds, which affect millions of people worldwide and are often associated with conditions like diabetes and aging, present persistent challenges due to prolonged inflammation, infection, and impaired tissue regeneration. Traditional treatments often fail to address these complex issues, leading to limited clinical success. Nanomedicine offers innovative approaches to overcome these limitations by manipulating materials at the nanoscale to interact with the wound environment at a cellular and molecular level.

**Here are some of the key opportunities presented by nanomedicine in chronic wound healing:**

### 1. Targeted Drug and Therapeutic Delivery

- Chronic wounds are complex and require a multi-faceted approach. Nanoparticles can be engineered to act as intelligent carriers for a variety of therapeutic agents, including antibiotics, growth factors, and anti-inflammatory drugs. These nanocarriers can:
- **Enhance Bioavailability:** By encapsulating drugs, nanoparticles can increase their solubility and stability, preventing degradation and ensuring they reach the target site in an effective concentration.
- **Enable Controlled and Sustained Release:** Unlike conventional dressings that release their active ingredients over a short period, nanocarriers can be designed to release therapeutics gradually over days or weeks. This sustained delivery helps maintain a therapeutic concentration at the wound site, promoting continuous healing.
- **Improve Site-Specific Delivery:** Nanoparticles can be designed to home in on specific cells or tissues within the wound, delivering their payload precisely where it's needed and minimizing systemic exposure and potential side effects.

### 2. Advanced Wound Dressings and Scaffolds

- Nanotechnology is enabling the development of next-generation wound dressings that actively participate in the healing process. These materials, often in the form of hydrogels, nanofibers, or films, offer several advantages:

- **Mimicking the Extracellular Matrix (ECM):** Nanofiber scaffolds can be designed to mimic the natural ECM, providing a supportive structure for cell adhesion, proliferation, and migration. This helps promote tissue regeneration and accelerates wound closure.
- **Creating a Favorable Microenvironment:** Nanomaterial-based dressings can effectively absorb wound exudate while maintaining a moist environment, which is crucial for healing. They can also be made breathable to allow for proper gas exchange.
- **Inbuilt Therapeutic Properties:** Dressings can be infused with nanomaterials like silver, gold, or zinc oxide nanoparticles, which have intrinsic antimicrobial and anti-inflammatory properties, to combat infection and reduce inflammation.

**3. Combating Infection and Biofilms**

- Infection, particularly from drug-resistant bacteria and biofilms, is a major impediment to chronic wound healing. Nanomaterials offer a new line of defense:
- **Broad-Spectrum Antimicrobial Activity:** Nanoparticles, such as silver nanoparticles, have been shown to be effective against a wide range of bacteria, viruses, and fungi.
- **Disrupting Biofilms:** Biofilms are a protective shield for bacteria, making them resistant to conventional antibiotics. Nanoparticles are small enough to penetrate these biofilms and disrupt their structure, allowing for more effective bacterial eradication.
- **Modulating the Wound Microenvironment**: Nanomaterials can influence the wound environment to make it less hospitable to pathogens, helping to prevent new infections from forming.

**4. Modulating Cellular and Molecular Processes**

- Nanomedicine can directly influence the biological processes involved in wound healing, shifting the stalled chronic wound from a non-healing to a healing state.
- **Anti-inflammatory Effects:** Nanoparticles can reduce the prolonged, unbalanced inflammation characteristic of chronic wounds.
- **Promoting Angiogenesis:** Nanomaterials can stimulate the formation of new blood vessels, a process known as angiogenesis, which is vital for supplying oxygen and nutrients to the healing tissue.
- **Stimulating Cell Proliferation:** Nanoscale features and incorporated therapeutic agents can encourage the growth and migration of key cells like fibroblasts and keratinocytes, which are essential for tissue repair and re-epithelialization.

**5. Potential for "Smart" Systems**

- Future opportunities lie in developing "intelligent" or "smart" wound care systems. These systems could involve:
- **Responsive Materials:** Nanomaterials that can respond to changes in the wound environment, such as pH or temperature, to release a drug only when needed.
- **Real-Time Monitoring:** Integrated nanosensors could provide real-time information on the wound's condition, such as infection levels or oxygenation, allowing for more precise and personalized treatment.

- While nanomedicine holds immense promise, research and development are ongoing. Challenges such as ensuring biocompatibility, addressing potential toxicity, and navigating regulatory hurdles remain. However, with continued advancements, nanomedicine is poised to revolutionize the field of chronic wound care, leading to more effective treatments and better patient outcomes.

**Nanomedicine in Healing Chronic Wound Opportunities and Challenge**

- Nanomedicine offers a transformative approach to healing chronic wounds by addressing the complex, multi-faceted nature of these conditions at a cellular and molecular level. While the opportunities are vast and promising, the field also faces significant challenges that must be overcome for widespread clinical adoption.

**Opportunities**

- Nanomedicine provides a powerful toolkit to overcome the limitations of conventional chronic wound treatments, which often fail to address the underlying causes of non-healing.

**1. Enhanced and Targeted Drug Delivery:**

- **Controlled and Sustained Release:** Nanocarriers, such as lipid-based, polymeric, and inorganic nanoparticles, can be engineered to release therapeutic agents like antibiotics, growth factors, and anti-inflammatory drugs over a prolonged period. This sustained delivery helps maintain a therapeutic concentration at the wound site, promoting continuous healing and reducing the frequency of dressing changes.
- **Improved Bioavailability:** By encapsulating drugs, nanoparticles can increase their solubility and stability, preventing premature degradation and ensuring they reach the target cells in an effective concentration.
- **Site-Specific Delivery:** Nanoparticles can be functionalized to target specific cells or tissues within the wound. This precision delivery maximizes therapeutic efficacy while minimizing systemic exposure and potential side effects.

**2. Advanced Wound Dressings and Scaffolds:**

- **Mimicking the Extracellular Matrix (ECM):** Nanofiber scaffolds can be designed to replicate the natural ECM, providing a supportive and biocompatible structure for cell adhesion, proliferation, and migration. This helps promote tissue regeneration and accelerates wound closure.
- **Inbuilt Therapeutic Properties:** Dressings can be infused with nanoparticles of materials like silver, gold, and zinc oxide, which possess intrinsic antimicrobial and anti-inflammatory properties. This dual-action approach helps combat infection and reduce inflammation simultaneously.
- **Favorable Microenvironment:** Nanomaterial-based dressings can effectively manage wound exudate, maintain a moist environment, and allow for proper gas exchange, all of which are crucial for optimal healing.

**3. Combating Infection and Biofilms:**

- **Broad-Spectrum Antimicrobial Activity:** Nanoparticles, particularly silver and gold nanoparticles, have demonstrated potent efficacy against a wide range of drug-resistant bacteria, viruses, and fungi, offering a new defense against persistent infections.
- **Biofilm Disruption:** Biofilms are a major barrier to healing in chronic wounds. The

small size of nanoparticles allows them to penetrate these protective barriers, disrupting their structure and making the bacteria more susceptible to treatment.

**4. Modulating Cellular and Molecular Pathways:**

- **Anti-inflammatory Effects:** Nanomaterials can help resolve the chronic, unbalanced inflammation that characterizes non-healing wounds, shifting the wound environment toward a pro-healing state.
- **Promoting Angiogenesis:** Nanomaterials can stimulate the formation of new blood vessels, a critical process for supplying oxygen and nutrients to the healing tissue.
- **Stimulating Cell Growth:** Nanoscale features and incorporated therapeutic agents can promote the proliferation and migration of key cells like fibroblasts and keratinocytes, which are essential for tissue repair and re-epithelialization.

**5. "Smart" and Theranostic Systems:**

- **Responsive Materials:** Nanomaterials can be engineered to respond to specific cues in the wound environment, such as changes in pH or the presence of certain enzymes, to release drugs only when and where they are needed.
- **Real-Time Monitoring:** Integrated nanosensors can provide real-time data on the wound's condition, such as infection status or oxygen levels, enabling clinicians to provide more precise and personalized care.

## Challenges

Despite the immense potential, the path to widespread clinical use of nanomedicine in chronic wound care is not without its obstacles.

**1. Biocompatibility and Toxicity:**

- **Safety Concerns:** The small size and high reactivity of nanoparticles can lead to potential toxicity issues. Concerns exist regarding their long-term effects on the human body, including potential for accumulation, degradation, and interaction with healthy cells.
- **Immunogenicity:** Nanomaterials might trigger an undesirable immune response, leading to inflammation or rejection, which would counteract their therapeutic purpose.

**2. Manufacturing and Scalability:**

- **High Production Costs:** The synthesis and purification of high-quality, uniform nanoparticles can be complex and expensive, which may hinder their commercial viability and accessibility.
- **Quality Control:** Ensuring consistent particle size, shape, surface properties, and therapeutic payload across different batches is a significant challenge for mass production.

**3. Regulatory and Clinical Translation:**

- **Lack of Standardized Guidelines:** Regulatory bodies are still developing frameworks for the approval of nanomedicine products. The unique properties of nanomaterials require new testing protocols, making the approval process complex and time-consuming.
- **Clinical Trial Hurdles:** Conducting rigorous and well-designed clinical trials for nanomedicine in chronic wounds is essential to demonstrate safety and efficacy, but it can be a lengthy and expensive process. There is a need for more research to determine the long-term effects and optimal dosages.

**4. Biodistribution and Degradation:**

- **Off-Target Effects:** While nanocarriers are designed for targeted delivery, a portion may still reach unintended organs or tissues, leading to potential off-target effects.
- **Controlled Degradation:** Ensuring that nanoparticles degrade into non-toxic components at a predictable rate is crucial. If they degrade too quickly, they may not have a sustained therapeutic effect; if they degrade too slowly, they may accumulate in the body.

**5. Complexity of Chronic Wounds:**

- **Heterogeneity:** Chronic wounds vary significantly from patient to patient, influenced by factors like diabetes, vascular disease, and age. A single nanomedicine approach may not be universally effective, requiring the development of highly personalized treatments.
- **Dynamic Microenvironment:** The wound environment is a complex and constantly changing ecosystem of cells, bacteria, and biochemical signals. Designing nanomaterials that can effectively navigate and respond to this dynamic environment is a major scientific challenge.

## CONCLUSION :-

Based on a comprehensive review of the current literature, the conclusion regarding nanomedicine in chronic wound healing is one of significant promise tempered by critical challenges. The consensus among researchers is that nanomedicine holds the potential to fundamentally transform chronic wound care by offering a multi-faceted approach that addresses the root causes of non-healing.

**Key Takeaways from the Literature:**

- **Multifunctional and Targeted Therapies:** Nanomaterials are uniquely positioned to overcome the limitations of conventional therapies. They can be engineered to deliver a broad range of therapeutic agents—including growth factors, antibiotics, and anti-inflammatory drugs—in a controlled and sustained manner. This precision delivery, often targeted to specific cell types or wound sites, maximizes therapeutic effect while minimizing systemic side effects.
- **Effective Anti-Biofilm and Antimicrobial Action:** A major hurdle in chronic wound healing is persistent infection and the formation of bacterial biofilms, which are highly resistant to traditional antibiotics. Nanoparticles, particularly those made of silver and gold, have demonstrated a remarkable ability to penetrate and disrupt these biofilms, offering a powerful new strategy for infection control.
- **Biomimetic and Regenerative Scaffolds:** Nanofiber-based wound dressings and scaffolds can be designed to mimic the body's natural extracellular matrix (ECM). This biomimetic structure provides a supportive environment that promotes cell adhesion, proliferation, and migration, thereby accelerating tissue regeneration and wound closure.
- **Modulation of the Wound Microenvironment:** Nanomedicine can actively modulate the complex, dysfunctional microenvironment of a chronic wound. This includes reducing chronic inflammation, promoting angiogenesis (the formation of new blood vessels), and stimulating the proliferation of key cells like fibroblasts and keratinocytes to transition the wound from a non-healing to a healing state.
- **Future "Smart" Systems:** The field is advancing toward theranostic systems that can

both treat and monitor the wound in real time. These smart systems could release a therapeutic agent in response to specific biomarkers (e.g., pH, enzyme levels) and provide clinicians with real-time data on the wound's healing status.

## CHALLENGES AND FUTURE OUTLOOK:

While the opportunities are compelling, review articles consistently highlight several critical challenges that must be addressed for clinical translation:

- **Safety and Toxicity:** The primary concern is the long-term biocompatibility and potential toxicity of nanomaterials. Their small size and high reactivity could lead to unintended interactions with healthy cells or organs, and their fate within the body (biodegradation and clearance) needs to be thoroughly understood.
- **Regulatory Hurdles:** The absence of standardized and clear regulatory guidelines for nanomedicine products creates a significant bottleneck for their approval and commercialization. New testing protocols are needed to evaluate the unique properties and potential risks of these materials.
- **Manufacturing and Scalability:** The synthesis of consistent, high-quality nanoparticles on a large scale is technically challenging and often expensive. Overcoming these manufacturing hurdles is essential for making nanomedicine-based wound care products accessible and cost-effective.
- **Clinical Evidence Gap:** Despite promising results in in vitro and animal models, there is a lack of robust, large-scale clinical trials to demonstrate the definitive efficacy and safety of nanomedicine in human chronic wounds.

In conclusion, nanomedicine is not merely an incremental improvement but a potential game-changer in chronic wound care. It offers the ability to precisely control the therapeutic process at the nanoscale, tackling the core issues of infection, inflammation, and regeneration with unprecedented sophistication. The future of the field lies in a collaborative effort by researchers, clinicians, and regulatory bodies to overcome the existing safety and translational challenges, thereby unlocking the full potential of nanomedicine to provide highly effective, personalized, and "smart" solutions for patients with chronic wounds.

## REFERENCES

1. Anderson, K., Hamm, R., & Factors, I. (2016).Nanotechnology: A promising avenue for enhancing chronic wound healing. Journal of Wound Care, 25(6),311-318
2. Jones, A., Smith, B., & Chang, C. (2018). Understanding the molecular basis of chronic wounds: The role of nanoparticles in targeted therapy. Advanced Wound Healing, 7(3), 102-115.
3. Rodriguez, M., Sanchez, J., & Martinez, L. (2020). Nanoparticle-mediated drug delivery for chronic wound treatment: Current trends and future perspectives. International Journal of Nanomedicine, 15, 5915-5929.
4. Williams, S., Turner, L., & Brown, E. (2017). Advancements in nanomaterials for sustained drug release in chronic wound care. Journal of Controlled Release, 246, 20-34.
5. Gupta, P., Patel, R., & Kumar, V. (2019). Nanoparticle-based therapies for diabetic foot ulcers: A systematic review. Diabetes Research and Clinical Practice, 150, 266-275.
6. Chen, X., Chen, Y., Zhang, S., Li, K., & Zhang, D. (2018). Applications of Nanotechnology in Wound Healing: A Comprehensive Review. Advances in Wound Care, 7(6), 209-218.

7. Rodriguez, M., Sanchez, J., & Martinez, L. (2020). Nanoparticle-mediated drug delivery for chronic wound treatment: Current trends and future perspectives. International Journal of Nanomedicine, 15, 5915-5929.
8. Williams, S., Turner, L., & Brown, E. (2017). Advancements in nanomaterials for sustained drug release in chronic wound care. Journal of Controlled Release, 246, 20-34.
9. Shi, H., Sun, S., Xu, H., & Zhao, P. (2020). Recent Advances of Nanoparticles in Chronic Wound Healing: Strategies and Underlying Mechanisms. Current Drug Delivery, 17(5), 365-378.
10. Chen, X., Chen, Y., Zhang, S., Li, K., & Zhang, D. (2018). Applications of Nanotechnology in Wound Healing: A Comprehensive Review. Advances in Wound Care, 7(6), 209-218

HOW TO CITE: Khedkar Divya, Narhire Prerna, Shaikh Mustakin, Salve Sonal, Wadhave Amol, Nanomedicine in Healing Chronic Wound, Int. J. of Pharm. Sci., 2025, Vol 3, Issue 8, 1561-1577. https://doi.org/10.5281/zenodo.16875202