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Advances in Nanotechnology in Drug Delivery Systems for Burn Wound Healing: A Review

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Burn wounds (BWs) are among the most complex injuries to manage, often leading to prolonged healing times, heightened infection risks, and significant scarring. Traditional therapies frequently fall short in addressing these challenges, highlighting the need for innovative solutions. Nanotechnology has emerged as a transformative approach in BWs care, offering advanced drug delivery systems that improve therapeutic outcomes. These systems, including nanoparticles, liposomes, micelles, and hydrogels, provide controlled drug release, enhanced stability, and targeted delivery of bioactive compounds. This review explores recent advancements in nanotechnology-based drug delivery for BWs, emphasizing their potential to promote faster healing, reduce infections, and minimize scarring. Additionally, emerging technologies, such as stimuli-responsive nanomaterials and theranostic platforms, hold promise for personalized treatment approaches. By integrating these innovations, nanotechnology is paving the way for more effective, patient-centered BWs management strategies.

Keywords: Antimicrobial agents, Burn wound healing, Drug delivery systems, Growth factors, Hydrogels, Liposomes, Nanotechnology, Nanoparticles, stimuli-responsive nanomaterials, Tissue regeneration.

Wound healing is a complex and highly specialized process that involves replacing damaged or injured tissues with new, healthy ones. Among the most challenging types of wounds to manage are chronic wounds, especially BWs, which disrupt the natural healing process and require advanced medical care.[1] BWs pose significant challenges due to their complexity, risk of infection, and potential for scarring. These injuries are some of the most severe and impactful forms of trauma, caused by damage to both the skin and deeper tissues due to heat, chemicals, electricity, or radiation.[2]

According to the World Health Organization (WHO), burn injuries are responsible for over 180,000 deaths annually, marking them as a critical global public health issue. A significant proportion of these fatalities occur in low- and middle-income countries, where limited access to advanced medical care exacerbates the problem.[3] Survivors often face long-term health complications, including disfigurement, disability, and psychosocial challenges.[4] Scald, injury caused by hot liquid or steam, are particularly common and represent a significant cause of morbidity worldwide, affecting children, adults, and elderly patients alike.[5] Burns are the 11th leading cause of death among children aged 1–9 years and the 5th leading cause of non-fatal injuries in this age grou Vulnerable populations, including diabetic patients and individuals with mental disorders, face an elevated risk of burn-related complications, underscoring the need for targeted prevention and care strategies.[6]

The healing process of BWs is complex and influenced by factors such as the depth of the burn, the extent of tissue damage, and the patient's overall health. Burns compromise the skin's protective barrier, increasing susceptibility to infections.[7] Though BWs are initially sterile, they are highly prone to bacterial colonization, especially in larger burns. In severe cases where more than 40% of the body surface area is affected, infections like sepsis become a leading cause of death. The risk of severe infection is particularly high during the first 10 days post-injury due to a weakened immune response.[8] While advancements in BWs care, including pulmonary management, nutritional support, and novel therapeutic strategies, have improved survival rates, significant challenges remain. Current treatments, such as topical agents, systemic drugs, and surgical interventions, often fail to address critical issues like prolonged healing times, infection control, and effective scar management. These limitations highlight the pressing need for innovative solutions.[9]

Nanotechnology has emerged as a transformative field in medicine, offering groundbreaking advancements in drug delivery systems. By manipulating materials at the nanoscale (1–100 nanometers), nanotechnology provides unique capabilities to improve drug stability, enhance bioavailability, and enable targeted delivery of therapeutic agent.[10] In the context of BWs care, nanoscale materials—such as metallic and polymeric nanoparticles—can deliver antimicrobial agents, growth factors, and other therapeutic compounds directly to the wound site, promoting faster healing and reducing systemic side effects.[11] Recent studies demonstrate the ability of nanomaterials to overcome bacterial resistance, enhance drug penetration into tissue barriers, and provide broad-spectrum antimicrobial propertie.[12] Furthermore, innovations in smart delivery systems, such as stimuli-responsive nanoparticles, have revolutionized the precision and efficacy of BWs treatments.[13]

This review focuses on the advancements in nanotechnology for drug delivery systems specifically tailored to BWs healing. By examining a range of nanoformulations and their mechanisms of action, the review seeks to highlight the transformative potential of these technologies in addressing current challenges in burn care. Through this exploration, we aim to underscore the critical role of nanotechnology in improving patient outcomes and shaping the future of BWs management.

Skin Structure and BWs Classification

The skin, the largest organ of the human body, consists of three main layers: the epidermis, dermis, and hypodermis. These layers play essential roles in temperature regulation, environmental protection, and metabolic functions. The epidermis acts as a protective barrier, while the dermis contains blood vessels, nerve endings, and connective tissue. The hypodermis, or subcutaneous layer, provides insulation and connects the skin to underlying muscles and bones. Burn injuries are classified based on their depth and severity, providing a framework for understanding tissue damage and guiding treatment as shown in Figure 1.[16] First-degree burns affect only the epidermis, causing redness and minor pain.[5] Second-degree burns, extend into both the epidermis and part of the dermis, leading to blisters and more intense pain.[17] Third-degree burns, penetrate through the full thickness of the skin, potentially reaching underlying tissues and causing significant scarring and loss of sensation.18 Fourth-degree burns, These are the most severe, affecting deeper tissues such as muscles and bones, often requiring surgical intervention.[19]

Burn wounds are also divided into three zones: the coagulation zone, where tissue damage is irreversible; the stasis zone, which has reduced blood flow but may be salvageable with proper treatment; and the hyperemia zone, which has increased blood flow and can heal unless further complications arise.[13]

BWs Healing Process

The healing process of BWs begins with an understanding of the mechanisms underlying normal or acute wound healing. The body frequently undergoes cycles of skin injuries and tissue repair. The healing process of acute wounds follows four distinct stages, each playing a critical role in ensuring that the wound heals in an efficient and timely manner as shown in Figure 2.[22]

First, there's hemostasis, where blood clots are formed to stop bleeding. Then comes the inflammatory stage, where immune cells clean the wound area and fight off infection. The next stage is called the proliferative phase. During this phase, collagen is made, new blood vessels grow, and skin cells start to cover the wound. The final stage is maturation, where collagen changes and the scar forms, which can take a long time, from months to even years.[23] Burn wounds don't heal in the same way as regular wounds, especially serious burns due to deep tissue damage, which makes recovery longer.[24] Burns that only go partway through the skin, also known as partial-thickness burns, heal more quickly. However, full-thickness burns, which reach deeper layers, might take years to fully recover. Infections with bacteria or fungi can seriously slow down healing. This is an even bigger issue for people with weak immune systems due to problems like biofilm formation and resistance to antibiotics.[25]

Factors Affecting Burn Healing

Various intrinsic and extrinsic parameters affect the healing process of BWs and those can hinder patients' recovery and result in poor outcome.[29] One important cause could be the increased susceptibility to infection due to burns, in which the underlying dermis is exposed, and the epidermis is altered, increasing the risk of microbial invasion. Infections can significantly delay the healing process by extending the period of inflammation and interfering in granulation tissue formation.[30] Pathogens most associated with BWs infections include common bacteria, such as Staphylococcus aureus and Pseudomonas aeruginosa. Management strategies such as the use of antimicrobial treatments and appropriate wound dressings are crucial, as they can decrease these risks and optimize the conditions for healing. Another important element is the regulation of

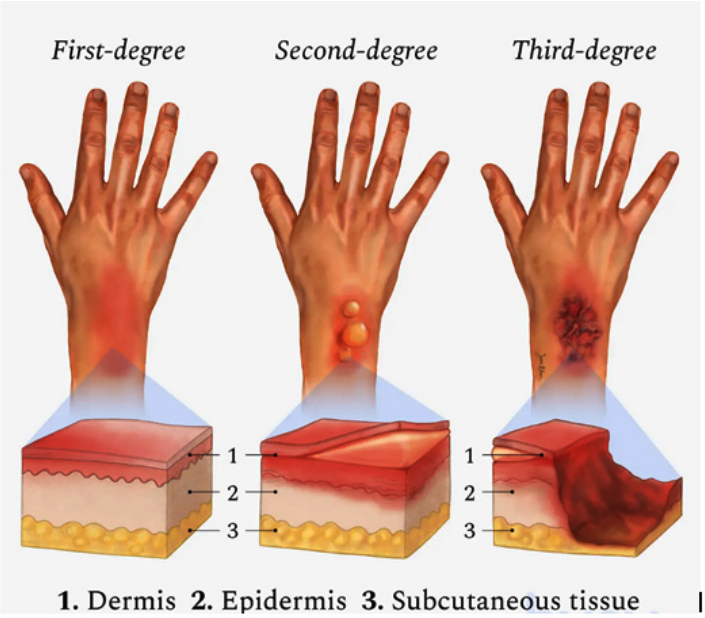

Fig. 1. BWs Classification

the inflammatory response that is critical in the healing of BWs.[28] The inflammatory response must strike a balance, as uncontrolled inflammation can have deleterious outcomes, such as chronic wounds or hypertrophic scarring. Overproduction of pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-a) and interleukin-1 (IL-1), can aggravate tissue injury and impede

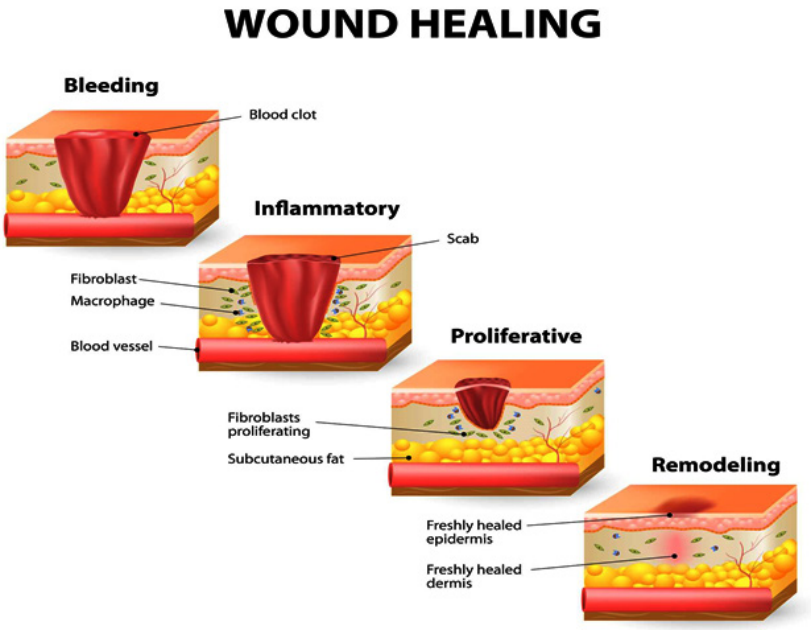

Fig. 2. Representation of four Stages of BWs healing which involve Bleeding, Inflammation, Proliferative and Remodeling

Table 1. Stages for Wound Healing Process

Stage	Timeframe	Key Processes	Key Players
Hemostasis Phase	Immediately (0-1 hour)	• Vasoconstriction and platelet aggregation • Clot formation and fibrin deposition • Activation of coagulation cascade	Platelets, clotting factors, fibrin
Inflammatory Phase	0-3 days	• Vasodilation and immune cell infiltration • Pathogen clearance and debris removal	Neutrophils, macrophages, cytokines
Proliferative Phase	4 days - 3 weeks	• Granulation tissue formation • Fibroblast proliferation and collagen production • Angiogenesis	Fibroblasts, keratinocytes, VEGF
Maturation Phase	Month to years	• Collagen remodeling (type III to type I) • Scar formation and tensile strength restoration	Fibroblasts, MMPs

the repair process.[6] Conversely, inadequate inflammation may hinder essential activities like wound debridement and tissue regeneration, hence prolonging recovery. Scar development constitutes a significant obstacle in the healing process of BWs. Excessive collagen deposition and disordered extracellular matrix remodeling frequently lead to hypertrophic scarring and contractures.[31] Outcomes may be affected by factors including genetic predisposition, the extent and severity of the burn injury, and the duration of inflammation. Such a typical scarring not only detracts from aesthetic results but can also hinder mobility and functional recovery, highlighting the necessity for targeted interventions to modulate ECM remodeling and reduce long-term complications.[30]

Nano-therapeutics for Managing BWs

Traditional burn care methods, including systemic antibiotics and surgical interventions, have limitations, such as the risk of antibiotic resistance and the difficulty in delivering treatments to deeper tissues in severe burns (third- and fourth degree). These complications have led to a growing interest in local treatments that can effectively target and heal the wound site.[32] Nanotechnology has emerged as a promising approach in BWs management, offering innovative solutions to longstanding challenges such as infection control, delayed healing, and inadequate drug penetration into deeper tissues. The distinct properties of nanomaterials, typically sized between 10 and 100 nanometers, enable the targeted delivery of therapeutic agents, including antibiotics, growth factors, and gene therapies, directly to the wound site.[33] This targeted approach enhances the healing process by improving drug delivery efficiency and protecting therapeutic molecules from degradation within the wound environment. Nanoparticles in wound care are generally classified into two categories: those with intrinsic wound-healing properties and those engineered as drug delivery vehicles.[34,35] These nanoparticles tailored to act as therapeutic agents or as carriers for controlled and sustained release of therapeutic compounds, significantly improving the wound healing process and supporting skin regeneration.[36]

Nanocarriers are a critical component in advancing the effectiveness of Nano-therapeutics. These tiny vehicles encapsulate or attach to therapeutic agents, facilitating their transport to target sites within the body. Some common types of nanocarriers as shown in the Figure 3, such as polymeric nanoparticles, have been used for BWs care due to their stability, large drug-loading capacity, and ability to enable slow drug release. These properties are particularly beneficial in

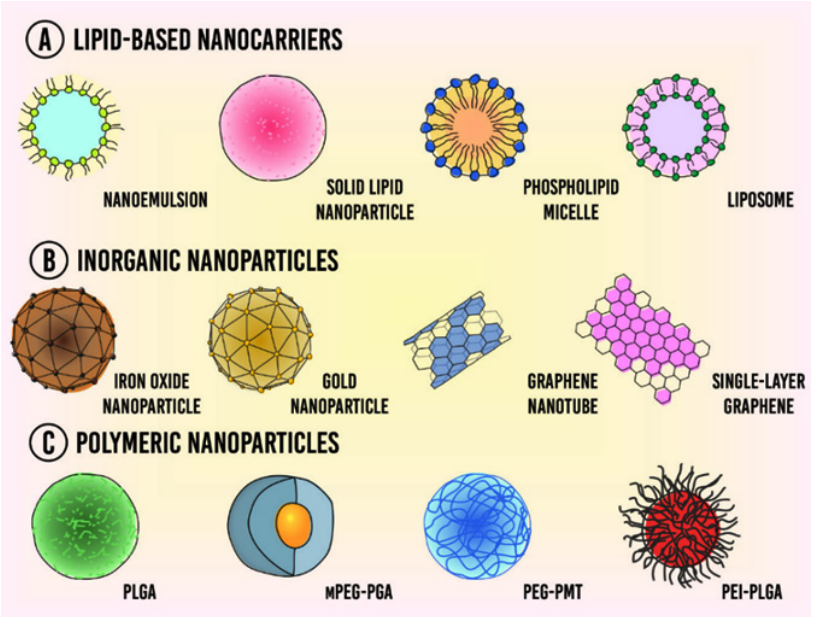

Fig. 3. Different Types of Nanocarriers used in drug delivery for the BWs healing process

Table 2. Innovative Nano therapies for BWs healing

Type of Nanotechnology	Key Features	Application	References
Nanomaterials			
Silver Nanoparticles (AgNPs)	Broad-spectrum antimicrobial activity: sustained silver ion release ensures prolonged action	BWs and diabetic ulcers; used in dressings, creams, and topical formulations	[62, 63]
Copper Nanoparticles (CuNPs)	Antimicrobial properties; promotes angiogenesis and tissue repair	Excisional wounds in a rat model	[64]
Cerium Nanoparticles (Nanoceria)	Antioxidant properties; accelerate wound closure	Full-thickness murine wounds	[65]
Nanosized Bioactive Glass Particles	Encourages cell proliferation, angiogenesis, and faster wound closure	In vitro assay using human umbilical vein endothelial cells	[66]
Zinc Oxide Nanoparticles	Infection control, promotes angiogenesis, and supports cell proliferation	Wound-healing assay using endothelial cells	[67]
Carbon-based Nanomaterials	Antioxidant and anti-inflammatory effects; supports cell proliferation	In vitro assay with primary human keratinocytes	[68]
Nanomaterials for Therapeutic Agent Delivery			
Chitosan–Pectin–Titanium Dioxide Nano dressing	Antimicrobial and bioactive; combines mechanical strength of TiO2 with the gelling property of pectin	Excisional wounds in rats	[69]
Gold Nanoparticles	Functionalized with antibiotics, antioxidants, and reactive oxygen species scavengers; supports gene therapy	Diabetic murine wounds	[70]
Nitric Oxide-Loaded Nanoparticles	Promotes wound closure, reduces inflammation, enhances collagen deposition, and prevents biofilm formation	Pseudomonas aeruginosa-infected murine excisional wounds	[71, 72]
Lipid-Based Nanomaterials (e.g., Liposomes)	Deliver antioxidants and anti-inflammatory Phyto drugs to wound sites	Full-thickness skin defect models (in vitro and in vivo)	[73]
Electrospun Silver Mats	Polymer-based fibers release silver ions for antibacterial activity	Effective against Staphylococcus aureus and Escherichia coli	[74]
Scaffolds			

PLGA/Silk Fibroin Hybrid Scaffold	Supports cell attachment and proliferation; requires optimization for effective usefor effective use	Excisional wound model in diabetic rats	[75]
Gelatin and Poly-Caprolactone (PCL) Nanofibers	Fabricated using electrospinning; supports adhesion and cell proliferation	Full-thickness wounds in rats	[76]
Fibrin–Collagen–Fibrin Porous Scaffold	Provides a matrix for fibroblasts, keratinocytes, and epidermal cells	Skin regeneration	[77]
Anodic Aluminum Oxide (AAO)	Features a porous structure; biocompatible and facilitates keratinocyte migration	In vitro keratinocyte migration studies	[78]
Gene Therapy and RNA-Based Nanocarriers			
Dendrimers	Delivers VEGF-encoding plasmids for enhanced angiogenesis	Diabetic murine wounds	[79]
PLA and PCL Electrospun Nanofibers	Loaded with DNA plasmids encoding keratinocyte growth factor to promote healing	Murine wounds	[80]
Spherical Nucleic Acid (SNA) Gold Nanoparticles	siRNA-loaded particles targeting pro-inflammatory genes; reduce inflammation and improve healing	Diabetic murine wounds	[81]
Growth Factor Delivery			
PLGA Nanoparticles with VEGF	Enhances VEGF bioactivity; promotes angiogenesis	Nondiabetic and diabetic murine wounds	[82]
Core/Shell bFGF/PCL–PEG Nanofibers	Dual release of bFGF and EGF for enhanced fibroblast and keratinocyte activity	Diabetic murine wounds	[83]
Stem Cell Therapy			
Nanofiber Scaffolds with BM-MSCs	Promotes faster wound closure; supports epidermal differentiation	Acute full-thickness BWs	[84]
Aloe Vera–PCL	Combines stem cell therapy and Nanoscaffold with hWJSCs aloe vera's antibacterial properties	Excisional and diabetic murine wounds	[85]

the context of burn treatment, where controlled, sustained release of drugs is necessary to manage pain, promote healing, and prevent infection.[37] Lipid-based nanoparticles are an important type of nanocarriers in BWs care due to their versatility, biocompatibility, and ability to encapsulate both hydrophilic and hydrophobic drugs. Their properties make them ideal for controlled, sustained drug release, which is essential in the healing of BWs. LNPs can improve drug bioavailability and ensure the targeted delivery of therapeutic agents like antimicrobial drugs, growth factors, and anti-inflammatory compounds.[38] Metallic nanoparticles, such as gold and silver, are also highly effective due to their antimicrobial properties, helping to control infections and promote tissue repair processes essential for wound healing.[39]

Additionally, other nanocarriers such as nanoemulsions, liposomes, micelles, dendrimers, and hydrogels are being explored for their effectiveness in BWs therapy. These materials offer enhanced drug solubility, targeted delivery, and sustained release, all of which are critical for managing BWs. Nanoemulsions, Improve drug bioavailability and solubility, ensuring fast and prolonged therapeutic effects for BWs.[40] Whereas, the liposomes deliver antimicrobial agents directly to the infection site, offering controlled drug release and combating multi-drug-resistant infections.[41] Micelles and Dendrimers, enhance drug solubility and enable targeted delivery, improving BWs treatment.[38] Hydrogels and nanogels promote healing by maintaining a moist environment and providing sustained drug release.[42] Carbon Quantum Dots (CQDs), these are emerging as promising nanomaterials for BWs treatment due to their antibacterial properties, biocompatibility, and stability. With diameters under 10 nanometers, CQDs are highly soluble in water and possess photoelectric capabilities, making them effective in therapeutic applications. When combined with photothermal and photodynamic therapies, CQDs help eliminate harmful microorganisms and promote healing. Photothermal therapy uses heat generated by light absorption to kill bacteria, while photodynamic therapy relies on reactive oxygen species (ROS) to destroy bacterial cells. Both therapies not only combat infections but also enhance the healing process by reducing infection risks.[43] Nanocarriers utilize various mechanisms to release drugs precisely at the target site. 1) Passive Targeting, nanocarriers accumulate in tissues with leaky vasculature (such as tumor tissues) through the Enhanced Permeability and Retention (EPR) effect. 2) Active Targeting, by functionalizing the surface of nanocarriers with specific ligands or antibodies, drugs can be delivered more precisely to target cells. 3) Stimuli-Responsive Release, nanocarriers can release drugs in response to specific stimuli, such as pH changes or enzymatic activity, ensuring drug release at the desired site. 4) Controlled Release, drugs can be released over time through diffusion-controlled mechanisms or matrix degradation, allowing for sustained therapeutic effects.[44]

The integration of nanotechnology into BWs care not only enhances drug bioavailability but also improves treatment precision, reduces side effects, and enables multimodal therapies, which combine diagnostic tools, imaging, and therapeutic agents within a single system. This makes Nano-therapeutics a versatile and powerful approach in treating BWs and their complications.[32]

Practical Applications of Nanotechnology in Burn Treatment

Nanotechnology is transforming burn wound treatment by helping wounds heal faster, reducing infection risks, and making drug delivery more efficient. Some nanotechnology treatments are already used in medicine, while others are still being tested. One of the most prominent applications is nanoparticle-based dressings, particularly those infused with silver nanoparticles, which exhibit strong antimicrobial properties. Dressings with silver nanoparticles are especially effective because they prevent infections, which is crucial for quicker recovery with fewer complications.[45] Another approach involves nanofiber scaffolds, made from very fine, spun materials. These scaffolds imitate the body's natural framework, encouraging cell growth and tissue repair.[46] Researchers are also investigating exosome-based therapies. Exosomes are tiny packets from special stem cells that help cells communicate, which is important for wound healing. These are being studied for their potential to repair tissues in burn victims.[47] Additionally, some products using nanotechnology are already available. For example, a dressing called Acticoat® creates strong germ protection

using silver nanoparticles. These products show how nanotechnology is moving from research labs into actual medical use, improving treatment and care standards for burn patients.[48]

Nanotechnology-Based Drug Delivery Systems for BWs Healing

Antimicrobial Nanomaterials

Silver nanoparticles (AgNPs) are among the most extensively studied antimicrobial nanomaterials for BWs healing. Known for their broad-spectrum antimicrobial activity, AgNPs effectively combat bacteria, fungi, and viruses, making them ideal for use in wound dressings, creams, and topical formulations.49 These nanoparticles ensure sustained release of silver ions, maintaining prolonged antimicrobial activity at the wound site. Similarly, copper nanoparticles (CuNPs) exhibit potent antimicrobial properties, with additional benefits such as promoting angiogenesis and tissue repair. Other nanomaterials, including zinc oxide and titanium dioxide nanoparticles, have also demonstrated significant antimicrobial efficacy, further expanding the range of options for infection control in BWs.[50] The antimicrobial activity of nanomaterials is attributed to several mechanisms. For silver nanoparticles, the release of silver ions plays a central role, as these ions disrupt bacterial cell membranes, interfere with metabolic enzymes, and generate reactive oxygen species (ROS) that induce oxidative stress in microbial cells.[51] Copper nanoparticles exhibit similar mechanisms, including ROS generation and disruption of bacterial DNA and proteins. Additionally, the nanoscale size of these materials facilitates penetration into microbial cells, enhancing their antimicrobial efficacy. These mechanisms collectively reduce microbial colonization and biofilm formation, both of which are common challenges in BWs infections.[52]

Growth Factor Delivery

Growth factors play a pivotal role in wound healing, particularly in the context of burn injuries. Key growth factors such as Vascular Endothelial Growth Factor (VEGF) and Epidermal Growth Factor (EGF) are crucial for promoting various biological processes essential for effective healing.[53] VEGF is primarily involved in angiogenesis, the formation of new blood vessels, which is vital for supplying nutrients and oxygen to the healing tissue. It stimulates endothelial cell migration and proliferation, contributing to the development of granulation tissue and enhancing vascular permeability during the initial phases of wound healing.[54] EGF, on the other hand, promotes epithelial cell growth and migration, facilitating re-epithelialization of the wound surface and combating fibroblast activity that can hinder healing. Both factors are released by platelets and macrophages in response to tissue injury, highlighting their importance in initiating and sustaining the healing process. To maximize their therapeutic potential, nanocarriers have been developed for the controlled release of these growth factors. These nanocarriers can encapsulate VEGF and EGF, ensuring that these bioactive molecules are delivered at optimal concentrations over extended periods. This controlled release not only enhances the stability of the growth factors but also allows for sustained therapeutic effects at the wound site, thereby improving overall healing outcomes.[55]

Anti-inflammatory Nanocarriers

Anti-inflammatory nanocarriers are designed to deliver therapeutic agents such as corticosteroids and non-steroidal anti-inflammatory drugs (NSAIDs) directly to the wound site, ensuring targeted action while minimizing systemic side effects.[56] These nanocarriers enhance the bioavailability and controlled release of anti-inflammatory drugs, allowing for sustained therapeutic effects. For instance, corticosteroids loaded into nanoparticles can reduce cytokine-mediated inflammation, while NSAIDs delivered via nanocarriers help mitigate prostaglandin synthesis, thereby reducing swelling and pain.[57]

Gene Therapy and RNA-Based Nanocarriers

Gene therapy and RNA-based nanocarriers represent a frontier in advanced wound healing strategies. The delivery of therapeutic genes or small interfering RNA (siRNA) can modulate cellular behavior to enhance healing and minimize scarring. Nanotechnology has enabled the development of carriers such as lipid nanoparticles and polymeric nanocarriers for precise gene delivery and expression regulation.[58] These systems protect genetic material from degradation while ensuring efficient cellular uptake and controlled release. For example, siRNA targeting pro-inflammatory cytokines can suppress excessive inflammation, while gene delivery for growth factors such as

VEGF can promote angiogenesis and tissue regeneration.[59]

Hydrogels and Nanofibers for Wound Dressings

Nanostructured hydrogels and nanofibers have revolutionized BWs management by offering superior properties compared to traditional dressings. These materials provide an optimal moist environment, which is crucial for wound healing, and reduce pain by acting as a protective barrier. Nanostructured hydrogels can incorporate bioactive agents such as antimicrobial peptides or growth factors, enabling sustained and localized release to the wound site. Similarly, nanofibers fabricated through electrospinning techniques mimic the extracellular matrix, supporting cell adhesion, proliferation, and migration.[60] The porous structure of nanofibers allows for efficient gas exchange while preventing microbial infiltration. Compared to conventional dressings, nanostructured hydrogels and nanofibers offer enhanced healing outcomes, reduced infection rates, and improved patient comfort, making them a preferred choice for BWs care.[61] A growing array of innovative Nano therapies has been developed for wound healing and is actively being explored in clinical studies and shown in Table 2.

Biodegradable nanomaterials have become a breakthrough in BWs treatment, offering significant advantages due to their ability to naturally degrade within the body. These materials gradually release therapeutic agents over time, eliminating the need for surgical removal and reducing complications associated with retained foreign materials.[86] This innovation simplifies the treatment process while enhancing safety and effectiveness. Among the most prominent biodegradable nanomaterials is Poly (lactic-co-glycolic acid) (PLGA), a versatile polymer capable of encapsulating various therapeutic agents, such as antibiotics, growth factors, and anti-inflammatory drugs. PLGA nanoparticles ensure a controlled and sustained release of these agents, providing a consistent supply to the wound site and promoting efficient healing.[87] Similarly, chitosan, a natural polysaccharide derived from chitin, has gained attention for its excellent biocompatibility, biodegradability, and inherent antimicrobial properties. Chitosan-based nanomaterials are utilized in multiple forms, including drug delivery systems, wound dressings, and tissue scaffolds, to accelerate healing and reduce infection risks.88 Nanostructured scaffolds have also revolutionized tissue regeneration by replicating the body's extracellular matrix. These scaffolds create a supportive three-dimensional structure that fosters cell growth, proliferation, and differentiation. By fine-tuning characteristics like pore size and surface chemistry, nanoscaffolds enhance tissue repair and stimulate the growth of new blood vessels through angiogenesis. Additionally, bioactive films infused with nanomaterials offer dual benefits: they act as a protective barrier while delivering therapeutic agents directly to the wound site. This combined function accelerates healing, promotes cell adhesion, and minimizes infection risks, making bioactive films an essential tool for burn treatment.[89] The smart nanomaterials are engineered to respond to environmental triggers, such as pH changes, temperature fluctuations, or enzyme activity.[90] For instance, pH-sensitive nanomaterials can release antibiotics or growth factors in response to the acidic conditions commonly found in inflamed wounds, targeting infection and aiding tissue repair. The versatility of smart nanomaterials supports personalized, adaptive treatments. By integrating sensors and actuators, these materials can monitor wound healing in real-time and adjust drug delivery as needed. This precision reduces side effects and enhances treatment outcomes, offering a tailored approach to meet individual patient requirements.[91]

CONCLUSION

Nanotechnology has revolutionized the field of BWs healing, offering advanced solutions for promoting tissue repair and infection control. The efficacy and safety of nanotechnology-based drug delivery systems have been validated in numerous studies, highlighting their potential to address the limitations of traditional therapies. Despite challenges such as regulatory approval and scalability, emerging trends in nanomedicines, including the integration of stem cell therapy and advancements in 3D printing, provide a promising outlook. The continuous evolution of nanotechnology paves the way for innovative, effective, and personalized approaches in regenerative therapy for BWs.

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This study did not involve human participants, and therefore, informed consent was not required.

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This research does not involve any clinical trials.

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