Advanced Pharmaceutical Bulletin

Accepted Manuscript (unedited)

The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form.

Mini Review

How to cite this article:
Hassan M, Ghaffari S. Wound Healing and Nanotechnology: Recent Advances and Future Perspectives. Advanced Pharmaceutical Bulletin, doi: 10.34172/apb.47125

Wound Healing and Nanotechnology: Recent Advances and Future Perspectives

Maryam Hassan[1], **Solmaz Ghaffari** [2,*]

[1] Pharmaceutical Biotechnology Research Center, Zanjan University of Medical Sciences, Zanjan, Iran
[2] Department of Pharmaceutics, TeMS.C., Islamic Azad University, Tehran, Iran

ARTICLE INFO

Keywords:
Wound healing,
Nanotechnology,
Drug delivery,
Tissue regeneration;
Smart wound dressings

Article History:
Submitted: February 01, 2026
Revised: May 10, 2026
Accepted: June 22, 2026
ePublished: June 27, 2026

ABSTRACT

Wound healing is a complex, multifactorial biological process encompassing cellular migration, modulation of inflammatory responses, and tissue remodeling. Despite significant progress in conventional therapeutic approaches, delayed or incomplete wound closure remains a prevalent clinical challenge. This review provides a comprehensive analysis of recent advancements in nanotechnology-driven strategies for wound management, emphasizing their underlying mechanisms, therapeutic benefits, and translational potential. A systematic literature search was conducted across electronic databases, including PubMed and Scopus, covering publications from 2000 to 2025. Studies focusing on nanomaterials, drug delivery platforms, and wound care interventions were prioritized. Nanotechnology offers innovative modalities that enhance drug delivery precision, stimulate angiogenesis, regulate inflammatory pathways, and mitigate microbial contamination. Diverse nanostructures—such as metallic nanoparticles, polymeric carriers, liposomes, and nanofibers—have demonstrated promising efficacy in both preclinical and clinical settings. Current evidence suggests that integrating nanotechnology into wound care holds substantial promise for accelerating tissue repair and improving regenerative outcomes. However, further research is warranted to address long-term safety, scalable manufacturing processes, and clinical validation through large-scale trials.

***Corresponding Author**
Solmaz Ghaffari, Email: soligh1396@gmail.com, ORCID: 0000-0002-5166-5112

Introduction

Wound healing restores the structural and functional integrity of skin and underlying tissues through overlapping phases: hemostasis, inflammation, proliferation, and remodeling. Disruption of this process—such as in chronic or diabetic wounds—leads to delayed healing and increased infection risk.[1–6] Conventional wound care modalities, including dressings, antibiotics, and growth factor-based therapies, often provide incomplete regeneration due to limitations such as poor bioavailability, uncontrolled drug release, and the emergence of antimicrobial resistance. To address these challenges, nanotechnology has emerged as a promising therapeutic strategy. Nanomaterials offer distinctive physicochemical features—including a high surface-to-volume ratio, tunable drug-loading, controlled release, and targeted antimicrobial activity—that improve therapeutic performance while reducing adverse effects. [6–11]

This review provides a comprehensive information of mechanistic insights, summarizes key findings from recent preclinical and clinical studies, and outlines existing challenges and future perspectives necessary for successful clinical translation.

Nanomaterials and their mechanisms of action in wound healing

Nanotechnology offers a transformative approach to wound management through engineered nanomaterials designed to accelerate tissue repair and prevent infection. These nanosystems enhance drug stability and bioavailability, protect therapeutic agents, and provide controlled release at the wound site. Different nanosystems enhance wound healing by variety of mechanisms as described below. [12-30]

Metallic Nanoparticles

Silver, gold, zinc oxide, and copper oxide nanoparticles possess antimicrobial and anti-inflammatory properties.[19–22] Silver nanoparticles (AgNPs) disrupt bacterial membranes and generate reactive oxygen species (ROS) for bacterial death [17-18] as well as stimulate keratinocyte migration and collagen deposition, aiding re-epithelialization. Gold nanoparticles (AuNPs) have antioxidant and anti-inflammatory effects that promote angiogenesis and fibroblast proliferation. Zinc oxide nanoparticles (ZnO NPs) inhibit microbial growth and regulate cellular proliferation and collagen synthesis.[12-14] Composite systems, combining metallic nanoparticles with polymeric carriers like PVA, exemplify the emerging trend of hybrid nanomaterials designed to optimize both biological activity and mechanical performance in wound care applications.[12-16]

Polymeric Nanoparticles

Polymeric nanocarriers such as those fabricated from biodegradable polymers like PLGA, chitosan, and alginate are highly versatile delivery platforms capable of encapsulating a wide range of therapeutic and bioactive agents. These nanoparticulate systems ensure controlled, sustained, and site-specific drug release, thereby maintaining optimal therapeutic concentrations at the wound site over prolonged durations among them, chitosan-based nanoparticles have gained particular attention for their inherent antimicrobial, hemostatic, and bioadhesive properties, as well as their capacity to enhance fibroblast adhesion, migration, and proliferation. [19-23]

Lipid-Based Nanocarriers

Lipid-based nanocarriers, including solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) and liposomes, have attracted growing interest as effective delivery systems for topical wound applications. These nanocarriers enhance the penetration of therapeutic agents across the skin barrier and improve the physicochemical stability of labile bioactive molecules such as growth factors and natural compounds. Recent investigations have demonstrated that SLNs loaded with curcumin, resveratrol, or antibiotics can accelerate wound closure, reduce oxidative stress, and inhibit microbial colonization, thereby promoting faster and more efficient tissue regeneration. [22-26]

Nanofibers and Scaffolds

Electrospun nanofibers and bioactive scaffolds mimic the extracellular matrix (ECM) structure, providing an optimal environment for cell migration and proliferation. Nanofibers fabricated from polymers such as polycaprolactone (PCL), gelatin, and silk fibroin can be loaded with bioactive molecules to create multifunctional wound dressings. These structures support gas exchange, maintain moisture, and deliver antimicrobial or regenerative agents in a sustained manner.For example, electrospun polyvinyl alcohol (PVA) nanofibers incorporating silver chloride nanoparticles have shown enhanced antibacterial and electroconductive properties, promoting both infection control and tissue regeneration. Such hybrid scaffolds highlight the potential of combining polymeric matrices with metallic nanoparticles to accelerate wound closure and improve healing outcomes.[31-35]

Tables 1 shows a brief list of types of Nanomaterials Used in Wound Healing and Their Therapeutic Roles and mechanisms of nanotechnology in enhancing of wound healing, respectively.

Table 1. Types of Nanomaterials Used in Wound Healing and Their Therapeutic Roles

	EXAMPLES	THERAPEUTIC ROLE	KEY MECHANISM	REFERENCES
METAL NANOPARTICLES	Silver (AgNPs), Gold (AuNPs), Zinc Oxide (ZnO NPs)	Antimicrobial, anti-inflammatory	Disrupt bacterial membranes, enhance angiogenesis, modulation of cytokines, improve cell migration	12-16
POLYMERIC NANOPARTICLES	PLGA, Chitosan, PCL	Sustained drug release, biocompatibility	Controlled delivery of growth factors, promote fibroblast proliferation ,improve bioavailibility	19-23
LIPID-BASED NANOCARRIERS	SLN, NLC, Nanoemulsions	Skin penetration, drug stability	Improved topical absorption and sustained release	23-26
NANO HYDROGELS		Moist wound healing	High water retention, drug release	36-37

NANOFIBERS (ELECTROSPUN)		Skin substitute, scaffold	Cell adhesion	23,31,38,39
CARBON-BASED NANOMATERIALS	Graphene oxide, CNTs	Antibacterial, conductive scaffold	Promotes cell migration and electrical stimulation	32
HYBRID NANOCOMPOSITES	Metal-polymer composites	Multifunctional wound dressing	Combine antimicrobial and regenerative effects	40

Clinical Studies and Recent Advances

Recent years significant progress in the clinical translation of nanotechnology-based wound therapies, with many formulations demonstrating safety and efficacy in preclinical and clinical studies was stablished.[17,23] These systems not only improve wound closure but also reduce infections, control inflammation, and enhance cosmetic results. [41-43]

Metallic Nanoparticle Formulations

Several clinical trials have assessed the benefits of silver nanoparticle (AgNP)-containing dressings, which are among the most widely studied nanotechnology-based products. AgNP dressings significantly decreased healing time in patients with burn wounds and chronic ulcers compared with conventional gauze or antibiotic creams. Moreover, their broad-spectrum antibacterial activity reduces the need for systemic antibiotics and minimizes microbial resistances. Similarly, electrospun silver chloride-loaded PVA nanofibers have shown strong antibacterial and electroconductive performance in preclinical studies, supporting their potential as next-generation wound dressings with enhanced regenerative capacity. [44-46]

Gold nanoparticle-based formulations have progressed to clinical evaluation owing to their excellent biocompatibility, intrinsic antioxidant activity, and low cytotoxicity. Pilot studies have demonstrated that hydrogels incorporating AuNPs promote granulation tissue formation, accelerate wound contraction, and do so without eliciting adverse effects, highlighting their potential as safe and effective wound healing agents. [13]

Polymeric and Lipid-Based Nanoparticles in Clinical Applications

Polymeric nanoparticles loaded with antibiotics, curcumin, or growth factors have shown considerable potential in wound management.[17,23] In diabetic foot ulcer patients, topical application of chitosan-based nanoparticles enhanced epithelialization rates and reduced infection recurrence.These beneficial outcomes are attributed to the polymer’s intrinsic antimicrobial and regenerative properties, as well as its ability to maintain a moist and protective microenvironment conducive to healing. [45,46]

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) have likewise been evaluated in clinical and semi-clinical studies. For example, SLN-based curcumin gels were reported to improve wound contraction and collagen deposition in human subjects without causing irritation or toxicity. Similarly, NLC formulations encapsulating natural bioactives, such as aloe vera or resveratrol, accelerated tissue repair and enhanced elasticity in post-surgical wounds. [23,47]

Nanofibers and Bioactive Scaffolds

Electrospun nanofibers have recently gained attention as biomimetic wound dressings capable of delivering therapeutic agents in a controlled manner.[27,29] In animal models and early human studies, nanofiber mats loaded with antibiotics or growth-promoting peptides resulted in superior re-epithelialization compared with standard dressings. Bioengineered scaffolds incorporating nanomaterials and stem cells have further demonstrated synergistic effects on angiogenesis and tissue regenerate. In line with these findings, electrospun silver chloride-loaded PVA nanofibers have been shown to combine antibacterial efficiency with electroconductive properties, thereby enhancing cell proliferation and promoting faster wound closure.[48-50]

Smart and Responsive Nano platforms

Recent advances have led to the design of smart wound dressings that respond to pH, temperature, or bacterial metabolites. These responsive systems release drugs “on-demand,” reducing dosing frequency and maintaining therapeutic levels at the wound site. Some hydrogel-based nanoplatforms have even integrated biosensors capable of monitoring wound pH and temperature, providing real-time feedback for clinicians.[50-53]

Challenges with nanotechnology in wound healing

Despite remarkable progress in the application of nanotechnology for wound healing, several critical challenges continue to limit its full clinical translation.[54,55]

Safety and Toxicological Concerns

A major challenge is the comprehensive toxicological assessment of nanomaterials used in wound care.[39,40] While nanoscale features and surface properties enhance therapeutic performance, they may also cause unintended interactions with cells and tissues.[56] For example, metallic nanoparticles such as silver and zinc oxide can induce oxidative stress, trigger inflammation, or cause DNA damage at higher concentrations. Additionally, the long-term biodistribution, metabolic fate, and clearance pathways after topical or systemic exposure remain insufficiently characterized. As a result, regulatory agencies require extensive preclinical toxicology testing (in vitro and in vivo) to define safety margins and support clinical use.[57-60]

Manufacturing and Scalability Issues

Producing nanocarriers with uniform size, charge, and surface properties at industrial scale is difficult. Small changes in synthesis parameters (e.g., temperature, pH, solvent choice) can substantially alter performance, stability, reproducibility, and therefore complicate regulatory approval and commercial translation. This variability affects not only reproducibility but also regulatory approval and commercial viability. Developing cost-effective, scalable and reproducible synthesis methods that comply with Good Manufacturing Practice (GMP) standards is critical for translating laboratory findings into clinically wound care products.[61-64]

Regulatory and Ethical Challenges

Nanotechnology-based therapeutics occupy a gray area within existing pharmaceutical regulations. There is no universal framework for evaluating their quality, efficacy, and safety, which results in delays in approval and commercialization. In addition, ethical concerns arise regarding potential environmental accumulation of nanomaterials and long-term patient exposure. The lack of specific standards for characterization, labeling, and post-market surveillance further complicates regulatory pathways. For example, although electrospun silver chloride-loaded PVA nanofibers show promising antibacterial and biocompatible properties, approval would require detailed toxicological profiling, environmental risk assessment, and alignment with medical device and pharmaceutical regulations. Harmonized international guidelines and multidisciplinary evaluation strategies are therefore urgently needed clear regulatory definitions, transparent ethical frameworks, and rigorous clinical validation will help bridge laboratory innovation and safe clinical application. [63,65-68]

Biological Barriers and Variability

Biological responses to nanomaterials can vary with wound type, patient age, comorbidities, and skin physiology. In diabetic or immunocompromised patients, altered wound microenvironments may affect nanoparticle penetration, distribution, and treatment effectiveness. Moreover, the wound microbiome can influence nanoparticle behavior, antimicrobial activity, and healing outcomes. Future progress may rely on personalized nanomedicine approaches supported by biomarker-based diagnostics and patient-specific formulations. [69-71]

Future Perspectives

Future directions emphasize multifunctional, stimuli-responsive, and patient-specific systems. Smart nanoplatforms that integrate controlled drug delivery, biosensing, and real-time monitoring are emerging as next-generation wound dressings. Coupling these platforms with AI/ML could enable predictive and personalized wound care by interpreting healing patterns and optimizing treatment strategies. In parallel, biomimetic and bioresorbable nanomaterials—such as peptide-based or cell-derived nanoparticles—are gaining interest due to their improved safety and regenerative potential. Electrospun silver chloride-loaded PVA nanofibers reflect this trend by combining antibacterial, electroconductive, and biocompatible functions within a single scaffold, illustrating how multifunctional nanomaterials can support faster healing and better outcomes. [72-74]

Conclusion

Nanotechnology has emerged as a highly promising frontier in wound management by providing innovative materials and delivery systems that address the limitations of conventional therapies. Through precise control over particle size, surface functionalization, and drug release kinetics, nanomaterials can modulate inflammation, accelerate angiogenesis, and enhance tissue regeneration.The selection of an optimal nanostructure for wound healing is strictly context-dependent, as the therapeutic efficacy of a nanomaterial is intrinsically linked to the specific characteristics of the wound, such as its etiology (e.g., diabetic, burn, or acute), depth, and microbial load. While liposomal systems offer superior stability and penetration for labile bioactive molecules, and metallic nanoparticles provide potent, targeted antimicrobial action, electrospun nanofibers emerge as the most versatile and comprehensive platform. By effectively mimicking the natural extracellular matrix (ECM), nanofibers can integrate multiple functionalities—such as structural scaffolding, controlled drug release, and enhanced angiogenesis—into a single system. Therefore, the future of advanced wound care lies in the development of hybrid, stimuli-responsive nanostructures that can be tailored to the unique physiological requirements of different wound types, ensuring personalized and highly efficient regenerative outcomes.

In conclusion, the synergistic convergence of nanotechnology, regenerative medicine, and bioengineering represents a transformative direction in modern wound care. With continued interdisciplinary collaboration and robust clinical validation, regulatory alignment, nanotechnology-based interventions are expected to transition from experimental prototypes to clinically approved therapeutic standards in the near future. [75-78]

Contribution:

Conceptualization: Maryam Hassan, Solmaz Ghaffari
Data curation: Solmaz Ghaffari, Maryam Hassan
Investigation: Solmaz Ghaffari
Project administration: Solmaz Ghaffari, Maryam Hassan
Supervision: Solmaz Ghaffari

Acknowledgment

The authors gratefully acknowledge the contributions of colleagues and research teams whose efforts have advanced the fields of wound healing and nanotechnology. Special appreciation is extended to the investigators whose work has been cited throughout this review, and to the editorial board of *Advanced Pharmaceutical Bulletin* for their dedication to promoting high-quality scientific research in pharmaceutical sciences. Also authors would like to acknowledge the English polishing and scientific writing edition of the manuscript by Prof. Shirzad Azarmi.

References:

1. Dhivya S, Padma VV, Santhini E. Wound dressings-a review. *BioMedicine*. 2015;5(4):22-28. doi:10.7603/s40681-015-0022-9

2. Boateng JS, Matthews KH, Stevens HN, Eccleston GM. Wound healing dressings and drug delivery systems: a review. *J Pharm Sci*. 2008;97(8):2892-2923. doi:10.1002/jps.21210

3. Gurtner GC, Werner S, Barrandon Y, Longaker MT. Wound repair and regeneration. *Nature*. 2008;453(7193):314-321. doi:10.1038/nature07039

4. Gupta A, Singh AK, Shukla R, Verma R, Pandey A, Mishra N, et al. Nanotechnology-based approaches for wound healing: a review. *J Drug Deliv Sci Technol*. 2020;60:102017. doi:10.1016/j.jddst.2020.102017

5. Liang Y, Zhao X, Hu T, Han Y, Guo B. Smart hydrogels for wound care. *Adv Drug Deliv Rev*. 2022;188:114457. doi:10.1016/j.addr.2022.114457

6. Augustine R, Hasan A, Patan NK, Dalvi YB, Varghese R, Antony A, et al. Emerging applications of nanotechnology in wound care: trends and prospects. *J Mater Chem B*. 2020;8(29):6511-6527. doi:10.1039/D0TB01058D

7. Raghuwanshi N, Dandekar P, Jain R, Kale V, Patil UK, Sharma M, et al. Metal nanoparticles in wound healing: new era of therapeutic interventions. *Pharmaceutics.* 2022;14(6):1123. doi:10.3390/pharmaceutics14061123

8. Monteiro N, Martins A, Reis RL, Neves NM. Wound healing using nanotechnology: recent advances and future perspectives. *Nanomedicine*. 2019;14(7):997-1015. doi:10.2217/nnm-2018-0370

9. Atiyeh BS, Dibo SA, Hayek SN. Wound cleansing, topical antiseptics and wound healing. *Int Wound J*. 2009;6(6):420-430. doi:10.1111/j.1742-481X.2009.00639.x

10. Rigo C, Ferroni L, Tocco I, Roman M, Munivrana I, Gardin C, et al. Active silver nanoparticles for wound healing. *Int J Mol Sci*. 2013;14(3):4817-4840. doi:10.3390/ijms14034817

11. Nethi SK, Das S, Patra CR, Mukherjee S. Recent advances in nanomaterials for wound healing and tissue regeneration. *Adv Funct Mater*. 2023;33(7):2210451. doi:10.1002/adfm.202210451

12. Tian J, Wong KK, Ho CM, Lok CN, Yu WY, Che CM, et al. Topical delivery of silver nanoparticles promotes wound healing through modulation of inflammation. *Appl Microbiol Biotechnol*. 2014;98(2):900-913. doi:10.1007/s00253-013-5395-0

13. Singh R, Shedbalkar UU, Wadhwani SA, Chopade BA. Gold nanoparticles: an emerging therapeutic agent in wound healing applications. *Front Bioeng Biotechnol.* 2018;6:47. doi:10.3389/fbioe.2018.00047

14. Paladini F, Pollini M. Antimicrobial silver nanoparticles for wound healing application: progress and future trends. *Appl Sci*. 2019;9(4):779. doi:10.3390/app9040779

15. Diniz FR, Maia RC, Rannier L, Carreira A, Andrade L, dos Santos CB, et al. Silver nanoparticles-comprising dressings: anti-infection and healing effects. *Int J Nanomedicine*. 2020;15:1239-1260. doi:10.2147/IJN.S233189

16. Sirelkhatim A, Mahmud S, Seeni A, Kaus NHM, Ann LC, Bakhori SKM, et al. Review on zinc oxide nanoparticles: antibacterial activity and toxicity mechanism. *Nano-Micro Lett*. 2015;7(3):219-242. doi:10.1007/s40820-015-0040-x

17. Mishra B, Sahu K, Mishra V, Ghosh G. Nanotechnology-based antimicrobial formulations: clinical perspectives. *Ther Adv Infect Dis*. 2021;8:20499361211041928. doi:10.1177/20499361211041928

18. Kaur P, Singh K, Gupta R, Kaur H, Bansal R, Kumar N. Polymeric nanoparticles in wound healing: recent advances and future directions. *Int J Polym Mater Polym Biomater*. 2022;71(18):1429-1445. doi:10.1080/00914037.2020.1851785

19. Hariharan S, Bhattacharya SS, Kumar M, Chatterjee K. Advances in polymeric nanoparticle systems for wound healing applications. *Polymers (Basel).* 2021;13(12):1950. doi:10.3390/polym13121950

20. Luo Z, Li J, Chen Y, Sun L, Lin J, Wang C, et al. Sustained release of antibiotics from polymeric nanoparticles: a review. *J Mater Chem B*. 2020;8(9):1846-1856. doi:10.1039/C9TB02344G

21. Jain A, Thakur K, Sharma G, Kush P, Jain UK. Nanostructured lipid carriers for topical drug delivery. *J Control Release*. 2016;239:169-185. doi:10.1016/j.jconrel.2016.08.003

22. Huang C, Soenen SJ, van Gulck E, Vanham G, Rejman J, Van Calenbergh S, et al. Chitosan nanoparticles as drug carriers for wound healing. *Int J Nanomedicine*. 2019;14:10267-10277. doi:10.2147/IJN.S216691

23. Souto EB, Wissing SA, Barbosa CM, Mller RH. Development of a controlled release formulation based on SLN and NLC for topical clotrimazole delivery. *Drug Dev Ind Pharm*. 2004;30(8):889-894. doi:10.1081/DDC-200040641

24. Deng X, Ratnayake J, Ali A. Curcumin-Loaded Drug Delivery Systems for Acute and Chronic Wound Management: A Review. *Bioengineering (Basel).* 2025;12(8):860. doi:10.3390/bioengineering12080860.

25. Abazari M, Sharafi A, Hassan M, Moghimi HR, Andalib S, Ghaffari A. Electrospun silver chloride-loaded PVA nanofibers as a potential antibacterial and electroconductive scaffold for the management of wound infection and healing. *Polym. Bull*. 2024;81: 14921-14956. 10.1007/s00289-024-05405-8

26. de Souza ML, Dos Santos WM, de Sousa ALMD, de Albuquerque Wanderley Sales V, Nbrega FP, de Oliveira MVG, Rolim-Neto PJ. Lipid Nanoparticles as a Skin Wound Healing Drug Delivery System: Discoveries and Advances. *Curr Pharm Des*. 2020;26(36):4536-4550. doi:10.2174/1381612826666200417144530.

27. Chen S, Liu B, Carlson MA, Gombart AF, Reilly DA, Xie J. Recent advances in electrospun nanofibers for wound healing. *Nanomedicine* 2017; 12(11):1335-1352. doi:10.2217/nnm-2017-0017.

28. Chouhan D, Mandal BB. Silk biomaterials in wound healing and skin regeneration therapeutics: From bench to bedside. *Acta Biomater* 2020;103:24-51. doi:10.1016/j.actbio.2019.11.050.

29. Bacakova L, Zikmundova M, Pajorova J, Broz A, Filova E, Blanquer A, et al., Nanofibrous Scaffolds for Skin Tissue Engineering and Wound Healing Based on Synthetic Polymers \. *Applications of Nanobiotechnology* 2019. doi:10.5772/intechopen.88744

30. Arampatzis, A.S, Kontogiannopoulos, K.N, Theodoridis, K.et al.Electrospun wound dressings containing bioactive natural products: physico-chemical characterization and biological assessment. *Biomater Res*2021; 25. 10.1186/s40824-021-00223-9

31. Azari A, Golchin A, Mahmoodinia Maymand M, Mansouri F, Ardeshirylajimi A. Electrospun polycaprolactone nanofibers: current research and applications in biomedical application. *Adv Pharm Bull*. 2022;12(4): 658-672.doi:10.34172/apb.2022.070

32. Kandhola G, Park S, Lim JW, Chivers C, Song YH, Chung JH, Kim J, Kim JW. Nanomaterial-Based Scaffolds for Tissue Engineering Applications: A Review on Graphene, Carbon Nanotubes and Nanocellulose. *Tissue Eng Regen Med*. 2023; 20(3):411-433. doi:10.1007/s13770-023-00530-3.

33. Sangnim T, Puri V, Dheer D, Venkatesh DN, Huanbutta K, Sharma A. Nanomaterials in the Wound Healing Process: New Insights and Advancements. *Pharmaceutics*. 2024 Feb 21; 16(3):300. doi:10.3390/pharmaceutics16030300.

34. Nifontova G, Safaryan S, Khristidis, Y.et al.Advancing wound healing by hydrogel-based dressings loaded with cell-conditioned medium: a systematic review. *Stem Cell Res Ther*2024; 15: 10.1186/s13287-024-03976-x

35. Zahedi P, Rezaeian I, Ranaei-Siadat SO, Jafari SH, Supaphol P. A review on wound dressings with an emphasis on electrospun nanofibrous polymeric bandages. *Polym Adv Technol.* 2010;21(2):77-95. doi:10.1002/pat.1625

36. Augustine R, Hasan A, Patan NK, Dalvi YB, Varghese R, Antony A, et al. Cerium oxide nanoparticle-loaded gelatin methacryloyl hydrogel wound dressing promotes healing of full-thickness wounds. *Mater Sci Eng C Mater Biol Appl*. 2021;119:111588. doi:10.1016/j.msec.2020.111588

37. Liang Y, He J, Guo B. Functional hydrogels as wound dressing to enhance wound healing. *ACS Nano*. 2021;15(8):12687-12722. doi:10.1021/acsnano.1c04034

38. AL-Jbour ND, Beg M.D. Gimbun J, Alam AKMM. An Overview of Chitosan Nanofibers and their Applications in the Drug Delivery Process. *Curr Drug Deliv*. 2019;16 (4):272-294. doi:10.2174/1567201816666190123121425

39. Li A, Han Z, Li Z, Li J, Li X, Zhang Z. A PTHrP-2 loaded adhesive cellulose acetate nanofiber mat as wound dressing accelerates wound healing. *Mater*. 2021;212:110241. doi:10.1016/j.matdes.2021.110241.

40. Augustine R, Hasan A, Dalvi Y.B, Rehman SRU, Varghese R, Unni RN, et al., Growth factor loaded in situ photocrosslinkable poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/gelatin methacryloyl hybrid patch for diabetic wound healing. *Mater Sci. Eng* . 2021;118:111519. doi:10.1016/j.msec.2020.111519

41. Poon VKM, Burd A. In vitro cytotoxicity of silver: implication for clinical wound care. *Burns*. 2004;30(2):140-147. doi:10.1016/j.burns.2003.09.030

42. Baum CL, Arpey CJ. Normal cutaneous wound healing: clinical correlation with cellular and molecular events. *Dermatol Surg*. 2005;31(6):674-686. doi:10.1111/j.1524-4725.2005.31612

43. Aghamoosa M, Arbabi Bidgoli S, Ghaffari S, Sabokbar A, Harzandi N, Preclinical Evaluation of Silver-Curcumin Nano- gel : A complete assessment on a new topical antimicrobial product for burn, *J. Nanoanalysis*. 2020: 7(1): 62-72.

44. 97. Zhao X, Liang Y, Huang Y, He J, Guo B. Physical double-network hydrogel adhesives with rapid shape adaptability, fast self-healing, antioxidant and NIR/pH stimulus-responsiveness for multidrug-resistant bacterial infection and wound healing. *Adv Funct Mater*. 2020;30(17):1910748. doi:10.1002/adfm.201910748

45. Kamoun EA, Kenawy ERS, Chen X. A review on polymeric hydrogel membranes for wound dressing applications: PVA-based hydrogel dressings. *J Adv Res*. 2017;8(3):217-233. doi:10.1016/j.jare.2017.01.005

46. Wu C, Zhou Y, Xu H, Zhang Q, Li X, Yang G, et al. Sustained release of silver ions from chitosan-based hydrogel enhances antibacterial activity and wound healing. *Mater Sci Eng C Mater Biol Appl*. 2020;110:110716. doi:10.1016/j.msec.2020.110716

47. Ghaffari S, Alihosseini F, Rezayat Sorkhabadi SM, Arbabi Bidgoli S, Mousavi SE, Haghighat S, et al. Nanotechnology in Wound Healing; Semisolid Dosage Forms Containing Curcumin-Ampicillin Solid Lipid Nanoparticles, in -Vitro, Ex- Vivo and in -Vivo Characteristics. *Adv Pharm Bull*. 2018;8(3):395-400. doi:10.15171/apb.2018.046

48. Ghosh S, Kaushik R, Nagalakshmi K, et al. Nanotechnology in wound healing-a review. *Curr Drug Deliv*. 2020;17(8):653-670. doi:10.2174/1567201817666200316104601

49. Chhabra R, Nanda S, Tyagi VK. Nanotechnology-based smart wound dressings: recent trends and future perspectives. *Mater Today Chem.* 2022;23:100753. doi:10.1016/j.mtchem.2021.100753

50. Tavakoli S, Klar AS. Advanced hydrogels as wound dressings. *Biomolecules*. 2020;10(8):1169. doi:10.3390/biom10081169

51. Gaharwar AK, Peppas NA, Khademhosseini A. Nanocomposite hydrogels for biomedical applications. *Biotechnol Bioeng*. 2014;111(3):441-453. doi:10.1002/bit.25160

52. Boateng JS, Catanzano O. Advanced therapeutic dressings for effective wound healing-A review. *J Pharm Sci*. 2015;104(11):3653-3680. doi:10.1002/jps.24610

53. Annabi N, Tamayol A, Uquillas JA, Akbari M, Bertassoni LE, Cha C, et al. 25th anniversary article: Rational design and applications of hydrogels in regenerative medicine. *Adv Mater*. 2014;26(1):85-124. doi:10.1002/adma.201303233

54. Moura LI, Dias AM, Carvalho E, de Sousa HC. Recent advances on the development of wound dressings for diabetic foot ulcer treatment-a review. *Acta Biomater*. 2013;9(7):7093-7114. doi:10.1016/j.actbio.2013.03.033

55. Okshevsky M, Meyer RL. The role of extracellular DNA in the establishment, maintenance and perpetuation of bacterial biofilms. *Crit Rev Microbiol*. 2015;41(3):341-352. doi:10.3109/1040841X.2013.841639

56. Mehwish HM, Liu G, Rajoka MSR, Cai H, Zhong J, Song X. et al., Therapeutic potential of Moringa oleifera seed polysaccharide embedded silver nanoparticles in wound healing. *Int. J. Biol. Macromol*. 2021;184:144-158. doi:10.1016/j.ijbiomac

57. Ehsani P, Farahpour MR, Mohammadi M, Mahmazi S, Jafarirad S. Green fabrication of ZnO/magnetite-based nanocomposite-Using Salvia officinalis extract with antibacterial properties enhanced infected full-thickness wound. *Colloids Surf Physicochem Eng Asp*. 2021;628:127362. doi:10.1016/j.colsurfa.2021.127362

58. Negut I, Grumezescu V, Grumezescu AM. Treatment strategies for infected wounds. *Molecules.* 2018;23(9):2392. doi:10.3390/molecules23092392

59. Landn NX, Li D, Sthle M. Transition from inflammation to proliferation: a critical step during wound healing. *Cell Mol Life Sci*. 2016;73(20):3861-3885. doi:10.1007/s00018-016-2268-0

60. Wilkinson HN, Hardman MJ. Wound healing: cellular mechanisms and pathological outcomes. *Open Biol*. 2020;10(9):200223. doi:10.1098/rsob.200223

61. Martin P, Nunan R. Cellular and molecular mechanisms of repair in acute and chronic wound healing. *Br J Dermatol*. 2015;173(2):370-378. doi:10.1111/bjd.13954

62. Pastar I, Stojadinovic O, Yin NC, Ramirez H, Nusbaum AG, Sawaya A, et al. Epithelialization in wound healing: a comprehensive review. Adv Wound Care (New Rochelle). 2014;3(7):445-464. doi:10.1089/wound.2013.0473

63. Tracy LE, Minasian RA, Caterson EJ. Extracellular matrix and dermal fibroblast function in the healing wound. *Adv Wound Care*. 2016;5(3):119-136. doi:10.1089/wound.2014.0561

64. Gurtner GC, Dauskardt RH, Wong VW, Bhatt KA, Wu K, Vial IN, et al. Improving cutaneous scar formation by controlling the mechanical environment: large animal and phase I studies. *Ann Surg.* 2011;254(2):217-225. doi:10.1097/SLA.0b013e318226a763

65. Eming SA, Martin P, Tomic-Canic M. Wound repair and regeneration: mechanisms, signaling, and translation. *Sci Transl Med*. 2014;6(265):265sr6. doi:10.1126/scitranslmed.3009337

66. Farahani RM, Kloth LC. The hypothesis of "biophysical matrix contraction": wound contraction revisited. *Wound Repair Regen*. 2008;16(3):347-352. doi:10.1111/j.1524-475X.2008.00382.x

67. Wang PH, Huang BS, Horng HC, Yeh CC, Chen YJ. Wound healing. *J Chin Med Assoc*. 2018;81(2):94-101. doi:10.1016/j.jcma.2017.11.002

68. Enoch S, Leaper DJ. Basic science of wound healing. *Surgery* (Oxford). 2008;26(2):31-37. doi:10.1016/j.mpsur.2007.11.005

69. Burdu?el AC, Gherasim O, Grumezescu AM, Mogoant? L, Ficai A, Andronescu E. Biomedical applications of silver nanoparticles: an up-to-date overview. *Nanomaterials* (Basel). 2018;8(9):681. doi:10.3390/nano8090681

70. Tang J, Chen Q, Xu L, Zhang S, Feng L, Cheng L, et al. Thermosensitive chitosan-based hydrogel loaded with curcumin for wound healing. *Biomaterials*. 2014;35(15):4565-4577. doi:10.1016/j.biomaterials.2014.02.003

71. Choudhury H, Pandey M, Lim YQ, Low CY, Lee C, Marilyn TCM, et al. Silver nanoparticles: advanced and promising technology in diabetic wound therapy. *Mater Sci Eng C Mater Biol Appl.* 2020;112:110925. doi:10.1016/j.msec.2020.110925

72. Bielefeld KA, Amini-Nik S, Alman BA. Cutaneous wound healing: recruiting developmental pathways for regeneration. *Cell Mol Life Sci*. 2013;70(12):2059-2081. doi:10.1007/s00018-012-1152-9

73. Gurtner GC, Werner S, Barrandon Y, Longaker MT. Wound repair and regeneration. *Nature.* 2008;453(7193):314-321. doi:10.1038/nature07039

74. Gushiken LFS, Beserra FP, Bastos JK, Jackson CJ, Pellizzon CH. Cutaneous wound healing: an update from physiopathology to current therapies. *Life* (Basel). 2021;11(7):665. doi:10.3390/life11070665

75. Gaoo J, Nie X, Wei Z, Yao J, Xie L. Nanomaterials for wound healing: current status and future prespectives. *Pharmaceutics*. 2023:15(3):885. doi:103390/pharmaceutics 15030885.

76. Fhimirad S, Sanjarian F. Nanoparticle-based approaches for wound healing: A review of current trends and future directions. *Heliyon*. 2024;10(5):e25917. doi:10.1016/j.heliyon.2024.e25917

77. Alhadi L, Al-Aali KA,Almilaibary A, Mirghani ME. Ahmed RA. Mimicking ECM: Recentadvancements in utilizing nanoparticles, nanofibers, and nanosheets for wound healing. *Bioengineering*. 2024;11(6):568. doi:10.3390/bioengineering11060568.

78. Hamdan S, Pastar I, Drakulich S, Dikici E, Tomic-Canic M, Deo S, et al. Nanobiomaterials in chronic wound healing: advances and future challenges. *Front Bioeng Biotechnol*. 2021;9:718372. doi:10.3389/fbioe.2021.718372