Advances in Wound Healing and Tissue Regeneration: Biomaterials, Regenerative Strategies, and Translational Challenges

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***Abstract*—Wound healing and tissue regeneration are biological processes that are highly regulated and intricate in nature and are necessary to restore tissue integrity after injury, surgery, or chronic disease. Although there have been considerable improvements in clinical care, impaired wound healing is still a leading health burden in the world, especially in the elderly and those with comorbidities of metabolic, vascular and psychosocial conditions. In the last twenty years, a lot of ground has been covered in the field of wound biology as well as the development of the regenerative approaches, including the use of biomaterials, stem cells, growth factors, nanotechnology, and sophisticated drug delivery systems. This narrative review is a synthesis of modern developments in wound healing and tissue regeneration focusing on the biological processes, new technologies, translational, and systemic factors that predetermine the results in wound healing and tissue regeneration. The review also discusses the importance of digital health, precision medicine, and psychosocial factors on the development of regenerative care. Altogether, the accumulated data have contributed to a change in values of passive wound coverage towards biologically active, patient-centered, and data-driven regenerative therapies.**

***Index Terms*—Wound healing, Tissue regeneration, Biomaterials, Nanotechnology, Regenerative medicine, Chronic wounds**

I. Introduction

Wound healing is a basic biological process that is characterized by the co-ordinated cellular, molecular and extracellular events that aim at repairing the structure and functionality of tissues. An acute wound usually takes a sequential process of hemostasis, inflammation, proliferation and remodelling. Nevertheless, it might be interrupted by ischemia, infection, inflammation, metabolic dysfunction, or psychosocial stress and results in chronic non-healing wounds (Bello & Phillips, 2000; Tottali et al., 2020). Chronic wounds such as diabetic wounds, pressure injuries, and venous leg wounds are increasingly becoming a major global health issue with enormous clinical, economic, and social implications (Oliveira et al., 2022; Ghosh et al., 2024). The traditional wound care models that put emphasis on moisture and infection control have shown a weak potential in managing challenging cases, and regenerative approaches have been developed that actively regulate the wound microenvironment (Ho et al., 2017; Fani et al., 2024). More recent developments in tissue engineering, biomaterials, nanotechnology and regenerative medicine have radically redefined care paradigms of wounds. They are designed to eliminate wounds as well as to regenerate useful tissue structure by means of biological stimulation and directed regeneration to achieve this (Vig et al., 2017; Jorgensen et al., 2023). Meanwhile, the impact of systemic health conditions, psychosocial well-being, and social determinants on wound healing outcomes are noted in the context of the impact of holistic and patient-centered approaches (Ashifa, 2021; Ashifa, 2022).

II. Biological Foundations of Wound healing and Regeneration

The healing of wounds is a complex process that is controlled by the cooperation of keratinocytes, fibroblasts, endothelial cells, immune cells, and extracellular materials. The migration of cells, angiogenesis, collagen deposition and tissue remodelling are coordinated by cytokines, chemokines and growth factors (Singer & Boyce, 2017; Han, 2023). Persistent inflammation, oxidative stress and impaired angiogenesis, as well as dysregulated immune responses are often linked with impaired healing. Nutritional condition and immunometabolic homeostasis are essential factors since micronutritional and protein deficiency and immune mediators retard tissue healing (Chow and Barbul, 2014). There is also emerging evidence to show that prolonged psychological stress and mental illnesses may have a negative impact on wound healing by modifying neuroendocrine and inflammatory pathways (Ranganathan et al., 2024; Elkin et al., 2025). The results of these studies are important to underline that wound healing does not only occur as a local biological process but a systemic process, which is affected by physical, psychological, and social factors.

III. Approaches to Bioengineering Biomaterials and Tissues

The use of tissue engineering has become part of contemporary wound healing studies. The biomaterial scaffolds can offer structural functionality, cellular behavioral control, and bioactive molecule delivery to the wound (Ho et al., 2017; Vig et al., 2017). Natural polymers, including collagen, chitosan, alginate and hyaluronic acid, have shown good biocompatibility and bioactivity whereas synthetic polymers have tunable degradation and mechanical characteristics (Tottali et al., 2020). To achieve the optimal strength, porosity, and biological signaling, advanced composite scaffolds are achieved by incorporating these materials. Skin analogs and fabricated tissue models have demonstrated specific excellence in burn treatment and complicated wounds, enhancing epithelialization and scars (Singer and Boyce, 2017; Jorgensen et al., 2023). Nevertheless, there are still difficulties in vascularization, immune integration, and affordable scaling.

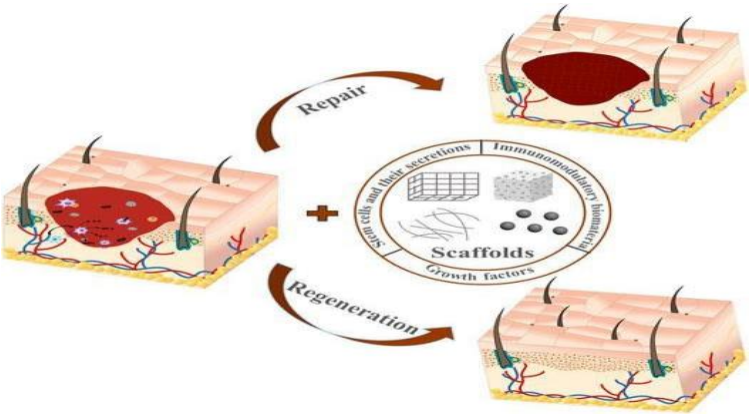
IV. Nanotechnology and Stimuli-Responsive Systems

Nanotechnology has become a revolutionary instrument in treatment and regeneration of wounds and tissues. Nanomaterials help to preserve drug stability, increase the penetration, and deliver therapeutic agents directly in the microenvironment of the wound under control (Bhattacharya et al., 2019; Banerjee et al., 2025). Nanomaterials that respond to stimuli, such as pH, temperature, enzymes, oxidative stress, and others, enable site-specific delivery of therapeutics and on-demand delivery of therapeutics to treat diseases and improve efficacy by reducing systemic exposure (Bellarmin et al., 2025; Rathna & Kulandhaivel, 2024). These systems suit chronic wounds with abnormal pH and never-healing inflammation. Antimicrobial, angiogenic, and anti-inflammatory effects have been demonstrated by nanofibrous dressings, metallic nanoparticles, and bioactive nanocarriers to promote improved healing, which are supported by preclinical and early clinical studies (Kolimi et al., 2022; Ghosh et al., 2024).

V. Stem Cells, Growth Factors and Regenerative Signaling

One of the major strategies in regenerative wound therapy is growth factor delivery. Platelet-derived growth factor, vascular endothelial growth factor and fibroblast growth factor are some of the agents that stimulate angiogenesis and tissue development but must be delivered in controlled quantities so that they are not harmful (Koria, 2012). Mesenchymal stem cells and induced pluripotent stem cells have a regenerative potential with paracrine signaling and immunomodulation, which is provided by stem cell-based therapies (Freedman et al., 2023; Fani et al., 2024). Although preliminary indications are encouraging, safety issues, regulatory complexity and cost render use in a broader clinical environment problematic. Bioactives and phytochemical-polymer conjugates made of medicinal plants are also complementary to each other, especially under resource-limited conditions, providing an anti-inflammatory and antioxidant effect that facilitates healing (Das et al., 2016).

Figure 1. Biological phases of Wound Healing



An example Wound healing as a biological cascade and highly coordinated dynamic process entails; hemostasis, inflammation, proliferation and tissue remodelling. Clot formation immediately after injury stabilizes the wound environment triggering inflammatory signaling. Inflammatory phase brings in immune cells which eliminate debris and control activities of cytokines. In the proliferative stage, the movement of fibroblasts, angiogenesis, and the deposition of the extracellular matrix enhance the formation of granulation tissue, and epithelialization restores the surface integrity. Lastly, at the remodelling stage, collagen fibres are rearranged and tensile strength is enhanced, which seals the functional tissue restoration. Current regenerative approaches interfere in these stages in order to maximise the healing dynamics. The scaffolds are biomaterials that offer mechanical stability and control cellular processes, the angiogenesis and cellular proliferation is triggered by the growth factors, and the regeneration of tissues is promoted by the paracrine signalling mediated by stem cells. Localised and controlled therapeutic delivery in the wound microenvironment is also made possible by nanotechnology-based systems of delivery. These combined biological and technology solutions transform passive wound care coverage to biologically active regeneration to enhance the quality of healing and slow down the chronic wound progression.

VI. Chronic Wounds, Aging and Health Disparities

Older adults and people with underlying health and socioeconomic vulnerabilities have a disproportionate number of chronic wounds. Research points out correlations between delayed healing and burden of chronic disease, work stress, unhealthy eating habits and access to care (Ashifa, 2019; Ashifa and Ramya, 2019). Studies of the aged population and marginalized groups indicate that social isolation, mental health issues, and the lack of self-care ability play an important role in the wound prognosis (Ashifa, 2022; Rasi and Ashifa, 2019). The results serve as the reminder of the need to consider the combination of rehabilitation, patient education, and community-based support in models of wound care (Vettriselvan et al., 2026).

VII. Digital Health, Precision Medicine and Data-Driven Wound Care

Digital health technologies are becoming more and more a part of wound management. Machine learning applications, image-based wound analysis, and remote monitoring allow the detection and prevention of complications at the early stage and the design of a specific treatment (Catherine et al., 2025; Shanthi et al., 2025). Precision medicine strategies use patient-specific information such as genetics, comorbidities, and psychosocial profiles to customize regenerative therapies and forecast the healing patterns (Devi et al., 2025). The efficiency of the healthcare system and continuity of care are the other tools it supports. Nevertheless, the ethical issues connected with data privacy, algorithmic bias, and fair access are the subject of serious concern, especially in low-resource contexts (Vettriselvan and Anto, 2018).

VIII. Translational and Regulatory issues

Although there is fast innovation, there are hurdles to the translation of regenerative wound therapies into standard clinical practices associated with manufacturing complexity, regulatory approval, and reimbursement. Both broader adoption and safety data (long-term and outcome) should be standardized (Han, 2023; Freedman et al., 2023). This will involve interdisciplinary work of clinicians, engineers, experts in public health and policymakers so that technological advances can be translated into patient benefit and not isolated laboratory success.

IX. Conclusion

The innovation of wound healing and tissue regeneration has changed the practice of wound care as passive management of wounds toward biologically active, regenerative, and patient-focused care. New biomaterials, nanotechnology, growth factor delivery, and digital health present new opportunities to enhance the outcome in acute and chronic wounds. But to be successful, translation involves the incorporation of biological science with the psychosocial consciousness, health equity, and implementing data. It will be built upon interdisciplinary research, future development based on ethical innovation, and future solutions based on scalability that integrate both biological complexity and real-world healthcare challenges.

References

[1] Ashifa, K. M. (2019). Developmental initiatives for persons with disabilities: Appraisal on village-based rehabilitation of Amar Seva Sangam. Indian Journal of Public Health Research & Development, 10(12), 1257–1261.

[2] Ashifa, K. M. (2020). Effect of substance abuse on physical health of adolescents. European Journal of Molecular & Clinical Medicine, 7(2), 3155–3160.

[3] Ashifa, K. M. (2020). Effect of sustenance abuse on physical health of adolescents. European Journal of Molecular & Clinical Medicine, 7(2).

[4] Ashifa, K. M. (2020). Physical health hazards of schizophrenia patients. Systematic Reviews in Pharmacy, 11(12), 1848–1850.

[5] Ashifa, K. M. (2021). Analysis on the determinants of health status among tribal communities. Journal of Cardiovascular Disease Research, 12(3), 531–534.

[6] Ashifa, K. M. (2021). Health status of primitive tribal women in India. Journal of Cardiovascular Disease Research, 12(5), 772.

[7] Ashifa, K. M. (2022). A situation analysis of the social well-being of elderly during the COVID-19 pandemic. International Journal of Health Sciences, 6(3), 10156–10163.

[8] Ashifa, K. M., & Ramya, P. (2019). Health afflictions and quality of work life among women working in fireworks industry. International Journal of Engineering and Advanced Technology, 8(6S3), 1723–1725.

[9] Banerjee, D., Vydiam, K., Vangala, V., & Mukherjee, S. (2025). Advancement of nanomaterials-and biomaterials-based technologies for wound healing and tissue regenerative applications. ACS Applied Bio Materials, 8(3), 1877-1899.

[10] Bellarmin, M., Nandhini, J., Karthikeyan, E., Mahalakshmi, D., & Karthik, K. K. (2025). A comprehensive review on stimuli-responsive nanomaterials: advancements in wound healing and tissue regeneration. Biomedical Materials & Devices, 1-25.

[11] Bello, Y. M., & Phillips, T. J. (2000). Recent advances in wound healing. Jama, 283(6), 716-718.

[12] Bhattacharya, D., Ghosh, B., & Mukhopadhyay, M. (2019). Development of nanotechnology for advancement and application in wound healing: a review. IET nanobiotechnology, 13(8), 778-785.

[13] Catherine, S., Gupta, N., Gopi, E., & Swadhi, R. (2025). Enhancing Patient Engagement and Outcomes Through Digital Transformation: Machine Learning in Medical Marketing. In Impact of Digital Transformation on Business Growth and Performance (pp. 285-312). IGI Global.

[14] Chhabra, P., & Bhati, K. (2021). Bionanomaterials: Advancements in wound healing and tissue regeneration. In Recent Advances in Wound Healing. InTechOpen.

[15] Chow, O., & Barbul, A. (2014). Immunonutrition: role in wound healing and tissue regeneration. Advances in wound care, 3(1), 46-53.

[16] Das, U., Behera, S. S., Singh, S., Rizvi, S. I., & Singh, A. K. (2016). Progress in the development and applicability of potential medicinal plant extract-conjugated polymeric constructs for wound healing and tissue regeneration. Phytotherapy research, 30(12), 1895-1904.

[17] Devi, M., Manokaran, D., Sehgal, R. K., Shariff, S. A., & Vettriselvan, R. (2025). Precision Medicine, Personalized Treatment, and Network-Driven Innovations: Transforming Healthcare With AI. In AI for Large Scale Communication Networks (pp. 303-322). IGI Global.

[18] Elkin, N., Mohammed, A. K., Kılınçel, Ş., Soydan, A. M., Tanrıver, S. Ç., Çelik, Ş., & Ranganathan, M. (2025). Mental health literacy and happiness among university students: A social work perspective to promoting well-being. Frontiers in Psychiatry, 16, 1541316.

[19] Fani, N., Moradi, M., Zavari, R., Parvizpour, F., Soltani, A., Arabpour, Z., & Jafarian, A. (2024). Current advances in wound healing and regenerative medicine. Current stem cell research & therapy, 19(3), 277-291.

[20] Freedman, B. R., Hwang, C., Talbot, S., Hibler, B., Matoori, S., & Mooney, D. J. (2023). Breakthrough treatments for accelerated wound healing. Science Advances, 9(20), eade7007.

[21] Gayathri, R. K., Vettriselvan, R., Rajesh, D., Balakrishnan, R., Kumar, R., & Kavitha, J. (2025). Striking a Balance: Mental Health Challenges and Work-Life Integration among Women Faculty in Indian B-Schools. Texila International Journal of Public Health, 13(2).

[22] Gayathri, R. K., Vettriselvan, R., Rajesh, D., Balakrishnan, R., Kumar, R., & Kavitha, J. (2025). Strategic Role of Human Resource Management in Enhancing Occupational Health and Safety Practices in Business Schools in India. Texila International Journal of Public Health, 13(2).

[23] Ghosh, R., Singh, P., Pandit, A. H., Tariq, U., Bhunia, B. K., & Kumar, A. (2024). Emerging technological advancement for chronic wound treatment and their role in accelerating wound healing. ACS Applied Bio Materials, 7(11), 7101-7132.

[24] Han, S. K. (2023). Innovations and advances in wound healing. Springer Nature.

[25] Ho, J., Walsh, C., Yue, D., Dardik, A., & Cheema, U. (2017). Current advancements and strategies in tissue engineering for wound healing: a comprehensive review. Advances in wound care, 6(6), 191-209.

[26] Jenifer, R. D., Vettriselvan, R., Saxena, D., Velmurugan, P. R., & Balakrishnan, A. (2025). Green Marketing in Healthcare Advertising: A Global Perspective. In AI Impacts on Branded Entertainment and Advertising (pp. 303-326). IGI Global.

[27] Jorgensen, A. M., Mahajan, N., Atala, A., & Murphy, S. V. (2023). Advances in skin tissue engineering and regenerative medicine. Journal of Burn Care & Research, 44(Supplement_1), S33-S41.

[28] Kolimi, P., Narala, S., Nyavanandi, D., Youssef, A. A. A., & Dudhipala, N. (2022). Innovative treatment strategies to accelerate wound healing: trajectory and recent advancements. Cells, 11(15), 2439.

[29] Koria, P. (2012). Delivery of growth factors for tissue regeneration and wound healing. BioDrugs, 26(3), 163-175.

[30] Oliveira, A., Simões, S., Ascenso, A., & Reis, C. P. (2022). Therapeutic advances in wound healing. Journal of Dermatological Treatment, 33(1), 2-22.

[31] Ranganathan, M., Jacob, A., Ashifa, K. M., Kumar, G. J., Anthony, M., Vijay, M., Kumari, R. B. (2024). An investigation of the effects of chronic stress on attention in parents of children with neurodevelopmental disorders. Universal Journal of Public Health, 12(1), 37–50.

[32] Rasi, R. A., & Ashifa, K. M. (2019). Role of community-based programmes for active ageing: Elders self-help group in Kerala. Indian Journal of Public Health Research & Development, 10(12).

[33] Rathna, R. P., & Kulandhaivel, M. (2024). Advancements in wound healing: integrating biomolecules, drug delivery carriers, and targeted therapeutics for enhanced tissue repair. Archives of Microbiology, 206(4), 199.

[34] Shanthi, H. J., Gokulakrishnan, A., Sharma, S., Deepika, R., & Swadhi, R. (2025). Leveraging Artificial Intelligence for Enhancing Urban Health: Applications, Challenges, and Innovations. In Nexus of AI, Climatology, and Urbanism for Smart Cities (pp. 275-306). IGI Global.

[35] Singer, A. J., & Boyce, S. T. (2017). Burn wound healing and tissue engineering. Journal of Burn Care & Research, 38(3), e605-e613.

[36] Swadhi, R. (2025). Innovative strategies for widespread adoption in a climate-smart future: Scaling up agroforestry. In Agroforestry for a Climate-Smart Future (pp. 473-496). IGI Global.

[37] Swadhi, R., Gayathri, K., Suresh, N. V., Catherine, S., & Velmurugan, P. R. (2025). Leveraging Machine Learning for Enhanced Patient Engagement and Outcomes: Revolutionizing Healthcare Marketing. In Impact of Digital Transformation on Business Growth and Performance (pp. 313-340). IGI Global.

[38] Swadhi, R., Velmurugan, P. R., Gayathri, K., & Catherine, S. (2026). Evolving critical themes in advanced human resource management: Navigating change in the modern workplace. In Critical aspects in advanced human resource management (pp. 75-102). IGI Global.

[39] Tottoli, E. M., Dorati, R., Genta, I., Chiesa, E., Pisani, S., & Conti, B. (2020). Skin wound healing process and new emerging technologies for skin wound care and regeneration. Pharmaceutics, 12(8), 735.

[40] Venice, A., Swadhi, R., Gayathri, K., Chandra, P., & Sajana, K. P. (2026). Rehabilitation Robotics and Adaptive Motion Planning for Patient-Centric Care. In Intelligent Motion Control for Human-Centered Systems (pp. 51-76). IGI Global.

[41] Vettriselvan, R. (2025). Harnessing innovation and digital marketing in the era of industry 5.0: resilient healthcare SMEs. In The Future of Small Business in Industry 5.0 (pp. 163-186). IGI Global.

[42] Vettriselvan, R., & Anto, M. R. (2018). Pathetic health status and working condition of Zambian women. Indian Journal of Public Health Research & Development, 9(9), 259-264.

[43] Vettriselvan, R., & Rajan FSA, A. J. (2019). Occupational Health Issues Faced by Women in Spinners. Indian Journal of Public Health Research & Development, 10(1).

[44] Vettriselvan, R., Deepan, A., Jaiswani, G., Balakrishnan, A., & Sakthivel, R. (2025). Health Consequences of Early Marriage: Examining Morbidity and Long-Term Wellbeing. In Social, Political, and Health Implications of Early Marriage (pp. 189-212). IGI Global.

[45] Vettriselvan, R., Ramya, R., Selvalakshmi, V., Jyothi, P., & Velmurugan, P. R. (2026). Empowering Patients through Knowledge: Educational Strategies in Rehabilitation. In Holistic Approaches to Health Recovery (pp. 263-290). IGI Global.

[46] Vettriselvan, R., Velmurugan, P. R., Varshney, K. R., EP, J., & Deepika, R. (2025). Health Impacts of Smartphone and Internet Addictions Across Age Groups: Physical and Mental Health Across Generations. In Impacts of Digital Technologies Across Generations (pp. 187-210). IGI Global.

[47] Vig, K., Chaudhari, A., Tripathi, S., Dixit, S., Sahu, R., Pillai, S., ... & Singh, S. R. (2017). Advances in skin regeneration using tissue engineering. International journal of molecular sciences, 18(4), 789.

[48] Vijayalakshmi, M., Subramani, A. K., Vettriselvan, R., Catherin, T. C., & Deepika, R. (2025). Sustainability and Responsibility in the Digital Era: Leveraging Green Marketing in Healthcare. In Digital Citizenship and Building a Responsible Online Presence (pp. 285-306). IGI Global.

[49] Vijayalakshmi, M., Subramani, A. K., Vettriselvan, R., Velmurugan, P. R., & Hasine, J. (2025). Strategic Collaborations in Medical Innovation and AI-Driven Globalization: Advancing Healthcare Startups. In Navigating Strategic Partnerships for Sustainable Startup Growth (pp. 85-110). IGI Global.

[50] Zahoor, H., Mustafa, N., Ashifa, K. M., Safaei, M., & El Gamil, R. (2025). Unlocking resilience: Emotional intelligence and self-leadership shape stress perception among health students. International Journal of Innovation and Learning, 38(4), 395–419.