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Hydrogel Dressings in Wound Management: Advances, Applications, and Future Directions

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ABSTRACT

Introduction: Hydrogel dressings have emerged as pivotal tools in wound management, offering a moist environment conducive to tissue repair and demonstrating biocompatibility across various wound types. This literature review examines the historical evolution, properties, applications, recent advances, challenges, and future directions of hydrogel dressings.

Methodology: A comprehensive search of databases including PubMed, Web of Science, and Scopus was conducted using search terms such as "hydrogel dressings," "wound management," and "smart hydrogels." Selection criteria involved inclusion of articles on the properties, classifications, applications, and recent innovations of hydrogel dressings, with exclusion criteria focusing on non-peer-reviewed articles and non-English language publications.

Results: Historical milestones encompass the development of cross-linking techniques, integration of natural polymers, and recent advancements including smart hydrogels, 3D printing, and drug delivery systems. Challenges such as cost, availability, and potential complications exist. Unresolved questions persist regarding long-term effects and controversies surrounding their comparative efficacy in wound management.

Discussion: The findings highlight the need for future research in multifunctional dressings, sensor-integrated smart dressings, and biodegradable hydrogels to optimize wound healing. Moreover, exploration of their environmental impact and prolonged effects in chronic wounds is imperative. Addressing gaps in the literature is crucial to refine protocols and personalize wound care strategies.

Conclusion: Hydrogel dressings demonstrate significant promise in wound management. Further research is essential to address challenges, resolve controversies, and advance the efficacy and sustainability of these dressings for improved wound care.

ARTICLE DETAILS

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INTRODUCTION

In contemporary wound care and plastic surgery, the management of wounds represents a critical area of focus, demanding comprehensive approaches to facilitate optimal healing, reduce complications, and improve patient outcomes. Wounds, whether acute or chronic, pose a significant challenge in clinical practice, requiring tailored interventions to expedite the healing process and mitigate potential risks such as infection, impaired healing, and discomfort. As a result, the quest for advanced wound management strategies has gained momentum within the medical community.

Among the multifaceted solutions, hydrogel dressings have emerged as a promising and versatile tool in the armamentarium of wound care. Hydrogel dressings possess unique characteristics that make them highly suitable for various wound types. Their high moisture content, ability to maintain a moist environment, and biocompatibility contribute significantly to their effectiveness in promoting wound healing.[1-3]

In the context of plastic surgery and wound care, understanding the role of hydrogel dressings in promoting optimal healing and mitigating complications is crucial. The purpose of this literature review is to offer a comprehensive analysis and synthesis of the existing body of knowledge pertaining to hydrogel dressings in wound management and to underscore the importance of these dressings in clinical practice, emphasizing their relevance as a valuable adjunct in the armamentarium of wound management strategies. With a particular emphasis on recent advances, applications, and future directions, this review aims to provide an insightful overview for clinicians, researchers, and healthcare professionals involved in wound care. By delving into the properties, classifications, historical development, and recent innovations in hydrogel dressings, this review endeavors to highlight their significance in the wound care landscape, explores their diverse applications in both acute and chronic wounds, shedding light on their clinical utility and efficacy in different scenarios. Moreover, it will delve into the recent advances in hydrogel technology, such as smart hydrogels, drug delivery systems, and 3D-printed dressings, elucidating the potential for enhanced wound healing and patient care. By also identifying the gaps and future directions in this domain, it seeks to stimulate further research and innovation, aiming to advance the field and ultimately improve patient care and outcomes.

METHODOLOGY

In conducting this literature review, we adopted a meticulous and structured approach to gather a comprehensive array of scholarly articles and studies. The search process encompassed databases renowned for their extensive coverage in the biomedical and scientific domains, including PubMed, Web of Science, Scopus, and relevant peer-reviewed journals specific to wound care, biomaterials, and surgery. A combination of key search terms and Boolean operators such as "hydrogel dressings," "wound management," "biocompatible polymers," "smart hydrogels," and "3D printing in wound care" were employed to maximize the breadth and depth of the search. Articles published within the last decade were primarily considered to ensure relevance to contemporary advancements in hydrogel technology and wound healing practices.

The inclusion criteria were defined to encompass studies focusing on the applications, advancements, and efficacy of hydrogel dressings in wound management. Specifically, articles exploring the properties of hydrogel dressings, their classifications, and recent technological innovations were selected. Studies that examined their clinical applications in various wound types, including but not limited to acute and chronic wounds, burns, and surgical incisions, were prioritized. English-language articles in peer-reviewed journals and those featuring empirical research, systematic reviews, meta-analyses, and clinical trials were given precedence. Exclusion criteria involved articles that were not peer-reviewed, duplicates, non-English language publications, and those not directly relevant to the scope of hydrogel dressings in wound care. This stringent criterion was established to ensure the quality and relevance of the gathered literature for a comprehensive and focused review.

HISTORICAL DEVELOPMENT OF HYDROGEL DRESSINGS

Hydrogels are three-dimensional networks consisting of chemically or physically cross-linked hydrophilic polymers.[1] Hydrogels are insoluble polymers that expand in water and are available in sheet, amorphous gel or sheet hydrogel-impregnated dressings. Hydrogels provide a moist environment for cell migration and absorb some exudate.

Hydrogel dressings are semi-occlusive and composed of complex hydrophyllic polymers with a high (90%) water content. As the name implies, hydrogels can absorb and retain large amounts of water, and are designed to hydrate wounds, or to re-hydrate eschar or to aid in autolytic debridement.[2] The insoluble hydrophilic structures absorb polar wound exudates and allow oxygen diffusion at the wound bed to accelerate healing.[3] They are used to treat a variety of wounds, including burns, pressure ulcers, and diabetic ulcers. Hydrogel dressings have been around for several decades, and their development has been driven by the need for more effective wound care treatments.

The term "biomaterials" was first used in 1967 during the first International Biomaterials Symposium at Clemson University, South Carolina.[4] Synthetic polymers have been used as biomaterials since the early 1900s, when Bakelite was used as a dental filling material.[5] However, it was not until the latter half of the 20th century that synthetic polymers began to be used extensively as biomaterials.[4,5] The use of synthetic polymers as biomaterials has grown rapidly since then, and they are now widely used in a variety of biomedical applications such as wound dressing, drug delivery and tissue engineering.[6,7] The historical evolution of hydrogel dressings in wound management marks a compelling trajectory, originating in the mid-20th century with the synthesis and exploration of hydrophilic polymer-based materials. In the early phases, pioneering research introduced hydrogels primarily composed of hydrophilic polymers like polyvinyl alcohol (PVA) and polyethylene glycol (PEG), marking a pivotal milestone in the development of wound dressings.[8] These early hydrogel dressings exhibited exceptional moisture-retaining capabilities, serving as effective agents in wound healing by creating a moist environment conducive to tissue repair.

Researchers encountered initial challenges in balancing the mechanical integrity of hydrogel dressings with their moisture-retaining properties. The early formulations often lacked the requisite strength necessary for practical application. Overcoming this hurdle involved a progressive shift towards creating hybrid hydrogel dressings, incorporating reinforcing agents such as nanofibers or other polymers to enhance their mechanical strength while retaining the desired hydrophilic properties. This period of innovation saw a marked improvement in the durability and applicability of hydrogel dressings in diverse wound types.[9-

11

Key milestones and breakthroughs in hydrogel dressing technology emerged with the advent of cross-linking techniques, which enhanced the structural integrity of hydrogels while maintaining their hydrophilic nature. The introduction of cross-linking agents and methodologies significantly expanded the range of applications and enhanced the durability of hydrogel dressings, allowing for tailored solutions in wound care. Moreover, the utilization of natural polymers, like alginate and chitosan, alongside synthetic counterparts, broadened the spectrum of hydrogel dressings, addressing specific wound healing requirements and introducing more bioactive components conducive to tissue regeneration.[13-15] This era marked a significant leap in the customization and efficacy of hydrogel dressings, cementing their position as a valuable tool in modern wound management practices.

PROPERTIES AND CLASSIFICATION OF HYDROGEL DRESSINGS

Hydrogel dressings exhibit fundamental properties that underpin their effectiveness in wound management, primarily characterized by their high water content and exceptional biocompatibility. These dressings, composed of cross-linked hydrophilic polymers, retain moisture at the wound site, ensuring an optimal environment for healing (see **Image 1**). Their high-water content mimics the physiological conditions necessary for cell migration, proliferation, and the synthesis of extracellular matrix components, promoting tissue repair.[1-3] Additionally, the biocompatibility of hydrogel dressings minimizes the risk of adverse reactions,[16] making them suitable for a broad spectrum of wounds, even in sensitive or fragile tissue environments.

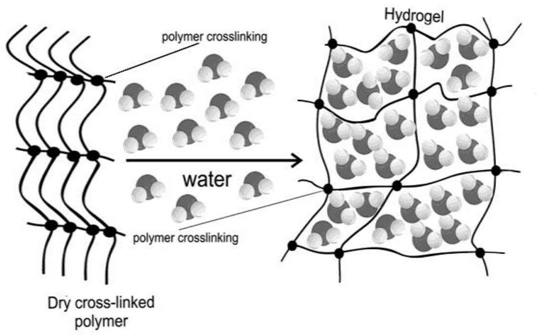

Image 1. Fundamental properties of hydrogels

The classification of hydrogel dressings is based on their composition and functionality. Regarding composition, hydrogel dressings are classified into synthetic and natural types. Synthetic hydrogels are typically engineered from polymers like polyethylene glycol (PEG, see **Image 2**) or polyvinyl alcohol (PVA), offering a high degree of customization in terms of their physical and chemical properties.[17] On the other hand, natural hydrogels are derived from biomaterials such as alginate (from brown algae), chitosan (from chitin shells of shrimp and other crustaceans), or collagen, leveraging their inherent biocompatibility and potential bioactive properties for wound healing applications.[13-15]

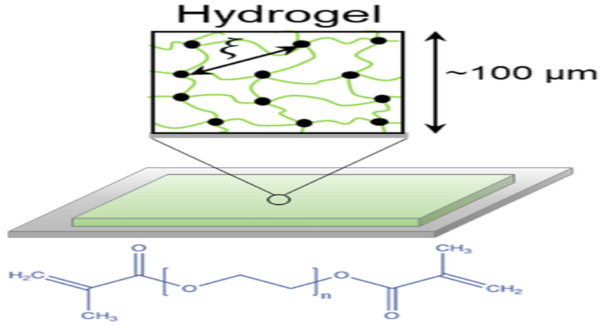

Image 2. Polyethylene glycol hydrogel, one of the synthetic hydrogels

Functionality-wise, hydrogel dressings encompass a diverse array, including smart hydrogels and drug delivery systems. Smart hydrogels are hydrogels with various chemically and structurally responsive moieties and exhibit excellent stimuli-responsive characteristics when reacting and changing their properties in response to different environmental conditions such as pH, temperature, light, electric field, magnetic field as well as biological and chemical stimuli or the presence of particular molecules.[17] These dressings adapt to the wound environment, providing tailored therapeutic responses for optimized wound healing. Similarly, hydrogel dressings utilized as drug delivery systems offer a platform for controlled and sustained release of therapeutic agents at the wound site, ensuring a targeted and efficient treatment approach.[18] These classifications and functionalities play a pivotal role in tailoring wound care to meet specific patient needs and diverse wound types, signifying a significant advancement in the field of wound management.

APPLICATIONS OF HYDROGELS DRESSING IN WOUND MANAGEMENT

With the rapid developments of material science, there are numerous highly efficient wound dressings being developed. Conventional bandages and gauzes, although they are still effective in controlling hemorrhage, have various limitations due to their lack of biodegradability, their susceptibility to infection and their unsuitability for irregularly shaped wounds. Conventional dressings have only a single function, making them less effective for wound treatment.

Hydrogel is a 3D network that is composed of hydrophilic polymers, which can absorb and swell in water. Polysaccharide-based hydrogels are biocompatible, biodegradable, and nontoxic. In contrast, synthetic polymer-based hydrogels are more easily modified and have better mechanical strength. Current hydrogel wound dressings are antibacterial, biodegradable, responsive, and injectable as well. When used as a wound dressing, hydrogel not only forms a physical barrier and removes excess exudate but also provides a moisture environment that promotes the wound healing process. Additionally, hydrogel can perfectly fill irregularly shaped wounds and may deal with deep bleeding efficiently.[1,3]

Hydrogel dressings have showcased versatile applications in wound care, proving to be effective solutions in the treatment of both acute and chronic wounds.[19,20] In acute wound management, hydrogel dressings have been extensively employed in various scenarios, such as post-surgical incisions, abrasions, and burns.[21-23] Their ability to create a moist wound environment promotes faster epithelialization and wound closure, reducing the risk of scarring and infection. Furthermore, in chronic wounds like diabetic ulcers and pressure injuries, hydrogel dressings have demonstrated remarkable efficacy in maintaining a conducive environment for healing, aiding in the removal of necrotic tissue, and facilitating granulation tissue formation.[24,25]

Numerous clinical cases and studies underscore the efficacy of hydrogel dressings across different wound types. For instance, a randomized controlled trial evaluating the use of hydrogel dressings in managing superficial and partial-thickness burns highlighted faster healing rates compared to traditional dressing of silver sulphadiazine and gauze.[26] Additionally, in chronic wounds like diabetic foot ulcers, longitudinal studies observed significant improvements in wound size reduction and healing rates with the application of hydrogel dressings.[24] A review paper by Güiza-Argüello and colleagues showed hydrogel wound dressings were effective for diabetic foot ulcer treatment. The study further revealed hydrogels have also been extensively studied for different types of biomedical applications, including drug delivery and tissue engineering applications.[24] Furthermore, in pressure injuries, the use of hydrogel dressings demonstrated better outcomes in terms of reducing pain, controlling exudate, and promoting tissue regeneration compared to other dressings.[25]

Another designs of hydrogel dressings are to prevent bacterial infection,[27-29] retain moisture, promote optimum adhesion to tissues,[30-32] and satisfy the basic requirements of biocompatibility. They can also be designed to respond to changes in the microenvironment at the wound bed. These clinical examples and studies underscore the versatility and effectiveness of hydrogel dressings across a spectrum of wounds, solidifying their role as a valuable tool in wound management protocols. Recent advances in hydrogel dressing technology have brought forth innovative methodologies, such as smart hydrogels,[17] 3D printing,[33-35] and drug delivery systems,[18] marking significant strides in the evolution of wound care. Smart hydrogels represent a groundbreaking development by exhibiting responsiveness to various stimuli, including pH, temperature, or specific biomarkers present in the wound environment. These intelligent dressings modify their properties dynamically, promoting tailored wound healing responses, as demonstrated in in vitro studies where pH-sensitive hydrogels adjusted their swelling and drug release profiles based on the pH levels, showcasing their potential for personalized wound care interventions.[17]

RECENT ADVANCES IN HYDROGEL DRESSINGS

The integration of **3D printing technology** in hydrogel dressing fabrication has revolutionized wound management by allowing the creation of customizable dressings that conform to the specific contours of a wound. Studies exploring 3D-printed hydrogel dressings have emphasized their superior adaptability and efficacy in irregular wound shapes or sizes, facilitating better wound coverage and contact with the wound bed, thereby promoting improved healing outcomes. Moreover, the incorporation of bioactive molecules within these 3D-printed dressings, such as growth factors or antimicrobial agents, has shown promising results in accelerating tissue regeneration and combating infection, as evidenced in animal model studies showcasing enhanced wound closure rates.[33-35]

The utilization of hydrogel dressings as drug delivery systems has demonstrated a paradigm shift in wound care. Research studies have highlighted the potential benefits of these systems in providing sustained and controlled release of therapeutic agents directly to the wound site. By encapsulating growth factors, antimicrobial agents, or anti-inflammatory compounds, these drug-loaded hydrogel dressings have displayed enhanced wound healing properties, as observed in clinical trials where accelerated wound closure and reduced infection rates were noted. The tailored release kinetics offered by these drug delivery systems offer a promising avenue for precise and efficient wound management strategies, laying the foundation for a more personalized and targeted approach to healing chronic and acute wounds.[18]

CHALLENGES AND LIMITATIONS IN HYDROGEL DRESSING APPLICATION

Hydrogel dressings, while presenting substantial promise in wound care, confront several challenges and limitations that impact their widespread adoption in clinical practice. Relatively higher cost and availability, especially in suburban/rural areas with poor healthcare economics, stand as significant concerns, where certain advanced formulations or customized hydrogel dressings may entail higher expenses, limiting their accessibility to some healthcare settings. The cost-effectiveness of these dressings, especially in long-term wound management scenarios, remains a point of consideration in healthcare economics. Additionally, the availability of specialized types of hydrogel dressings in certain regions or healthcare facilities might be limited, hindering their universal application and necessitating a focus on broader accessibility and affordability.

Moreover, potential complications associated with hydrogel dressings, such as maceration of periwound skin due to excessive moisture[36] or allergic reactions[37] in sensitive individuals, demand careful consideration. Hydrogels absorb their own volume in exudate and in the process of hydration may cause some maceration to the periwound margins. This may be a particular problem in patients with ischemic foot lesions.[36] Carvalho and colleagues reported two leg ulcer patients hypersensitized for different commercially available hydrogels.[37] Ensuring proper application and monitoring for adverse reactions are essential to prevent such complications, underscoring the need for clinician expertise and patient-specific assessments. Additionally, while the biocompatible nature of hydrogel dressings is generally acknowledged, unresolved questions persist regarding their long-term effects, especially in chronic wound management. These inquiries revolve around the optimal duration of use, potential interactions with wound exudate, and their impact on wound microenvironment, necessitating further research to ascertain their prolonged safety and efficacy profiles.

Furthermore, controversies exist regarding the comparative efficacy of various hydrogel dressing formulations in managing specific wound types. This engenders discussions about the most appropriate dressing choice for certain wound scenarios. For example, most hydrogel dressings still have poor mechanical strength[38] and therefore it limits their applications in the treatment of massive bleeding, such as arterial ruptures, as hydrogels cannot provide effective protection for the wound to prevent secondary damage. Consequently, the researchers should focus future researches on developing hydrogel dressings with high mechanical strength so these dressings could help with fatal severe hemorrhage.

Deciphering the ideal selection criteria for different wounds remains an ongoing debate among wound care specialists, highlighting the necessity for robust comparative studies and consensus-building within the medical community to guide effective decision-making in selecting the most suitable dressing for different clinical contexts. Resolving these challenges and controversies is pivotal for optimizing the application and effectiveness of hydrogel dressings in wound management.

FUTURE DIRECTIONS AND RESEARCH GAPS

Future research in the domain of hydrogel dressings and wound management should explore advanced functionalities and novel applications to address existing gaps and further optimize patient outcomes. Targeted investigation into the development of multifunctional hydrogel dressings capable of simultaneous wound healing promotion, infection control, and personalized drug delivery is a promising area. Studies focused on integrating sensors into hydrogel matrices to monitor wound status, providing real-time feedback to healthcare providers, represent an innovative avenue. Such 'smart' dressings could dynamically respond to the wound microenvironment, alerting clinicians to changes and optimizing therapeutic interventions, thus paving the way for personalized and responsive wound care solutions.

Additionally, delving into the realm of bioactive hydrogels, specifically the incorporation of growth factors, stem cells, or extracellular matrix components, is critical for enhancing tissue regeneration and promoting accelerated wound healing. Exploring the mechanisms behind their interactions within the wound bed and their influence on cellular responses represents a crucial frontier for future research. Furthermore, investigating the environmental impact and biodegradability of hydrogel dressings is imperative for sustainability. Advancements in creating biodegradable hydrogels that maintain efficacy while minimizing their ecological footprint should be a focus to address the growing concerns about environmental impact associated with medical waste.

Identifying gaps in the current literature is essential for steering research towards unexplored domains. One such gap lies in understanding the long-term effects of sustained use of hydrogel dressings in chronic wound management. Robust longitudinal studies examining the prolonged application and impact of these dressings on wound healing, scar formation, and overall tissue regeneration are lacking. Additionally, while much attention has been given to acute wound applications, there remains a dearth of comparative studies evaluating the efficacy of hydrogel dressings in various chronic wound types such as venous ulcers, diabetic foot ulcers, or pressure injuries. Addressing these gaps will provide a comprehensive understanding of the extended benefits and limitations of hydrogel dressings in diverse wound scenarios, paving the way for refined protocols and tailored wound care strategies.

CONCLUSION

In summary, the exploration of hydrogel dressings in wound management underscores their significance as a multifaceted tool in modern healthcare. These dressings, characterized by their high water content and biocompatibility, foster a conducive wound environment, playing a pivotal role in expediting tissue repair across acute and chronic wounds. The historical evolution of hydrogel dressings reveals a journey marked by pivotal milestones such as cross-linking techniques and the integration of natural polymers, revolutionizing their efficacy and applicability. Recent advances have seen the emergence of smart hydrogels, 3D printing, and drug delivery systems, offering personalized and responsive solutions, presenting a paradigm shift in wound care.

However, challenges such as cost, availability, and potential complications still persist, urging a focus on the economics and accessibility of these dressings. The unresolved questions around their long-term effects and controversies regarding their comparative efficacy necessitate in-depth research and consensus-building. Looking ahead, future research must explore multifunctional dressings, sensor-integrated smart dressings, and bioactive hydrogels to further optimize wound healing. Understanding the environmental impact and developing biodegradable options are essential to address sustainability concerns. Addressing gaps in the literature, particularly regarding the prolonged use of hydrogel dressings in chronic wounds and the comparative efficacy among different wound types, is crucial. These endeavors will pave the way for refined protocols and personalized wound care strategies, enhancing the effectiveness and ecological footprint of hydrogel dressings in the realm of wound management.

REFERENCES

I. Peppas NA, Hilt JZ, Khademhosseini A, Langer R. Hydrogels in biology and medicine: From molecular principles to bionanotechnology. Advanced Materials. 2006;18(11):1345–60. doi:10.1002/adma.200501612.

II. Weller C. Interactive Dressings and Their Role in Moist Wound Management. In: Rajendran S. Advanced Textiles for Wound Care. Boca Raton, Florida: CRC Press; 2009. p. 97–113.

III. Tavakoli S, Klar AS. Advanced hydrogels as wound dressings. Biomolecules. 2020 Aug 11;10(8):1169. doi: 10.3390/biom10081169.

IV. Nicholson JW. Synthetic Materials in Medicine. In: The Chemistry of Medical and Dental Materials. Cambridge, UK: Royal Society of Chemistry; 2020. p. 1–23.

V. Biobaku-Mutingwende B. Introduction to Biomaterials. In: Sharma NR, Subburaj K, Sandhu K, Sharma V (eds). Applications of 3D printing in Biomedical Engineering. Singapore: Springer; 2021. p. 1-19. doi: 10.1007/978-981-33-6888-0_1

VI. Nasiri SS, Ahmadi Z, Afshar-Taromi F. Synthesis Biomaterials in Biomedical Applications. In: Jana S, Jana S (eds). Functional Biomaterials. Singapore: Springer, Singapore; 2022. p. 285–317. doi: 10.1007/978-981-16-7152-4_11

VII. Kalirajan C, Dukle A, Nathanael AJ, Oh T-H, Manivasagam G. A critical review on polymeric biomaterials for biomedical applications. Polymers. 2021;13(17):3015. doi: 10.3390/polym13173015

VIII. Kaith BS, Singh A, Sharma AK, Dhiraj S. Hydrogels: synthesis, classification, properties and Potential applications—A brief review. J Polym Environ. 2021;29:3827–41. doi: 10.1007/s10924-021-02184-5

IX. Aderibigbe BA. Hybrid-Based Wound Dressings: Combination of Synthetic and Biopolymers. Polymers (Basel). 2022 Sep 12;14(18):3806. doi: 10.3390/polym14183806.

X. Alavi M, Nokhodchi A. Antimicrobial and wound healing activities of electrospun nanofibers based on functionalized carbohydrates and proteins. Cellulose. 2022;29:1331–47. doi: 10.1007/s10570-021-04412-6

XI. Vargas-Molinero HY, Serrano-Medina A, Palomino-Vizcaino K, López-Maldonado EA, Villarreal-Gómez LJ, Pérez-González GL, Cornejo-Bravo JM. Hybrid systems of nanofibers and polymeric nanoparticles for biological application and delivery systems. Micromachines (Basel). 2023 Jan 14;14(1):208. doi: 10.3390/mi14010208.

XII. Yuan N, Shao K, Huang S, Chen C. Chitosan, alginate, hyaluronic acid and other novel multifunctional hydrogel dressings for wound healing: A review. Int J Biol Macromol. 2023 Jun 15;240:124321. doi: 10.1016/j.ijbiomac.2023.124321.

XIII. Elangwe CN, Morozkina SN, Olekhnovich RO, Krasichkov A, Polyakova VO, Uspenskaya MV. A Review on chitosan and cellulose hydrogels for wound dressings. Polymers (Basel). 2022 Nov 27;14(23):5163. doi: 10.3390/polym14235163.

XIV. Cui R, Zhang L, Ou R, Xu Y, Xu L, Zhan XY, Li D. Polysaccharide-based hydrogels for wound dressing: Design considerations and clinical applications. Front Bioeng Biotechnol. 2022 Mar 7;10:845735. doi: 10.3389/fbioe.2022.845735.

XV. Dilruba Öznur KG, Ayşe Pınar TD. Statistical evaluation of biocompatibility and biodegradability of chitosan/gelatin hydrogels for wound-dressing applications. Polym. Bull. 2023 Apr. doi: 10.1007/s00289-023-04776-8.

XVI. Sikdar P, Uddin MdM, Dip TM, Islam S, Hoque MdS, Dhar AK, et al. Recent advances in the synthesis of smart hydrogels. Materials Advances. 2021;2(14):4532–73. doi:10.1039/d1ma00193k.

XVII. Jacob S, Nair AB, Shah J, Sreeharsha N, Gupta S, Shinu P. Emerging role of hydrogels in drug delivery systems, tissue engineering and wound management. Pharmaceutics. 2021 Mar 8;13(3):357. doi: 10.3390/pharmaceutics13030357.

XVIII. Qi L, Zhang C, Wang B, Yin J, Yan S. Progress in Hydrogels for Skin Wound Repair. Macromol Biosci. 2022 Jul;22(7):e2100475. doi: 10.1002/mabi.202100475.

XIX. Alven S, Aderibigbe BA. Chitosan and Cellulose-Based Hydrogels for Wound Management. Int J Mol Sci. 2020 Dec 18;21(24):9656. doi: 10.3390/ijms21249656.

XX. Fang Y, Li H, Chen J, Xiong Y, Li X, Zhou J, Li S, Wang S, Sun B. Highly Water-Absorptive and Antibacterial Hydrogel Dressings for Rapid Postoperative Detumescence. Front Bioeng Biotechnol. 2022 May 13;10:845345. doi: 10.3389/fbioe.2022.845345.

XXI. Beam JW. Occlusive dressings and the healing of standardized abrasions. J Athl Train. 2008 Oct-Dec;43(6):600-7. doi: 10.4085/1062-6050-43.6.600.

XXII. Surowiecka A, Strużyna J, Winiarska A, Korzeniowski T. Hydrogels in burn wound management-A review. Gels. 2022 Feb 15;8(2):122.

doi: 10.3390/gels8020122.

XXIII. Güiza-Argüello VR, Solarte-David VA, Pinzón-Mora AV, Ávila-Quiroga JE, Becerra-Bayona SM. Current Advances in the Development of Hydrogel-Based Wound Dressings for Diabetic Foot Ulcer Treatment. Polymers (Basel). 2022 Jul 6;14(14):2764. doi: 10.3390/polym14142764.

XXIV. Medical Advisory Secretariat. Management of chronic pressure ulcers: an evidence-based analysis. Ont Health Technol Assess Ser. 2009;9(3):1-203.

XXV. Wasiak J, Cleland H, Campbell F, Spinks A. Dressings for superficial and partial thickness burns. Cochrane Database Syst Rev. 2013 Mar 28;2013(3):CD002106. doi: 10.1002/14651858.CD002106.pub4.

XXVI. Maleki A, He J, Bochani S, Nosrati V, Shahbazi MA, Guo B. Multifunctional photoactive hydrogels for wound healing acceleration. ACS Nano. 2021 Dec 28;15(12):18895-18930. doi: 10.1021/acsnano.1c08334.

XXVII. Huang K, Liu W, Wei W, Zhao Y, Zhuang P, Wang X, Wang Y, Hu Y, Dai H. Photothermal hydrogel encapsulating intelligently bacteria-capturing Bio-MOF for infectious wound healing. ACS Nano. 2022 Nov 22;16(11):19491-19508. doi: 10.1021/acsnano.2c09593.

XXVIII. Yang K, Zhou X, Li Z, Wang Z, Luo Y, Deng L, He D. Ultrastretchable, self-healable, and tissue-adhesive hydrogel dressings involving nanoscale tannic acid/ferric ion complexes for combating bacterial infection and promoting wound healing. ACS Appl Mater Interfaces. 2022 Sep 28;14(38):43010-43025. doi: 10.1021/acsami.2c13283.

XXIX. Zheng Y, Baidya A, Annabi N. Molecular design of an ultra-strong tissue adhesive hydrogel with tunable multifunctionality. Bioact Mater. 2023 Jul 17;29:214-229. doi: 10.1016/j.bioactmat.2023.06.007.

XXX. Ren H, Zhang Z, Cheng X, Zou Z, Chen X, He C. Injectable, self-healing hydrogel adhesives with firm tissue adhesion and on-demand biodegradation for sutureless wound closure. Sci Adv. 2023 Aug 18;9(33):eadh4327. doi: 10.1126/sciadv.adh4327.

XXXI. Ouyang C, Yu H, Wang L, Ni Z, Liu X, Shen D, Yang J, Shi K, Wang H. Tough adhesion enhancing strategies for injectable hydrogel adhesives in biomedical applications. Adv Colloid Interface Sci. 2023 Sep;319:102982. doi: 10.1016/j.cis.2023.102982.

XXXII. Abdollahiyan P, Oroojalian F, Mokhtarzadeh A, de la Guardia M. Hydrogel-Based 3D Bioprinting for Bone and Cartilage Tissue Engineering. Biotechnol J. 2020 Dec;15(12):e2000095. doi: 10.1002/biot.202000095.

XXXIII. Bom S, Ribeiro R, Ribeiro HM, Santos C, Marto J. On the progress of hydrogel-based 3D printing: Correlating rheological properties with printing behaviour. Int J Pharm. 2022 Mar 5;615:121506. doi: 10.1016/j.ijpharm.2022.121506.

XXXIV. Nie R, Sun Y, Lv H, Lu M, Huangfu H, Li Y, Zhang Y, Wang D, Wang L, Zhou Y. 3D printing of MXene composite hydrogel scaffolds for photothermal antibacterial activity and bone regeneration in infected bone defect models. Nanoscale. 2022 Jun 9;14(22):8112-8129. doi: 10.1039/d2nr02176e.

XXXV. Knowles EA, Jackson NJ. Care of the diabetic foot. J Wound Care. 1997 May;6(5):227-30. doi: 10.12968/jowc.1997.6.5.227.

XXXVI. Carvalho R, Maio P, Amaro C, Santos R, Cardoso J. Hydrogel allergic contact dermatitis and imidazolidinyl urea/diazolidinyl urea. Cutan Ocul Toxicol. 2011 Dec;30(4):331-2. doi: 10.3109/15569527.2011.562270.

XXXVII. Hydrogel promotes wound healing better than traditional bandages, gauzes [Internet]. American Institute of Physics; 2021 [cited 2023 Oct 1]. Available from: https://www.sciencedaily.com/releases/2021/02/210216114953.htm