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Magnetically Responsive Biomaterials for Non-Invasive Drug Delivery and Enhanced Wound Repair

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ABSTRACT

Magnetically responsive biomaterials offer a novel and adaptable platform for non-invasive drug delivery and enhanced wound healing. These materials use outside magnetic stimuli to control when and where therapeutic agents are released, addressing problems with existing wound therapies, such as lack of targeting and inefficient activation of drugs. These biomaterials can be integrated with magnetic nanoparticles into hydrogels, nanofibrous scaffolds, or composite structures for remote activation and directional guidance that can modulate cellular behaviors, alter local microenvironments, and promote tissue regeneration. Furthermore, magnetic actuation enables controlled mechanical stimulation and drug release, helping to facilitate the crucial stages of wound healing like inflammation regulation, angiogenesis and tissue remodeling. Magnetically responsive biomaterials are promising candidates for advanced wound dressings, able to adapt to wound conditions and to improve healing outcomes without invasive procedures, due to their high biocompatibility, the possibility to repeat magnetic stimulation and the possibility to be multifunctional. Recent advances in smart wound management systems are targeted to combine the magnetic responsiveness and stimuli-sensitive drug release to improve the healing efficiency and the comfort of the patient, leading to clinical applications.

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1. Introduction

The Rapid development of biomaterials science has opened a new era of advanced therapies using the unique properties of magnetic responsive biomaterials for medical applications [1]. These innovations are anticipated to revolutionize conventional treatment methods, especially in non-invasive drug delivery and wound healing, by offering controllable, targeted and on-demand therapeutic options [2, 3]. The embedding of magnetic nanoparticles or components into biocompatible matrices has enabled researchers to create platforms that can be remotely activated or guided, allowing for an unprecedented spatial and temporal control in the delivery of therapy [1]. Modern medicine aims at maximizing therapeutic effectiveness, while minimizing patient discomfort and systemic side effects. Non-invasive drug delivery is a major goal of contemporary medicine [4].

Effective wound repair, especially for chronic and non-healing wounds, continues to be a significant burden for health care systems around the world [5-7]. Conventional wound care systems are often not able to provide the active and controlled support during the complex multispectral healing process [8]. Magnetically responsive biocomposites represent a major advance in this field, able to modulate cellular responses and stimulate tissue regeneration thru localized mechanical and biochemical stimulation. Using these materials can improve patient outcomes, reduce the risk of infections, and speed up the healing process due to the remote-control and bioactivity features of such technologies [9]. Technologies in this area are based on concepts of remote control, biocompatibility, and multifunctionality [10]. Magnetic nanostructured materials can be developed and tailored to operate in different strength and gradient fields [11]. The technology used to create dynamic biointerfaces enhances effectiveness and safety and minimizes the number of invasive procedures [12]. Moreover, the versatility of these materials to be used as drug carriers, wound dressings or scaffolds for tissue regeneration suggests their broad therapeutical possibilities [13]. This review presents the recent

advances in the field of magnetically responsive biomaterials with an emphasis on their use for non-invasive drug delivery and improved wound healing. It describes their preparation techniques, working principles, merits and current challenges. The review will outline recent findings and indicate future perspectives to exploit the potential of magnetic biomaterials for patient-centered non-invasive therapies.

2. Fundamentals of Magnetic Responsiveness

Magnetic responsiveness is a phenomenon of response of the substance or system according to the action of an external magnetic field [14]. This phenomenon is an essential concept in materials science, physics and engineering and has important applications in many fields including smart materials, bioengineering and device making [15].

2.1. Types of Magnetic Materials

Magnetic biomaterials represent a high-end technology in the field of tailored drug administration and trauma treatment that allows precise regulation of therapy and cell reactions. Ziv-Polat et al. [16] developed thrombin-conjugated maghemite ($\gamma\text{-Fe}_2\text{O}_3$) nanoparticles for wound healing and compared their efficacy with free thrombin in rat incisional wounds. The results showed that bound thrombin significantly enhanced skin tensile strength and promoted more advanced wound healing compared with free thrombin and the control group. Zhang et al. [17] have synthesized a magnetically responsive scaffold of HA/ Fe_3O_4 and proved that magnetic field-mediated deformations and water convections improved the release of the compound. As can be seen from Fig.1, the release rate of methylene blue was higher and more uniform under magnetic treatment compared to its absence. Table 1 provides an overview of the types of materials, their properties, and their applications in medicine.

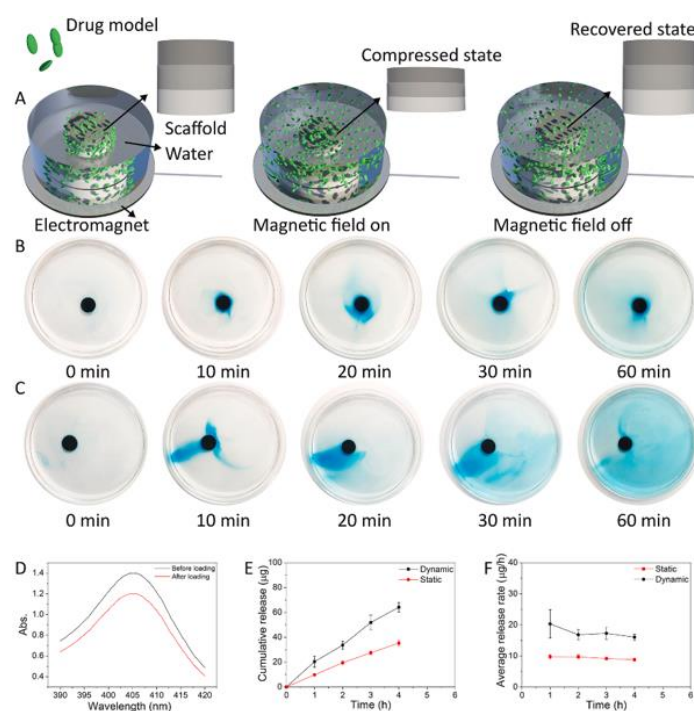


Fig. 1. (A) Schematic illustration of the on-demand drug delivery procedure from HA/Fe₃O₄ sandwich structures by alternating magnetic fields. (B, C) Photographs showing the release of methylene blue dye from HA/Fe₃O₄ sandwich structures without (B) and with (C) magnetic excitation within 1 h. (D) Absorption spectrum of Hb solution before and after immersing the HA/Fe₃O₄ sandwich structure in the solution. (E) Drug release curves for 4 h of Hb from HA/Fe₃O₄ sandwich structures with magnetic excitation, and without magnetic excitation. (F) Hb release rates of HA/Fe₃O₄ sandwich structures with and without magnetic excitation at different time points in 4 h [17].

Table 1
Types of Magnetic Materials.

Type of Magnetically Responsive Biomaterial	Composition/Mechanism.	Advantages for Drug Delivery and Wound Repair	Features/Challenges	References
Magnetic Nanoparticles (MNPs, e.g., SPIONs)	Superparamagnetic iron oxide (Fe ₃ O ₄ , γ -Fe ₂ O ₃); may be coated with polymers, proteins, or lipids	Enable remote, spatiotemporal control of drug release; targeted drug delivery guided by external magnetic fields.	Low toxicity and high stability; can be functionalized with drugs or ligands; potential for aggregation if not properly coated.	[18, 19]
Magnetically Responsive Hydrogels	Hydrogels incorporating magnetic nanoparticles	Controlled drug release through magnetic stimulation; improve cellular responses and tissue regeneration.	Soft, biocompatible, and responsive to external fields for on-demand therapy; features tunable porosity and release profiles.	[9, 20, 21]
Magnetic Nanofibers and Nanofibrous Mats	Electrospun fibers (e.g., gelatin, silk fibroin) embedded with MNPs.	Mimic the extracellular matrix; enable precise drug release and support cell growth.	High surface area, oxygen permeability; customizable for different drugs; mechanically flexible	[17, 22]
Magnetically Responsive Biocomposites	Hybrid matrices: polymers, ceramics, or proteins combined with magnetic particles.	Facilitate tissue reconstruction; modulate electrical and mechanical cues using magnetic fields.	Multi-responsive; enhance tissue integration; fabrication complexity can vary	[9]
Silk-Iron Microparticles (SIMPs)	Silk fibroin matrix chemically bonded with iron oxide nanoparticles.	Biodegradable, precisely controllable magnetic carrier for targeted delivery	FDA-approved silk reduces immunogenicity; reliable magnetic control; adaptable for drug loading	[19]
Magnetic Core-Shell Nanocarriers	Iron oxide core with a polymer, protein, or lipid shell	Precise drug release control and targeting; fewer off-target effects	Shell improves biocompatibility and stops MNP leaching; customizable surfaces.	[23]
Biodegradable polymeric vesicles	PLGA vesicles containing SPIONs, Mn:ZnS quantum dots, and busulfan; magnetic nanoparticles enable MRI response and QDs provide fluorescence imaging.	Controlled drug delivery and multimodal imaging; potential for localized therapeutic delivery.	Biodegradable, multifunctional, and trackable; organ accumulation and limited evaluation for wound repair are challenges	[24]
Magnetic iron oxide nanoparticles	Thrombin-conjugated iron oxide nanoparticles	Enhanced incisional wound healing	Magnetic, biocompatible; requires controlled thrombin activity	[16]
Biodegradable silk/MNP membrane	Silk fibroin containing iron oxide MNPs; alternating magnetic field generates nanopores through local heating	Remotely controlled and localized drug release; potential for implantable therapeutic systems.	Fully biodegradable and magnetically responsive; mainly demonstrated for drug delivery, not directly for wound repair.	[25]

2.2. Mechanisms of Magnetic Interaction with Biological Systems

Magnetically activated biomaterials have developed into an essential medium for drug delivery without the need for invasive procedures, as well as for accelerating tissue repair, due to their unique function of participating in biological processes when subjected to an external magnetic field [9]. The constituents of magnetically regulated biomaterials usually include magnetic nanoparticles such as iron oxide that can be operated in a non-invasive way, achieving drug release as well as control over cellular processes at certain points in time and space [26]. Application of magnetic fields can cause physical changes in these composites that lead to the reorientation of the materials or even

mechanical deformation, which eventually influences their biological microenvironment [27].

These materials make use of mechanical stimulation whereby magnetism influences the functions of cells, such as cell alignment, cell migration, and cell proliferation, which play an important role in tissue repair and healing [28, 29]. Furthermore, magnetic fields allow cellular communication via electrobiological signaling.

One of the most important mechanisms is the release of active substances upon contact or the controlled delivery of therapeutic agents: the magnetic field affects the permeability or compacts certain components of biological materials, allowing drug delivery at the site of injury with minimal systemic presence of the drug [19, 30]. The use of this method provides controlled dosage that

can be customized according to the stages of healing or dynamic processes of drug distribution.

Biocompatibility and safety are essential, with surface modifications like polymer or protein coatings improving the stability and decreasing the toxicity of magnetic nanoparticles in biological systems [31, 32]. The relevance of biological compatibility as well as other safety measures is a must in connection with surface modifications via coatings composed of both polymers and proteins [9, 30, 33].

3. Magnetically Responsive Drug Delivery Systems

Magnetically responsive drug delivery systems (MR-DDS) is a pioneering solution in targeted drug delivery [34]. In recent years, using the properties of magnetic nanoparticles combined with biocompatible carriers, it is possible to control the movements of the systems via magnetic fields from the outside [19].

3.1. Design Principles of Magnetic Drug Carriers

Design principles for magnetic drug carriers in biomaterials are mainly aimed at achieving optimization of the magnetism [35]. Efficient magnetic carriers possess high magnetic moments, allowing them to react properly to the application of an external magnetic field, thereby directing the carrier to a specific place in the body, as deep as tissues [36]. This is achieved due to the design of carriers from MNPs that assume shapes like nanorods, nanotubes, or nanochains, which ensure better magnetic behavior in comparison with standard spherical shape nanoelements. Moreover, drug carriers must be constructed of materials that allow loading of a drug at the desired level by implementing the idea of the presence of unfulfilled spaces in the carrier that should work as reservoirs [37, 38]. In addition, materials should have biocompatibility of the carrier that needs to be achieved by covering the devised carrier with biocompatible polymers or peptides that provide properties of stealth, promote circulation, and enhance uptake by cells [39]. This research that the magnetic drug carriers allow the operation of controlled drug delivery due to the use of a magnetic field when drugs are released at the disease site by force provided by magnetic waves used for drug induction [40].

Magnetic drug carriers are affected not only by their magnetic and structural design but also by their chemistry and the surface engineering process to which they were subjected [41]. Moreover, these carriers exhibit superparamagnetic on the nanoscale, thus eliminating the possibility of the carriers agglomerating in the bloodstream and ensuring that there is a high magnetic response only when they are subjected to the influence of an external magnet [42]. All of these aspects lead to the advantages of custom drug delivery schemes and accurate spatial control of the magnetic carriers, which is essential for minimizing the side effects and achieving maximum therapeutic effect [43].

3.2. Targeted Drug Delivery Mechanisms

In targeted pharmaceutical delivery systems, magnetically responsive biomaterials employ magnetic nanoparticles for the specific distribution and targeted delivery of drugs [44, 45]. By applying external magnetic fields to the system, drug-loaded nanoparticles are steered towards infected tissues, allowing them to release drugs locally while minimizing systemic toxicity [46]. It is worth mentioning that the effectiveness of the system is at its highest in tumor treatment due to the fact that in this situation the nanoparticles can concentrate in the tumor microenvironment due to the operations of passive permeability and magnetism [47-49]. Furthermore, the release of drugs can be evoked by alternating

magnetic fields or the use of responsiveness linkers responsive to external phenomena such as pH and temperature, making therapy controllable both in space and time [50]. The effectiveness of this method is determined by the properties and size of the magnetically-shaped biomaterials and the external magnetic field [51]. Recent studies have shown increased survival rates in animals treated with this method. The technology seems promising, providing improved targeted drug delivery [52].

4. Enhanced Wound Repair Using Magnetic Biomaterials

Magnificent wound rehabilitation by means of magnetically activated composites with respect to magnetically controlled bio-composites is primarily concerned with the utilization of unique characteristics displayed by magnetically affected bio-composites to enhance skin wound restoration [9]. These composites exhibit better biocompatibility and can be remotely controlled by external magnetic fields, thereby enabling precise control of spatiotemporal parameters of the healing environment [53]. Magneto-active bio-composites can accelerate the process of wound healing by modifying the behavior of cells (such as their proliferation, migration, and differentiation), providing required control over the drug delivery process, as well as promoting tissue repair through various means (e.g., magneto-induced orientation, mechanical stimulation, and thermal effects) [9]. All these processes facilitate better tissue regeneration, reduce fibrosis, and stimulate both angiogenesis and hair follicle regeneration [54].

4.1. Role of Magnetically Responsive Materials in Tissue Regeneration

Magnetically responsive biomaterials enable precise control over cell alignment, proliferation, differentiation, and functional maturation through the application of external magnetic fields [55]. In particular, the application of external fields leads to the generation of thermal, mechanical, or biochemical stimuli at precise locations using a non-invasive approach. The use of magnetic nanoparticles is an illustration of this, as, under the action of an alternating magnetic field, these particles generate heat at a specific location, thereby initiating a predetermined pathway in a cell [56]. The mechanism for nerve recovery and tissue regeneration based on magnetically active biomaterials is quite effective because it does not harm surrounding tissues [57].

Injectable magnetically controlled hydrogels are a minimally invasive strategy for regeneration of aligned tissues such as skeletal muscle, spinal cord and tendons, allowing rapid in situ gelation and guiding cellular organization [58]. The technique increases fibroblast growth and reprograms the immune responses needed for regeneration. Magneto-responsive scaffolds also enhance the mechanical environment of cells by delivering magneto mechanical forces that activate mechanosensitive signaling pathways such as YAP/TAZ that govern cytoskeletal structure and cell fate decisions [59]. This allows dynamic control of tissue growth and remodeling in response to external stimuli, and has advantages over static biomaterials [60].

4.2. Mechanisms of Action in Wound Healing

The mechanisms that are responsible for wound healing through the application of magnetically responsive biomaterials are intricate, arising from the specific physical, and biochemical relationships created by magnetic fields [61]. These biomaterials possess beneficial properties of biocompatibility and remote spatiotemporal management of the wound healing environment

[9]. mainly involve control of cell behavior, enhancement of electrical signaling, controlled drug release and acceleration of tissue regeneration [62].

Magnetically active composites can position cells and components within the extracellular matrix by activating cellular architecture in response to magnetic fields, thereby promoting more efficient tissue regeneration. The process of tissue repair is also favored because of mechanical stimulation that is induced by the magnetic field, which in turn influences Mechanotransduction pathways and leads to changes in some aspects of cell behaviour, such as migration, adhesion, and differentiation that are important to healing [63, 64]. The effect of magnetocaloric change can also optimize the wound microenvironment by inducing temperature changes, thereby aiding healing [65]. Other than that, these materials can control cellular processes owing to their influence on immune cell activity, which is achieved by controlling the balance between pro- and anti-inflammatory signals, which is important considering that inflammation may complicate the healing process [66]. Magnetic stimulation improves the (electrical) environment within the wound and thus improves cell communication and treatment [67]. Magnetically active biocomposites can also enable continuous, controlled delivery of medicines that might improve the effectiveness of treatment for injuries or wounds [68].

He et al. [69] developed a magnetically actuated GelMA hydrogel dressing coated with aligned magnetic nanocomposite–protein fibers. Magnetic stimulation generated mechanical cues that regulated fibroblast proliferation and migration, while the dressing promoted vascularization, hair follicle formation, and overall skin regeneration in a full-thickness wound model, demonstrating its potential for magnetically controlled wound healing. The magnetically tunable injectable hydrogel was created by Rossi et al. [70], which is made from gellan gum, hyaluronic acid, collagen, and magnetic nanoparticles (MNPs). Type I collagen was mixed with MNPs to create magnetic collagen bundles (MColLB), and the direction of these bundles was adjusted with an external low intensity magnetic field, which produced an anisotropic structure. The hydrogel was found to be biocompatible and promoted the proliferation of fibroblasts and activation of pro-regenerative macrophage. Fig.2 shows the composition and fabrication of the magnetically responsive injectable system, including magnetic collagen bundles and the injectable matrix, as well as its response to a low-intensity static magnetic field and the resulting injectability, mechanical properties, cellular response, and regenerative potential.

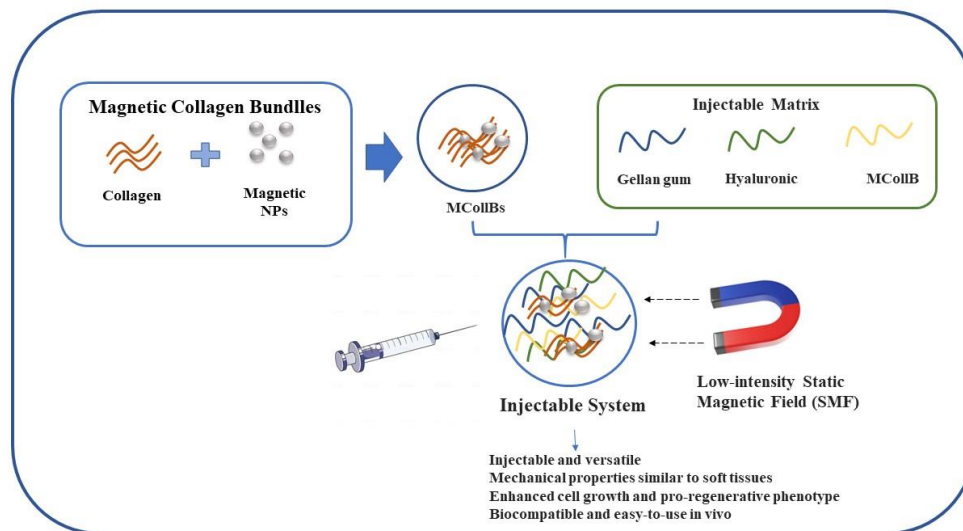


Fig. 2. Fabrication and properties of the magnetically responsive injectable system.

Peng et al. (2025) [71] introduced magneto-responsive microspheres incorporating stem cell secretome to promote rapid wound healing. The magnetic approach facilitated targeted delivery and prolonged release of the bioactive molecules, enabling a spatially and temporally regulated delivery of these agents for effective wound repair.

5. Challenges and Future Perspectives

The challenges and prospects of magnetically responsive biomaterials for non-invasive drug delivery and more effective wound healing hinge on many complicated and interrelated factors [72]. One important problem is precisely targeting deep-tissue sites using magnetic fields to steer therapeutic agents, as current imaging and magnetic control technologies are still not sufficient to operate at such depths. Likewise, the design of magnetic carriers that would specifically meet the needs of medicine is vital since the properties of such a carrier, including its size and shape, as well as the way it is coated, significantly influence its movement in

blood and tissues, drug loading, release, and biocompatibility or safety, since agglomeration prevents the carrier from blocking the blood vessels [73]. Before these types of carriers can be used according to the existing regulations, it is essential to study their performance in vivo. However, achieving this requires a coherent interplay of specialists such as nanofabricators, chemists, biologists, engineers, mathematicians, and practitioners [39].

The use of magnetically reactive biomaterials for wound healing shows potential benefits such as good compatibility and remote control over the release of medications and mechanical stimulation [9]. These materials provide a way to influence the behavior of cells, improve the capability of electrical signals, and enhance tissue repair, thus allowing the limits of classical dressings to be overcome [62]. Nonetheless, the difficulties associated with the complicated nature of wound healing processes involve the impossibility of using these materials [74]. The preparation method of biomaterials and their properties, including magneto-orientation, mechanical impact, and magnetocaloric effects, remain to be improved. The absence of comprehensive research

and review regarding biomaterials limits the understanding of this field of science and the possibility of clinical use. Moving forward, success in the sphere of magneto-responsive biocomposites design is essential for developing drug delivery capabilities and promoting tissue regeneration [9].

In the future, work should be directed to develop systems for non-invasive delivery of magnetic therapy deep inside the body, which is an unmet area at present [39]. Expanding the area of magnetic fields from small animals to human therapy would involve great innovations in magnet designs and coils so as to ensure efficient and targeted magnet stimulation without excessive heating or unfavorable influence on surrounding tissues [73]. In addition, creating the carriers of magnetic medicine that are durable and stealthy enough to avoid immune clearance while enabling controlled and regulated release of drugs is another goal that has yet to be achieved [75, 76]. Although much progress has been made in the case of the use of magnetic materials that have been approved for imaging and hyperthermia purposes, the reality is that the use of magnetic drug delivery in clinical practice is still quite limited, which indicates that it is necessary to continue working on the problem [77].

6. Conclusion

Magnetically responsive biomaterials show promise as breakthroughs in the field of non-invasive drug delivery and improved healing processes due to their capacity to perform remote and spatiotemporal control of therapies. These biomaterials that contain magnetic nanoparticles can enable a very precise drug release process and help in tissue engineering due to magnetic cell patterning, as well as mechanical stimulation. They not only offer solutions for wound healing, but also help tackle problems related to chronic and complex wounds by improving cellular response, stimulating blood vessel formation, controlling inflammation, and speeding up tissue regeneration. The malleability of the systems triggered by magnets has a great advantage in adaptation to changes in the microenvironment, thereby transferring tailored active substances for such conditions as diabetes or infection. However, despite the fact that magnetically responsive biomaterials show great effectiveness, much research should be done in order to develop them into accepted solutions.

Author contributions

Shiva Pishvaei: Conceptualization, Writing-Original Draft Preparation, Writing-review & editing; **Maryam Rezaei:** Resources, Writing-Original Draft Preparation, Writing-review & editing; **Marziyeh Azad:** Writing-review & editing; **Pantea Shahrivar:** Writing-Original Draft Preparation, Writing-review & editing.

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Data availability

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REFERENCES

- [1] V. Goranov, Biomaterials functionalized with magnetic nanoparticles for tissue engineering: between advantages and challenges, *Biomaterials and Biosystems* 15 (2024) 100100.
- [2] A.-G. Cristea, E.-L. Lisă, S. Iacob, I. Dragostin, C.S. Ștefan, I. Fulga, A.M. Anghel, M. Dragan, I.D. Morariu, O.-M. Dragostin, Antimicrobial Smart Dressings for Combating Antibiotic Resistance in Wound Care, *Pharmaceuticals* 18(6) (2025) 825.
- [3] A. Bakhtiari, L. Arabuli, F. Sadeghi, N. Tamimi, J. Hosseinzadeh, A.J. Rad, O.H. Najafabadi, Smart biomaterial composites for controlled drug release: mechanisms and applications, *Journal of Composites and Compounds* 5(17) (2023).
- [4] S.J. Sinha, B. Kumar, C.P. Prasad, S.S. Chauhan, M. Kumar, Emerging research and future directions on doxorubicin: a snapshot, *Asian Pacific journal of cancer prevention: APJCP* 26(1) (2025) 5.
- [5] S.A. Shah, M. Sohail, S. Khan, M.U. Minhas, M. De Matas, V. Sikstone, Z. Hussain, M. Abbasi, M. Kousar, Biopolymer-based biomaterials for accelerated diabetic wound healing: A critical review, *International journal of biological macromolecules* 139 (2019) 975-993.
- [6] H.S. Kim, X. Sun, J.-H. Lee, H.-W. Kim, X. Fu, K.W. Leong, Advanced drug delivery systems and artificial skin grafts for skin wound healing, *Advanced drug delivery reviews* 146 (2019) 209-239.
- [7] M.L. Fernandez, D. Stupar, T. Croll, D. Leavesley, Z. Upton, Xanthine oxidoreductase: a novel therapeutic target for the treatment of chronic wounds?, *Advances in wound care* 7(3) (2018) 95-104.
- [8] S. Das, A.B. Baker, Biomaterials and nanotherapeutics for enhancing skin wound healing, *Frontiers in bioengineering and biotechnology* 4 (2016) 82.
- [9] H. Ding, L. Hao, H. Mao, Magneto-responsive biocomposites in wound healing: from characteristics to functions, *Journal of Materials Chemistry B* 12(31) (2024) 7463-7479.
- [10] G. Huang, M. Li, Q. Yang, Y. Li, H. Liu, H. Yang, F. Xu, Magnetically actuated droplet manipulation and its potential biomedical applications, *ACS applied materials & interfaces* 9(2) (2017) 1155-1166.
- [11] G. Salmanian, S. Hassanzadeh-Tabrizi, N. Koupaei, Magnetic chitosan nanocomposites for simultaneous hyperthermia and drug delivery applications: A review, *International journal of biological macromolecules* 184 (2021) 618-635.
- [12] M. Suhail, A. Wahab, T. Eggers, Z. Ahmad, K. Shehzad, M.Z. Iqbal, Magnetically responsive hydrogel systems: Fundamental features, emerging applications, and future horizons, *Coordination Chemistry Reviews* 543 (2025) 216916.
- [13] D. Khorsandi, S. Jenson, A. Zarepour, A. Khosravi, N. Rabiee, S. Iravani, A. Zarrabi, Catalytic and biomedical applications of nanocelluloses: a review of recent developments, *International Journal of Biological Macromolecules* 268 (2024) 131829.
- [14] F.J. Vazquez-Perez, C. Gila-Vilchez, A. Leon-Cecilla, L. Álvarez de Cienfuegos, D. Borin, S. Odenbach, J.E. Martin, M.T. Lopez-Lopez, Fabrication and actuation of magnetic shape-memory materials, *ACS Applied Materials & Interfaces* 15(45) (2023) 53017-53030.
- [15] Y. Zou, Z. Sun, Q. Wang, Y. Ju, N. Sun, Q. Yue, Y. Deng, S. Liu, S. Yang, Z. Wang, Core-Shell Magnetic Particles: Tailored Synthesis and Applications, *Chemical Reviews* 125(2) (2024) 972-1048.
- [16] O. Ziv-Polat, M. Topaz, T. Brosh, S. Margel, Enhancement of incisional wound healing by thrombin conjugated iron oxide nanoparticles, *Biomaterials* 31(4) (2010) 741-747.
- [17] Y. Zhang, J. Li, P. Habibovic, Magnetically responsive nanofibrous ceramic scaffolds for on-demand motion and drug delivery, *Bioactive Materials* 15 (2022) 372-381.
- [18] J.L. Funnell, B. Balouch, R.J. Gilbert, Magnetic composite biomaterials for neural regeneration, *Frontiers in Bioengineering and Biotechnology* 7 (2019) 179.
- [19] A.X. Marini, G.N. Tomaraei, J.S. Weinbaum, M. Bedewy, D.A. Vorp, Chemical Conjugation of Iron Oxide Nanoparticles for

the Development of Magnetically Directable Silk Particles, *ACS Applied Materials & Interfaces* 17(6) (2025) 8901-8913.

[20] C. Hu, L. Yang, Y. Wang, Recent advances in smart-responsive hydrogels for tissue repairing, *MedComm-Biomaterials and Applications* 1(2) (2022) e23.

[21] Y. Fan, H. Wang, C. Wang, Y. Xing, S. Liu, L. Feng, X. Zhang, J. Chen, Advances in smart-response hydrogels for skin wound repair, *Polymers* 16(19) (2024) 2818.

[22] S. Saghazadeh, C. Rinoldi, M. Schot, S.S. Kashaf, F. Sharifi, E. Jalilian, K. Nuutila, G. Giatsidis, P. Mostafalu, H. Derakhshandeh, Drug delivery systems and materials for wound healing applications, *Advanced drug delivery reviews* 127 (2018) 138-166.

[23] A.A. Adedoyin, A.K. Ekenseair, Biomedical applications of magneto-responsive scaffolds, *Nano Research* 11(10) (2018) 5049-5064.

[24] F. Ye, Å. Barrefelt, H. Asem, M. Abedi-Valugerd, I. El-Serafi, M. Saghafian, K. Abu-Salah, S. Alrokayan, M. Muhammed, M. Hassan, Biodegradable polymeric vesicles containing magnetic nanoparticles, quantum dots and anticancer drugs for drug delivery and imaging, *Biomaterials* 35(12) (2014) 3885-3894.

[25] Y. Wang, G. Boero, X. Zhang, J. Brugger, Nanopore Generation in Biodegradable Silk/Magnetic Nanoparticle Membranes by an External Magnetic Field for Implantable Drug Delivery, *ACS Appl Mater Interfaces* 14(35) (2022) 40418-40426.

[26] E. Lacroce, F. Pizzetti, N.M.B. Urrego, G. Nunziata, M. Masi, F. Rossi, Magnetically active bicontinuous polymer structures for multiple controlled drug delivery, *Macromolecular Bioscience* 24(10) (2024) 2400084.

[27] Y. Sapir-Lekhovitser, M.Y. Rotenberg, J. Jopp, G. Friedman, B. Polyak, S. Cohen, Magnetically actuated tissue engineered scaffold: insights into mechanism of physical stimulation, *Nanoscale* 8(6) (2016) 3386-3399.

[28] Y. Chen, X. Zhang, M. Wang, Y. Liang, Z. Zheng, M. Liu, Q. Lu, Bioactive Silk Cryogel Dressing with Multiple Physical Cues to Control Cell Migration and Wound Regeneration, *Advanced Healthcare Materials* 14(7) (2025) 2404304.

[29] R. Sun, X. Jin, Y. Bao, Z. Cao, D. Gao, R. Zhang, L. Qiu, H. Yuan, C. Xing, Microenvironment with NIR-controlled ROS and mechanical tensions for manipulating cell activities in wound healing, *Nano Letters* 24(10) (2024) 3257-3266.

[30] A.E. Tolouei, N. Dülger, R. Ghatee, S. Kennedy, A magnetically responsive biomaterial system for flexibly regulating the duration between pro-and anti-inflammatory cytokine deliveries, *Advanced healthcare materials* 7(12) (2018) 1800227.

[31] S. Märkl, F. Przybilla, R. Rachel, T. Hirsch, M. Keller, R. Witzgall, Y. Mély, J. Wegener, Impact of surface chemistry of upconversion nanoparticles on time-dependent cytotoxicity in non-cancerous epithelial cells, *Scientific Reports* 14(1) (2024) 30610.

[32] A. Pusta, M. Tertis, I. Crăciunescu, R. Turcu, S. Mirel, C. Cristea, Recent advances in the development of drug delivery applications of magnetic nanomaterials, *Pharmaceutics* 15(7) (2023) 1872.

[33] Z. Kheradmand, M. Rabiei, A.N. Tahneh, E. Shirali, M. Abedi, B. Dashtipour, E. Barati, Targeted drug delivery by bone cements, *Journal of Composites and Compounds* 4(10) (2022) 59-73.

[34] M. Ahmad, M.U. Minhas, M. Sohail, M. Faisal, H. Rashid, Comprehensive review on magnetic drug delivery systems: A novel approach for drug targeting, *Journal of Pharmacy and Alternative Medicine* 2(4) (2013) 13-21.

[35] Y. Wang, Z. Shi, Y. Sun, X. Wu, S. Li, S. Dong, T. Lan, Preparation of amphiphilic magnetic polyvinyl alcohol targeted drug carrier and drug delivery research, *Designed Monomers and Polymers* 23(1) (2020) 197-206.

[36] K.E. Albinali, M.M. Zagho, Y. Deng, A.A. Elzatahry, A perspective on magnetic core-shell carriers for responsive and targeted drug delivery systems, *International journal of nanomedicine* (2019) 1707-1723.

[37] D. Zhao, N. Yang, L. Xu, J. Du, Y. Yang, D. Wang, Hollow structures as drug carriers: recognition, response, and release, *Nano Research* 15(2) (2022) 739-757.

[38] J. Varshosaz, Advancements in Nanostructured Drug Delivery Systems: A Commentary on Multifunctional Approaches for Cancer and Inflammatory Disease Treatment, *Journal of Composites and Compounds* 5(16) (2023) 210-211.

[39] P.M. Price, W.E. Mahmoud, A.A. Al-Ghamdi, L.M. Bronstein, Magnetic drug delivery: where the field is going, *Frontiers in chemistry* 6 (2018) 619.

[40] A. Tomitaka, Y. Takemura, Z. Huang, U. Roy, M. Nair, Magnetoliposomes in controlled-release drug delivery systems, *Critical Reviews™ in Biomedical Engineering* 47(6) (2019).

[41] T. Long, D. Song, Y. Zhou, X. Yu, X. Wang, C. Li, H. Chen, G. Li, F. He, Modulating Activity of Lattice Oxygen of ABO₃ Perovskite Oxides in Redox Reactions: A Review, *ACS Applied Materials & Interfaces* 17(14) (2025) 20590-20612.

[42] M.B. Lodi, E.M. Corda, F. Desogus, A. Fanti, G. Mazzarella, Modeling of magnetic scaffolds as drug delivery platforms for tissue engineering and cancer therapy, *Bioengineering* 11(6) (2024) 573.

[43] A. Al Ayidh, M. Abbas, M. Parayangat, T. Ijyas, Advances in nanomaterials for targeted drug delivery: emerging trends and future prospects in nanodrug development, *Current Cancer Drug Targets* (2025).

[44] L. Pereira, F.C. Ferreira, F. Pires, C.A. Portugal, Magnetic-Responsive Liposomal Hydrogel Membranes for Controlled Release of Small Bioactive Molecules—An Insight into the Release Kinetics, *Membranes* 13(7) (2023) 674.

[45] Y. Toropova, D. Korolev, M. Istomina, G. Shulmeyer, A. Petukhov, V. Mishanin, A. Gorshkov, E. Podyacheva, K. Gareev, A. Bagrov, Controlling the Movement of Magnetic Iron Oxide Nanoparticles Intended for Targeted Delivery of Cytostatics, *International Journal of Nanomedicine* (2021) 5651-5664.

[46] H. Shen, X. Wang, F. Tian, M. Li, K. Xie, X. Ma, Enhanced functionalization of superparamagnetic Fe₃O₄ nanoparticles for advanced drug enrichment and separation applications, *BMC chemistry* 18(1) (2024) 181.

[47] C. Caro, A. Avasthi, J.M. Paez-Muñoz, M.P. Leal, M.L. García-Martín, Passive targeting of high-grade gliomas via the EPR effect: a closed path for metallic nanoparticles?, *Biomaterials Science* 9(23) (2021) 7984-7995.

[48] A.K. Rengan, Enhanced permeability and retention effect: A key facilitator for solid tumor targeting by nanoparticles, (2022).

[49] H. Emadi, A. Hemmati, E. Behrouzi, Investigation of Fe₃O₄/SBA-15 magnetic nanocomposite synthesized by microwave-assisted solvothermal route as multi-therapeutic agent, *Journal of Composites and Compounds* 4(12) (2022) 141-144.

[50] H. Madineh, F. Mansourinia, P. Zarrintaj, M. Poostchi, P. Gnatowski, J. Kucinska-Lipka, M. Ghaffari, M.S. Hasanin, S. Chapi, M.K. Yazdi, Stimuli-responsive delivery systems using carbohydrate polymers: A review, *International Journal of Biological Macromolecules* (2025) 142648.

[51] R. Verkhovskii, A. Ermakov, O. Grishin, M.A. Makarkin, I. Kozhevnikov, M. Makhortov, A. Kozlova, S. Salem, V. Tuchin, D. Bratashov, The Influence of Magnetic Composite Capsule Structure and Size on Their Trapping Efficiency in the Flow, *Molecules* 27(18) (2022) 6073.

[52] S. Kralj, T. Potrc, P. Kocbek, S. Marchesan, D. Makovec, Design and fabrication of magnetically responsive nanocarriers for drug delivery, *Current medicinal chemistry* 24(5) (2017) 454-469.

[53] C. He, M. Yin, H. Zhou, J. Qin, S. Wu, H. Liu, X. Yu, J. Chen, H. Zhang, L. Zhang, Magnetic nanoactuator-protein fiber coated hydrogel dressing for well-balanced skin wound healing and tissue regeneration, *ACS nano* 19(1) (2025) 1713-1731.

[54] K.L. Williams, L.A. Garza, Diverse cellular players orchestrate regeneration after wounding, *Experimental dermatology* 30(4) (2021) 605-612.

[55] H. Choi, J. Jang, Magnetic-based tissue engineering: principles, applications, and future prospects in biofabrication, *Biomaterials science*

[56] A. Ito, R. Teranishi, K. Kamei, M. Yamaguchi, A. Ono, S. Masumoto, Y. Sonoda, M. Horie, Y. Kawabe, M. Kamihiro, Magnetically triggered transgene expression in mammalian cells by localized cellular heating of magnetic nanoparticles, *Journal of bioscience and bioengineering* 128(3) (2019) 355-364.

[57] A. Bukowiecki, D. Hos, C. Cursiefen, S.A. Eming, Wound-healing studies in cornea and skin: parallels, differences and

opportunities, *International journal of molecular sciences* 18(6) (2017) 1257.

[58] A. Rossi, F. Furlani, G. Bassi, C. Cunha, A. Lunghi, F. Molinari, F.J. Teran, F. Lista, M. Bianchi, A. Piperno, Contactless magnetically responsive injectable hydrogel for aligned tissue regeneration, *Materials Today Bio* 27 (2024) 101110.

[59] A. Totaro, M. Castellan, G. Battilana, F. Zanonato, L. Azzolin, S. Giulitti, M. Cordenonsi, S. Piccolo, YAP/TAZ link cell mechanics to Notch signalling to control epidermal stem cell fate, *Nature communications* 8(1) (2017) 15206.

[60] H.J. Anderson, J.K. Sahoo, R.V. Ulijn, M.J. Dalby, Mesenchymal stem cell fate: applying biomaterials for control of stem cell behavior, *Frontiers in bioengineering and biotechnology* 4 (2016) 38.

[61] H. Li, B. Li, D. Lv, W. Li, Y. Lu, G. Luo, Biomaterials releasing drug responsively to promote wound healing via regulation of pathological microenvironment, *Advanced drug delivery reviews* 196 (2023) 114778.

[62] C. Chen, X. Bai, Y. Ding, I.-S. Lee, Electrical stimulation as a novel tool for regulating cell behavior in tissue engineering, *Biomaterials research* 23(1) (2019) 25.

[63] X. Guo, Y. Gao, J. Yu, S. Qiu, X. Wang, S. Wang, C. Zhang, B. Yi, Y. Gao, Dynamic Mechanical Stimulation of Thermoresponsive Nanofibers for Activation of Fibroblasts in Skin Repair, *Advanced Healthcare Materials* (2025) 2500277.

[64] A. Monemian Esfahani, J. Rosenbohm, K. Reddy, X. Jin, T. Bouzid, B. Riehl, E. Kim, J.Y. Lim, R. Yang, Tissue regeneration from mechanical stretching of cell–cell adhesion, *Tissue Engineering Part C: Methods* 25(11) (2019) 631-640.

[65] C.R. Fernandes, J.O. Ventura, D.J. Silva, Impact of different numerical approaches on the magnetocaloric effect modeling, *Heliyon* 10(11) (2024).

[66] R.A. Villarreal-Leal, G.D. Healey, B. Corradetti, Biomimetic immunomodulation strategies for effective tissue repair and restoration, *Advanced drug delivery reviews* 179 (2021) 113913.

[67] Y. Xiao, S. Ahadian, M. Radisic, Biochemical and biophysical cues in matrix design for chronic and diabetic wound treatment, *Tissue Engineering Part B: Reviews* 23(1) (2017) 9-26.

[68] C. He, X. Lin, L. Shang, Multi-Functional Responsive Microcapsules with Sequential Release Capacity for Wound Healing, *Small* 21(9) (2025) 2410844.

[69] C. He, M. Yin, H. Zhou, J. Qin, S. Wu, H. Liu, X. Yu, J. Chen, H. Zhang, L. Zhang, Y. Wang, Magnetic Nanoactuator-Protein Fiber Coated Hydrogel Dressing for Well-Balanced Skin Wound Healing and Tissue Regeneration, *ACS Nano* 19(1) (2025) 1713-1731.

[70] A. Rossi, F. Furlani, G. Bassi, C. Cunha, A. Lunghi, F. Molinari, F.J. Teran, F. Lista, M. Bianchi, A. Piperno, M. Montesi, S. Panseri, Contactless magnetically responsive injectable hydrogel for aligned tissue regeneration, *Materials Today Bio* 27 (2024) 101110.

[71] J. Jiang, H. Liang, Y. Ye, W. Huang, J. Miao, H. Tan, Z. Hu, H. Tian, H. Qin, X. Zhang, Stem cell secretome armed magneto-actuated micromotors as spatio-temporal manipulators for wound healing acceleration, *Nature Communications* 16(1) (2025) 6754.

[72] N. Oliva, B.D. Almquist, Spatiotemporal delivery of bioactive molecules for wound healing using stimuli-responsive biomaterials, *Advanced drug delivery reviews* 161 (2020) 22-41.

[73] B. Shapiro, S. Kulkarni, A. Nacev, S. Muro, P.Y. Stepanov, I.N. Weinberg, Open challenges in magnetic drug targeting, *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology* 7(3) (2015) 446-457.

[74] F. Urciuolo, R. Passariello, G. Imparato, C. Casale, P.A. Netti, Bioengineered wound healing skin models: The role of immune response and endogenous ECM to fully replicate the dynamic of scar tissue formation in vitro, *Bioengineering* 9(6) (2022) 233.

[75] L. Jin, J. Liu, Y. Tang, L. Cao, T. Zhang, Q. Yuan, Y. Wang, H. Zhang, MnO₂-functionalized Co-P nanocomposite: a new theranostic agent for pH-triggered T1/T2 dual-modality magnetic resonance imaging-guided chemo-photothermal synergistic therapy, *ACS Applied Materials & Interfaces* 9(48) (2017) 41648-41658.

[76] H. Azimizonuzi, A. Ghayourvahdat, M.H. Ahmed, R.A. Kareem, A.J. Zrzor, A.S. Mansoor, Z.H. Athab, S. Kalavi, A state-of-the-art review of the recent advances of theranostic liposome

hybrid nanoparticles in cancer treatment and diagnosis, *Cancer Cell International* 25(1) (2025) 26.

[77] J.F. Liu, B. Jang, D. Issadore, A. Tsourkas, Use of magnetic fields and nanoparticles to trigger drug release and improve tumor targeting, *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology* 11(6) (2019) e1571.