

Next-Generation Multifunctional Stimuli-Responsive Self-Healing Hydrogels for Precision Therapeutics and Advanced Regenerative Tissue Engineering

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Abstract

This report provides a comprehensive structure and content outline for a review paper on next-generation multifunctional stimuli-responsive self-healing hydrogels. It begins with an introduction covering the evolution from conventional to smart hydrogels, the concepts of stimuli-responsiveness and self-healing, and their importance in precision therapeutics and tissue engineering. The core sections detail the fundamentals of self-healing mechanisms and stimuli-responsive principles, the materials (natural/synthetic polymers, nanomaterials) and advanced engineering/fabrication strategies used. It extensively covers biomedical applications in precision therapeutics (e.g., controlled drug delivery, cancer therapy) and regenerative tissue engineering (e.g., skin, bone, neural, cardiac repair). The report concludes with discussions on emerging functionalities (e.g., thermostics, AI- assisted design), biological safety, clinical translation challenges, and future perspectives, fully addressing the user's specified title and sub-headings.

Keywords: Hydrogels, Precision medicine, Self- healing, Tissue engineering, Personalized medicine

1. Introduction

Hydrogel technology has transformed from passive, water-retaining scaffolds first developed in the 1960s into sophisticated, stimuli-responsive platforms that actively engage with biological systems. This evolution addresses historical limitations of conventional materials by introducing adaptive properties essential for precision therapeutics and regenerative medicine (1,2).

Smart hydrogels are characterized by two defining properties: stimuli-responsiveness, which allows dynamic alterations in swelling, degradation, and mechanical behavior in response to physical, chemical, or biological cues; and self-healing, which confers autonomous recovery after mechanical damage via reversible molecular interactions. Together, these capabilities enable controlled drug release, durable implantable scaffolds, and minimally invasive injectable systems (3–5).

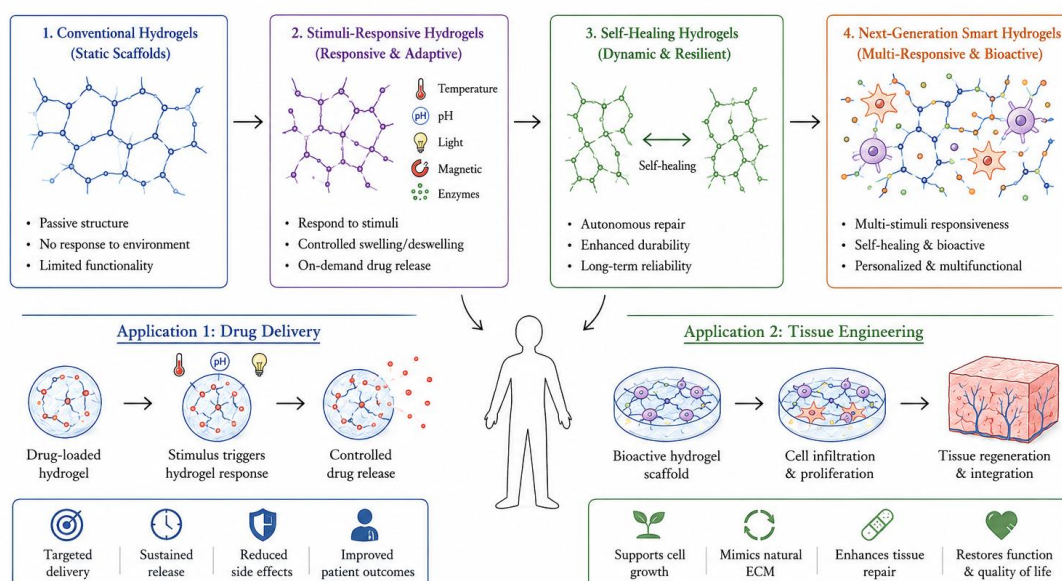


Figure 1. Schematic overview of smart hydrogel evolution

2. Self-Healing Mechanisms and Stimuli-Responsive Principles

Self-healing in hydrogels arises from reversible molecular interactions classified into two main categories:

2.1 Dynamic Covalent Bonding

Reversible chemical bonds — including imine (Schiff base), boronate ester, and disulfide exchange reactions — break and reform under defined conditions. These robust chemistries facilitate autonomous repair while preserving structural integrity (6,7).

2.2 Non-Covalent Interactions

Physical crosslinks offering faster healing kinetics include hydrogen bonding, ionic interactions, and host–guest recognition (e.g., cyclodextrin–hydrophobic guest pairs). Supramolecular assembly via π – π stacking and hydrophobic associations further expands design flexibility (8).

Key factors governing self-healing efficiency include crosslinking density, polymer architecture, and environmental conditions such as temperature and pH, all of which modulate healing kinetics and mechanical recovery (9).

3. Materials and Engineering Strategies

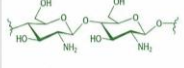
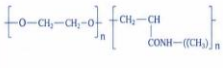
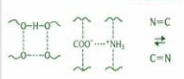
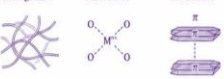
	I. Natural Polymers	II. Synthetic Polymers	III. Functional Nanomaterials
Representative Materials	Alginate, Chitosan, Gelatin, Hyaluronic Acid, Cellulose, Silk Fibroin, Collagen	Poly(ethylene glycol) (PEG), Poly(vinyl alcohol) (PVA), Poly(N-isopropylacrylamide) (PNIPAAm), Polyurethane (PU), Polyacrylamide (PAAm)	Graphene Oxide (GO), Clay (Laponite), Cellulose Nanocrystals (CNC), Silica (SiO ₂), Metal-Organic Frameworks (MOFs), Gold Nanoparticles (AuNPs)
Chemical Structure (Examples)			
Self-Healing Mechanisms (Representative)	Hydrogen Bonding, Ionic Interactions, Dynamic Covalent Bonds 	Hydrogen Bonding, Host-Guest Interactions, Dynamic Covalent Bonds 	Physical Entanglement, Coordination Interactions, Reversible Noncovalent Interactions 
Stimuli-Responsive Properties (Examples)	 Temperature, pH, Enzymes, Light, Magnetic	 Temperature, pH, Stress/Strain, Electric, Light	 Temperature, pH, Magnetic, Electric, NIR Light
Key Advantages	• Biocompatible & biodegradable • Abundant & renewable • Intrinsic biofunctionality	• Tunable structure & properties • Excellent mechanical stability • Versatile functionalization	• Enhanced mechanical strength • Multifunctional (electrical, optical, catalytic) • Enable advanced smart responses

Figure 2. Classification of hydrogel-forming materials

3.1 Natural Polymers

Alginate, chitosan, gelatin, hyaluronic acid (HA), and cellulose derivatives are widely used due to their inherent biocompatibility and extracellular matrix (ECM)-mimicking properties. HA and chitosan-based hydrogels are engineered with dynamic imine bonds and host–guest interactions to achieve injectable, shear-thinning formulations. Gelatin, derived from collagen, retains bioactive sequences and can be crosslinked via guest–host photochemistry for stretchable, fast-healing scaffolds (10,11).

3.2 Synthetic Polymers

Polyethylene glycol (PEG), poly (vinyl alcohol) (PVA), poly(N-isopropylacrylamide) (PNIPAAm), and polyacrylamide (PAAm) offer precise tunability. PNIPAAm undergoes sol–gel transitions near physiological temperature, enabling thermosensitive injectable systems. Double-network designs combining PVA with borax or cellulose derivatives achieve high tensile strength alongside self-healing capability through interchain hydrogen bonding (12,13).

3.3 Functional Nanomaterials

Metallic nanoparticles (gold, silver, iron oxide), carbon nanomaterials (carbon nanotubes, graphene oxide), and MXenes are incorporated to enhance mechanical, electrical, and photothermal properties. Iron oxide nanoparticles confer magnetic responsiveness for remote stimulation, while carbon-based materials enable electroconductive platforms for biosensing and neural interfaces (14,15).

Table 1. Summary of key hydrogel material categories and their characteristics

Material Class	Key Examples	Self-Healing Mechanism	Stimuli Responsiveness
Natural Polymers	Alginate, Chitosan, Gelatin, HA	Imine bonds, Host–guest	pH, Enzyme, Temperature

Synthetic Polymers	PEG, PVA, PNIPAAm, PAM	Boronate esters, H-bonding	Temperature, Light, pH
Nanomaterials	Au/Fe ₃ O ₄ NPs, CNTs, MXenes	Network reinforcement	Magnetic, Photothermal
Hybrid Systems	Double-network, Nanocomposites	Multiple combined mechanisms	Multi-stimuli responsive

3.4 Advanced Fabrication Technologies

Double-network engineering balances mechanical strength with healing efficiency by pairing a rigid covalent network with a reversible sacrificial network. Injectable in situ gelation systems exploit temperature or pH transitions for minimally invasive delivery. Three-dimensional and four-dimensional bioprinting enable spatial patterning of bioinks and living cells, with 4D printing incorporating stimuli-triggered shape morphing post-fabrication (16).

4. Biomedical Applications

4.1 Precision Therapeutics

Controlled and On-Demand Drug Delivery

Stimuli-responsive hydrogels exploit pathological triggers including acidic tumor microenvironments, elevated reactive oxygen species, and overexpressed enzymes for on-demand drug release. Thermosensitive PNIPAAm-based systems undergo sol–gel transitions at physiological temperatures, providing sustained local delivery following minimally invasive administration (17).

Targeted Cancer Therapy and Immunomodulation

Injectable hydrogels for intra-tumoral administration reduce systemic toxicity and lower required doses compared to conventional chemotherapy. pH-responsive degradation and magnetic nanoparticle-triggered hyperthermia enable non-invasive combination therapies. For immunotherapy, matrix metalloproteinase (MMP)-responsive hydrogels locally release immunomodulatory siRNA or cytokines, suppressing pathological inflammation with spatial precision (18).

Gene and Nucleic Acid Delivery

DNA-based hydrogel scaffolds encapsulate and protect vulnerable nucleic acids until stimulus-triggered release. The self-healing property helps these carriers recover from injection-induced shear stress, preserving structural integrity and ensuring consistent payload delivery (19).

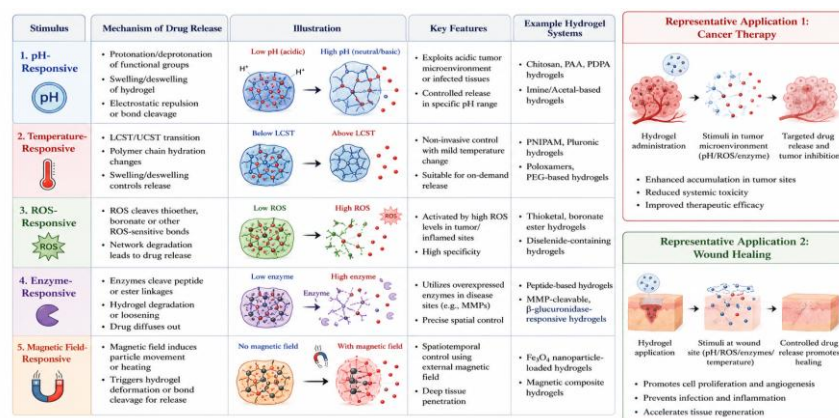


Figure 3: Mechanisms of stimuli-triggered drug release from multifunctional hydrogels

4.2 Regenerative Tissue Engineering

Skin and Wound Repair

Smart wound dressings respond to wound-specific cues: pH-responsive systems release antimicrobial agents in infected acidic environments; ROS-scavenging hydrogels mitigate oxidative stress in chronic wounds; thermoresponsive formulations adhere and contract at body temperature to mechanically support wound closure. Gelatin, chitosan, and HA provide biomimetic ECM environments that facilitate cell migration and tissue regrowth (10,11).

Bone and Cartilage Regeneration

Magnetic-responsive hydrogels incorporating iron oxide nanoparticles promote osteogenic differentiation via remote magnetic stimulation. Nanocomposites combining polymers with hydroxyapatite mimic natural bone ECM and release osteoinductive factors as the scaffold degrades to match new bone formation. For cartilage, HA-based formulations support chondrocyte function, while enzyme-responsive degradation creates space for nascent tissue (14).

Neural and Cardiac Repair

Conductive hydrogels incorporating carbon nanotubes or PEDOT transmit electrical signals, stimulating neurite outgrowth and bridging nerve gaps. Magnetically aligned nanoparticle arrays within hydrogel fibers create anisotropic scaffolds guiding unidirectional axon growth. For cardiac applications, electroconductive gelatin–graphene oxide or PEG–polyaniline hydrogels restore electrical conduction in infarcted regions, delivered as injectable formulations or engineered cardiac patches (15,20).

Tissue Type	Representative Hydrogel Composition (Examples)	Key Responsiveness (Stimuli)	Regenerative Mechanism	Illustration of Regeneration
Skin	- Gelatin methacryloyl (GelMA) - Chitosan - Hyaluronic acid (HA) - Collagen	Temperature pH ROS Light	- Promotes fibroblast proliferation and migration - Enhances angiogenesis - Maintains moist environment - Accelerates re-epithelialization and collagen deposition	
Bone	- GelMA - Nanohydroxyapatite (nHA) - Collagen - Chitosan / Alginate	pH Magnetic field Mechanical strain Electrical	- Supports osteoblast adhesion and proliferation - Provides osteoconductive scaffold - Promotes mineralization - Enhances vascularization and bone remodeling	
Cartilage	- Methacrylated hyaluronic acid (MeHA) - Chondroitin sulfate (CS) - GelMA - Collagen II	Temperature pH Mechanical compression ROS	- Mimics native ECM - Promotes chondrocyte viability and ECM synthesis - Reduces inflammation - Supports cartilage regeneration and integration	
Neural	- Gelatin - Hyaluronic acid (HA) - Laminin-derived peptides - Conductive polymers (e.g., PEDOT)	pH Light Electrical Near-infrared (NIR)	- Supports neuronal adhesion and neurite outgrowth - Provides neuroprotection - Modulates microenvironment - Enhances synaptic regeneration and functional recovery	
Cardiac	- GelMA - Decellularized ECM (dECM) - Alginate / HA - Conductive materials (e.g., rGO, MXene)	Electrical Mechanical strain pH ROS	- Enhances cardiomyocyte survival and alignment - Improves electrical conductivity - Promotes angiogenesis - Supports cardiac tissue remodeling and functional repair	

Figure 4. Tissue engineering applications of multifunctional hydrogels

5. Advanced Functionalities and Emerging Technologies

5.1 Theranostic Platforms and Biosensing

Integrating diagnostic and therapeutic functions within a single hydrogel platform enables real-time monitoring concurrent with treatment delivery. Hydrogel-based biosensors leverage tunable chemistry and optical/electrical signal readouts in biological fluids for non-invasive glucose monitoring, wound status assessment, and continuous wearable health surveillance (21,22).

5.2 Cell-Instructive and Immunomodulatory Systems

Next-generation hydrogels actively guide immune responses to favor regenerative over fibrotic outcomes. Collagen-based scaffolds can suppress engineered cartilage immunogenicity, while cellulose hybrid hydrogels functionalized with immunomodulatory peptides polarize macrophages toward pro-healing phenotypes. Controlled release of anti-inflammatory cytokines (IL-4, IL-10) in response to inflammatory triggers further refines immune modulation (23,24).

5.3 AI-Assisted Hydrogel Design

Computational methods — including molecular dynamics (MD) simulations, finite element analysis (FEA), and machine learning — are accelerating hydrogel discovery. Artificial neural networks (ANNs) predict mechanical properties from polymer composition inputs, while convolutional neural networks (CNNs) interpret colorimetric signals from pH-sensitive wound dressings to assess healing status. These data-driven approaches shift material development from empirical trial-and-error to predictive, rational design (25).

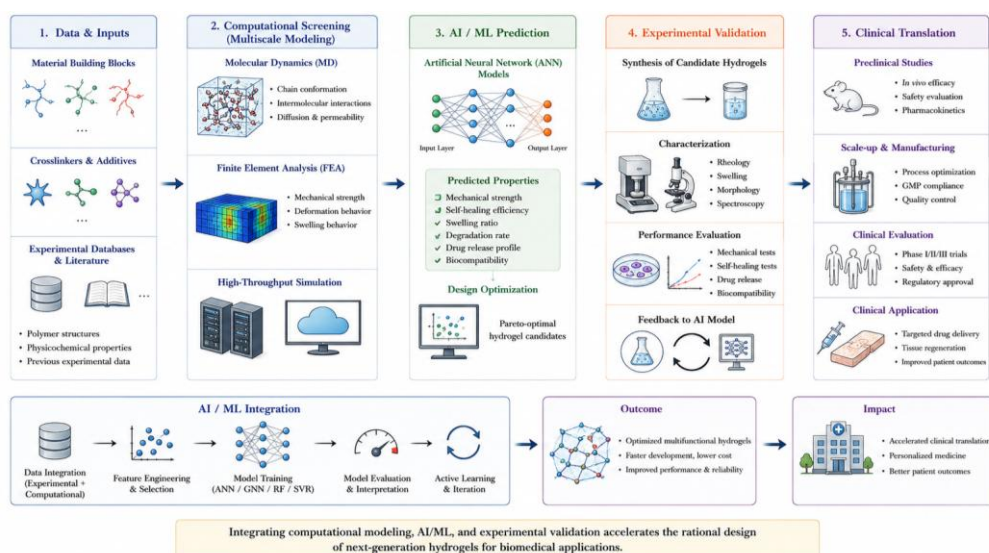


Figure 5. AI-assisted hydrogel design workflow

6. Biological Safety and Clinical Translation

6.1 Biocompatibility Assessment

Rigorous safety evaluation begins with in vitro cytotoxicity assays (MTT, LDH) on hydrogel extracts and direct contact models. PVA hydrogels prepared by physical crosslinking have demonstrated reliable biocompatibility in standardized assessments. Cation-crosslinked cellulose nanocrystal hydrogels show acceptable cell viability provided excess crosslinking cations are removed during fabrication (26,27).

6.2 Regulatory and Manufacturing Considerations

Hydrogel-based devices are typically classified as Class II or III under FDA and EU MDR frameworks, requiring comprehensive documentation of material characterization, sterilization validation, and clinical performance. Key

manufacturing challenges — batch variability, sterilization compatibility, and raw material consistency — are addressed through Quality-by-Design (QbD) approaches. Development timelines of 7–10 years and estimated costs between \$50–800 million underscore the importance of early regulatory engagement and industry partnerships (28,29).

7. Challenges and Limitations

A fundamental design tension exists between mechanical robustness and self-healing efficiency; dense crosslinked networks that provide load-bearing strength restrict the chain mobility required for efficient bond reformation. External healing triggers (heat, UV light, extreme pH) may also be biologically incompatible, limiting applicability in sensitive physiological environments.

Long-term stability in the dynamic in vivo environment, reproducible large-scale manufacturing, and the high cost of functional nanomaterials represent additional translational barriers. Regulatory pathways are further complicated when hydrogels incorporate drugs or live cells, potentially extending approval timelines and development costs significantly (30).

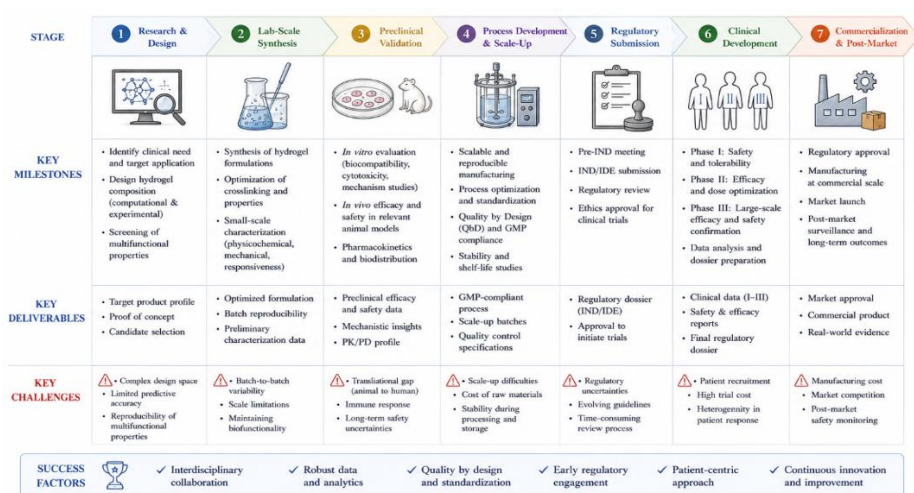


Figure 6. Roadmap for clinical translation of multifunctional hydrogels – From Lab-Scale synthesis to Patient impact

8. Future Perspectives

Forthcoming developments will center on orthogonal multi-stimuli platforms that integrate pH, enzyme, redox, light, and magnetic triggers for unprecedented spatiotemporal therapeutic control. AI-guided inverse design and high-throughput formulation screening will accelerate the identification of optimal material combinations. Four-dimensional bioprinting of patient-specific constructs with programmable post-implantation shape morphing, combined with closed-loop theranostic systems integrating wearable biosensors, represents the frontier of this field (31).

A structured translational roadmap encompassing QbD standardization, clinically relevant preclinical models, proactive regulatory consultation, and scalable manufacturing investment will be essential to convert laboratory innovations into approved clinical tools.

9. Conclusion

Next-generation multifunctional stimuli-responsive self-healing hydrogels represent a transformative class of biomaterials that uniquely combine autonomous repair, dynamic environmental responsiveness, and tailored functionality. These

properties enable precise, on-demand drug delivery, and provide instructive microenvironments that guide tissue regeneration across diverse clinical targets including tumors, wounds, bone, cartilage, nerve, and cardiac muscle.

Although material trade-offs, manufacturing complexity, and regulatory barriers remain significant hurdles, convergence with AI-assisted design, digital fabrication, and bioelectronics is charting a clear path forward. Sustained interdisciplinary collaboration across materials science, biology, engineering, and regulatory science will be critical to translating these remarkable laboratory innovations into patient-benefit-driven clinical therapies.

References

1. Wichterle, O., & Lim, D. (1960). Hydrophilic gels for biological use. *Nature*, 185(4706), 117–118. <https://doi.org/10.1038/185117a0>
2. Catoira, M. C., Fusaro, L., Di Francesco, D., Ramella, M., & Boccafroschi, F. (2019). Overview of natural hydrogels for regenerative medicine applications. *Journal of Materials Science: Materials in Medicine*, 30(10), 115. <https://doi.org/10.1007/s10856-019-6318-7>
3. Koehler, J., Brandl, F. P., & Goepferich, A. M. (2018). Hydrogel wound dressings for bioactive treatment of acute and chronic wounds. *European Polymer Journal*, 100, 1–11. <https://doi.org/10.1016/j.eurpolymj.2017.12.046>
4. Yuk, H., Lu, B., & Zhao, X. (2019). Hydrogel bioelectronics. *Chemical Society Reviews*, 48(6), 1642–1667. <https://doi.org/10.1039/C8CS00595H>
5. Jiang, Y., Chen, J., Deng, C., Suuronen, E. J., & Zhong, Z. (2014). Click hydrogels, microgels and nanogels: Emerging platforms for drug delivery and tissue engineering. *Biomaterials*, 35(18), 4969–4985. <https://doi.org/10.1016/j.biomaterials.2014.03.001>
6. Wei, Z., Yang, J. H., Liu, Z. Q., Xu, F., Zhou, J. X., Zrínyi, M., Osada, Y., & Chen, Y. M. (2015). Novel biocompatible polysaccharide-based self-healing hydrogel. *Advanced Functional Materials*, 25(9), 1352–1359. <https://doi.org/10.1002/adfm.201401502>
7. Phadke, A., Zhang, C., Arman, B., Hsu, C. C., Mashelkar, R. A., Lele, A. K., Tauber, M. J., Arya, G., & Varghese, S. (2012). Rapid self-healing hydrogels. *Proceedings of the National Academy of Sciences*, 109(12), 4383–4388. <https://doi.org/10.1073/pnas.1117560109>
8. Talebian, S., Mehrali, M., Taebnia, N., Pennisi, C. P., Kadumudi, F. B., Foroughi, J., Hasani-Sadrabadi, M. M., Dolatshahi-Pirouz, A., & Orive, G. (2019). Self-healing hydrogels: The next paradigm shift in tissue engineering? *Advanced Science*, 6(16), 1801664. <https://doi.org/10.1002/advs.201801664>
9. Zhao, X. (2014). Multi-scale multi-mechanism design of tough hydrogels: Building dissipation into stretchy networks. *Soft Matter*, 10(5), 672–687. <https://doi.org/10.1039/C3SM51655J>
10. Highley, C. B., Rodell, C. B., & Burdick, J. A. (2015). Direct 3D printing of shear-thinning hydrogels into self-healing hydrogels. *Advanced Materials*, 27(34), 5075–5079. <https://doi.org/10.1002/adma.201501234>
11. Lim, H. J., Oh, C. M., Kim, J. Y., Park, Y. H., & Ki, C. S. (2017). pH-responsive hyaluronic acid-based self-healing hydrogel. *Macromolecular Research*, 25(5), 533–536. <https://doi.org/10.1007/s13233-017-5077-2>
12. Hassan, C. M., & Peppas, N. A. (2000). Structure and applications of poly(vinyl alcohol) hydrogels produced by conventional crosslinking or by freezing/thawing methods. *Advances in Polymer Science*, 153, 37–65. https://doi.org/10.1007/3-540-46414-X_2
13. Schild, H. G. (1992). Poly(N-isopropylacrylamide): Experiment, theory and application. *Progress in Polymer Science*, 17(2), 163–249. [https://doi.org/10.1016/0079-6700\(92\)90023-R](https://doi.org/10.1016/0079-6700(92)90023-R)

14. Bock, N., Riminucci, A., Dionigi, A., Russo, A., Tampieri, A., Landi, E., Goranov, V. A., Marcacci, M., & Dediu, V. (2010). A novel route in bone tissue engineering: Magnetic biomimetic scaffolds. *Acta Biomaterialia*, 6(3), 786–796. <https://doi.org/10.1016/j.actbio.2009.08.019>
15. Shin, S. R., Li, Y. C., Jang, H. L., Khoshakhlagh, P., Akbari, M., Nasajpour, A., Zhang, Y. S., Tamayol, A., & Khademhosseini, A. (2016). Graphene-based materials for tissue engineering. *Advanced Drug Delivery Reviews*, 105, 255–274. <https://doi.org/10.1016/j.addr.2016.03.007>
16. Moroni, L., Boland, T., Burdick, J. A., De Maria, C., Derby, B., Forgacs, G., Groll, J., Li, Q., Malda, J., Mironov, V. A., Mota, C., Nakamura, M., Shu, W., Takeuchi, S., Woodfield, T. B. F., Xu, T., Yoo, J. J., & Vozzi, G. (2018). Biofabrication: A guide to technology and terminology. *Trends in Biotechnology*, 36(4), 384–402. <https://doi.org/10.1016/j.tibtech.2017.10.015>
17. Klouda, L., & Mikos, A. G. (2008). Thermoresponsive hydrogels in biomedical applications. *European Journal of Pharmaceutics and Biopharmaceutics*, 68(1), 34–45. <https://doi.org/10.1016/j.ejpb.2007.02.025>
18. Li, J., & Mooney, D. J. (2016). Designing hydrogels for controlled drug delivery. *Nature Reviews Materials*, 1(12), Article 16071. <https://doi.org/10.1038/natrevmats.2016.71>
19. Sun, J. E., Stewart, B., Litan, A., Lee, S. J., Bhanu, B., Bhanu, S., & others. (2016). Sustained release of active chemotherapeutics from injectable-solid block copolymer nanoparticle-gel composites. *Biomaterials Science*, 4(5), 839–848. <https://doi.org/10.1039/C5BM00556A>
20. Mihic, A., Cui, Z., Wu, J., Vlacic, G., Miyagi, Y., Li, S. H., Lu, S., Sung, H. W., Weisel, R. D., Li, R. K., & others. (2015). A conductive polymer hydrogel supports cardiac formation from MSCs and HUVEC cocultures. *Biomaterials*, 60, 129–142. <https://doi.org/10.1016/j.biomaterials.2015.04.049>
21. Bai, X., Lü, S., Cao, Z., Ni, B., Wang, X., Ning, P., Ma, D., Wei, Q., & Liu, M. (2017). Dual crosslinked chondroitin sulfate injectable hydrogel formed via continuous Diels–Alder click chemistry for stem cell therapy. *Carbohydrate Polymers*, 166, 123–130. <https://doi.org/10.1016/j.carbpol.2017.02.067>
22. Tavakoli, J., & Tang, Y. (2017). Hydrogel based sensors for biomedical applications: An updated review. *Polymers*, 9(8), 364. <https://doi.org/10.3390/polym9080364>
23. Sridharan, R., Cameron, A. R., Kelly, D. J., Kearney, C. J., & O'Brien, F. J. (2015). Biomaterial based modulation of macrophage polarization: A review and suggested design principles. *Materials Today*, 18(6), 313–325. <https://doi.org/10.1016/j.mattod.2015.01.019>
24. Huleihel, L., Hussey, G. S., Naranjo, J. D., Zhang, L., Dziki, J. L., Turner, N. J., Stolz, D. B., Badylak, S. F., & others. (2016). Matrix-bound nanovesicles within ECM bioscaffolds. *Science Advances*, 2(6), e1600502. <https://doi.org/10.1126/sciadv.1600502>
25. Garg, P., & Giri, J. (2023). Artificial intelligence in biomaterials: A comprehensive review. *Frontiers in Materials*, 10, 1130344. <https://doi.org/10.3389/fmats.2023.1130344>
26. Cascone, S., & Lamberti, G. (2020). Hydrogel-based commercial products for biomedical applications: A review. *International Journal of Pharmaceutics*, 573, 118803. <https://doi.org/10.1016/j.ijpharm.2019.118803>
27. Lv, X., Liu, Y., Song, S., Tong, C., Shi, X., Zhao, Y., Hou, M., & Wang, J. (2019). Influence of chitosan scaffold microstructure on the outcome of in vitro assays. *Carbohydrate Polymers*, 207, 601–611. <https://doi.org/10.1016/j.carbpol.2018.12.008>
28. Vasvani, S., Kulkarni, P., & Rawtani, D. (2020). Hyaluronic acid: A review of its history, structure, biotechnology, and clinical advances. *International Journal of Biological Macromolecules*, 151, 1286–1299. <https://doi.org/10.1016/j.ijbiomac.2019.11.191>

29. Sheikh, Z., Hamdan, N., Ikeda, Y., Gryn timer, M., Ganss, B., & Glogauer, M. (2017). Natural graft tissues and synthetic biomaterials for periodontal and alveolar bone reconstructive applications. *Biomaterials Research*, 21(1), 9. <https://doi.org/10.1186/s40824-017-0095-5>
30. Langer, R., & Tirrell, D. A. (2004). Designing materials for biology and medicine. *Nature*, 428(6982), 487–492. <https://doi.org/10.1038/nature02388>
31. Hoffman, A. S. (2012). Hydrogels for biomedical applications. *Advanced Drug Delivery Reviews*, 64(Suppl.), 18–23. <https://doi.org/10.1016/j.addr.2012.09.010>