Biomedical Technology 10 (2025) 100084

Contents lists available at ScienceDirect

Biomedical Technology

journal homepage: www.keaipublishing.com/en/journals/biomedical-technology

Review

Superparamagnetic hydrogels: Precision-driven platforms for biomedicine, robotics, and environmental remediation

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ARTICLE INFO

Keywords:
Hydrogels
Superparamagnetic iron oxide nanoparticles
Magnetic materials
Robotics
Superparamagnetic

ABSTRACT

Hydrogels are widely recognized for their biocompatibility and structural adaptability in regenerative medicine and three-dimensional (3D) bioprinting, yet their inherent static nature fundamentally limits applications demanding dynamic spatiotemporal control. The incorporation of superparamagnetic iron oxide nanoparticles (SPIONs) addresses this issue. The incorporation of SPIONs enables real-time programmable manipulation through magnetic field gradients. This amalgamation not only endows hydrogels with abilities such as magnetic propulsion, positioning, magnetoguidance, movement, and levitation, typical of magnetic materials, but also introduces novel functionalities like responsiveness to thermal effects and enhanced adsorption capabilities. This review delves into the transformative potential unlocked by the integration of SPIONs into hydrogels, showcasing their unique functional enhancements and targeted applications in robotics, precision medicine, and wastewater treatment.

1. Introduction

Hydrogels, characterized by their high water content and intricate 3D network structure, have become indispensable in biomedicine due to their versatile properties and diverse applications [1]. Hydrogels have revolutionized therapeutic approaches and regenerative medicine techniques from drug delivery systems to tissue engineering scaffolds. Their remarkable biocompatibility supports various applications, accommodating various bioactive agents and cells, thus advancing biomedical research and clinical practice [2,3].

Nevertheless, traditional hydrogels face challenges such as inadequate mechanical strength and insufficient control over spatial positioning and mobility. These shortcomings can impede their effectiveness in delivering therapeutic agents precisely and achieving optimal clinical outcomes, particularly in load-bearing tissue regeneration and spatially orchestrated drug release. For instance, the lack of control over the hydrogel's location can result in suboptimal therapeutic outcomes or inefficient drug delivery. To address these limitations, researchers have turned to the integration of magnetic materials, which offer the advantage of remote control and manipulation [4–6]. Conventional magnetic additives, however, often lead to hydrogels retaining magnetism even after the external magnetic field is removed, causing potential issues like unwanted interactions with biological tissues or impaired hydrogel functionality [7].

In response to these challenges, a refined approach has emerged: incorporating SPIONs. These nanoparticles, distinguished by their ability to respond to external magnetic fields without retaining magnetism once the field is removed, offer a promising solution [8,9]. Fe_3O_4 are highly

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Peer review under the responsibility of KeAi Communications Co., Ltd.
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https://doi.org/10.1016/j.bmt.2025.100084
Received 18 February 2025; Received in revised form 28 April 2025; Accepted 29 April 2025
Available online xxxx

regarded for their superparamagnetism, biocompatibility, and minimal cytotoxicity within specific concentration ranges [10–12]. The integration of SPIONs into hydrogels not only enhances their functionality but also enables precise magnetic manipulation, allowing for controlled movement and accurate positioning within biological systems. This capability is essential for targeted drug delivery, facilitating the guided delivery of SPION-loaded hydrogels to specific anatomical sites for localized therapeutic interventions [13,14].

Beyond biomedical applications, the magnetic properties of SPION-hydrogels have also been explored in robotics and environmental remediation. Such superparamagnetic response paves the way for the development of soft robotic actuators that can perform delicate and flexible movements, ideal for manipulating biological tissues [15]. The magnetic properties of these hydrogels also support the creation of micromotors for controlled mechanical motion at the microscale and magnetic grippers for micro-manipulation tasks [16,17]. Additionally, the magnetoguidance and orientation capabilities provided by superparamagnetic hydrogels are pivotal in tissue engineering, as they facilitate the precise spatial organization of cells and matrix components essential for the regeneration of functional tissue [18]. Moreover, SPIONs can induce localized hyperthermia when exposed to alternating magnetic fields, presenting novel opportunities for thermal therapies in cancer treatment and localized infections [19]. The magnetic characteristics of SPIONs enable efficient adsorption and separation processes, particularly for organic pollutant removal and oil spill remediation in wastewater treatment [20].

Beyond the previous applications, superparamagnetic hydrogels present advanced opportunities. In theragnostic applications, they could enhance magnetic resonance imaging (MRI) capabilities and enable combined diagnostic and therapeutic functions [21]. In the development of organoids, these hydrogels provide essential structural support and biocompatibility, fostering cell growth and tissue maturation [22]. Their pH-responsive swelling properties enable dynamic adjustment of their physical state and drug release profiles, making them suitable for targeted therapies in varying physiological conditions [23]. Additionally, the incorporation of SPIONs into 3D assembly opens up new avenues for creating biomimetic structures, thus advancing personalized medicine and tissue engineering applications [24].

To provide a comprehensive understanding of the advancements facilitated by SPIONs in hydrogels, this review will delve into the enhanced physicochemical properties and performance improvements resulting from their integration. Specifically, the discussion will cover a range of advanced applications, including, but not limited to, the enhanced mobility and precise positioning capabilities of SPION-loaded hydrogels, their magnetoguidance and orientation for tissue engineering, and their ability to induce localized hyperthermia for thermal therapies. Furthermore, we will explore the role of SPIONs in innovative fields such as robotics, where they contribute to magnetic response functionalities, as well as their potential in hydrogel micromotors and magnetorheological behaviors.

The integration of SPIONs into hydrogel matrices fundamentally resolves three persistent challenges in conventional biomaterial systems: the incapacity for spatiotemporal therapeutic control, inadequate responsiveness to physiological dynamics, and functional compartmentalization across treatment modalities. This composite system synergizes the innate biocompatibility of hydrogels with the magnetic reversibility of SPIONs, establishing an intelligent material platform capable of real-time mechanical adaptation, chronologically programmed drug release kinetics, and sub-millimeter spatial targeting capabilities that collectively transcend the limitations of static hydrogel

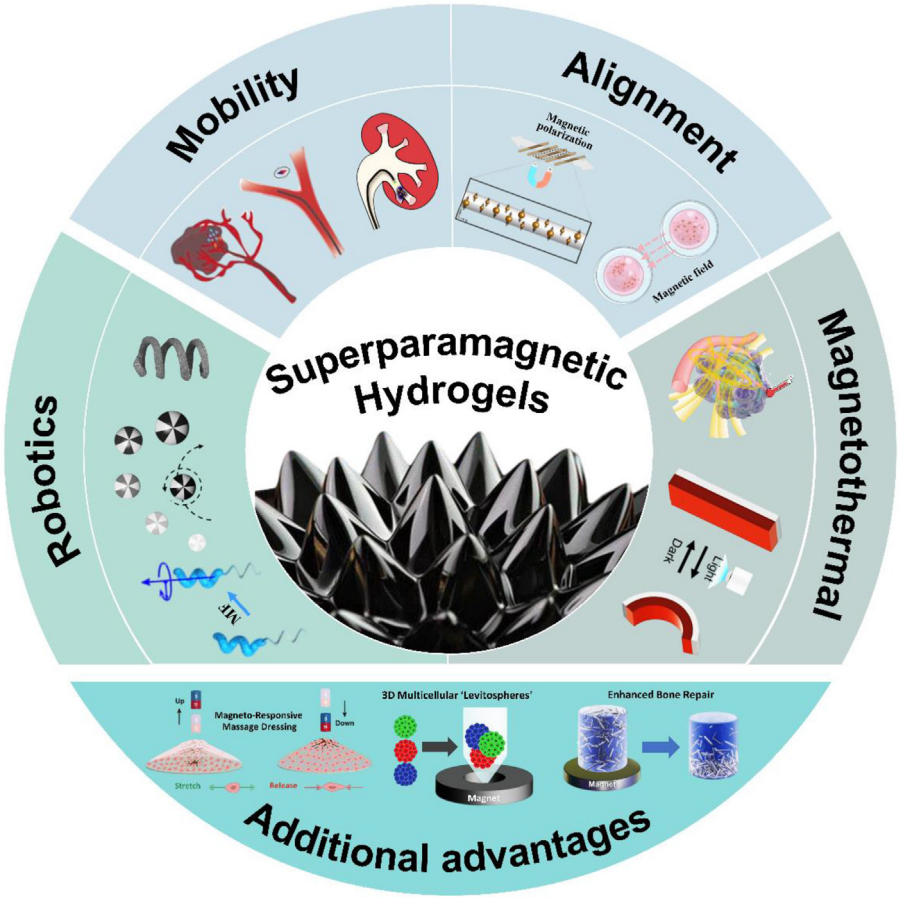


Fig. 1. Versatile SPIONs integrated hydrogels with ideal physicochemical properties.

architectures. Current breakthroughs reveal its translational dimensionality encompassing magnetically steerable soft robotics, extracellular matrix-mimetic topological alignment, and on-demand magnetothermal ablation therapies, demonstrating cross-domain applicability from precision medicine to biohybrid engineering (Fig. 1). As systematically summarized in Table 1, recent advances in SPIONs-hydrogel composites exhibit a versatile design space spanning hydrogel matrix, magnetic particle architectures, and application-specific functionalities ranging from MRI contrast enhancement to magneto-mechanical actuators. The forthcoming era will likely witness these intelligent hydrogels evolving into proactive biomedical systems capable of not only responding to but anticipating pathophysiological changes through embedded sensing-actuation paradigms.

Table 1
Composition and functional applications of SPIONs-hydrogel composites.

Application	Hydrogel	Concentration of Hydrogel	Magnetic particle	Concentration of magnetic particle	Function	Ref
Cell delivery	SA[a]	5 wt%	Fe_3O_4	80 mg/ml	Magnetic response	[98]
Artificial muscle	PVA[b]	Not mentioned	Fe_3O_4	1–10 wt%	Magnetic response	[181]
Antibacterial	GelMA[c]	10 % w/v	Fe_3O_4	200/500 μg/ml	Antibacterial	[152]
Magnetic drive	AA[d] and PEGDA[e]	0.5 wt%	Fe_3O_4	2 wt%	Magnetic response	[16]
Adsorption	AA[d] and VSA[f]	Not mentioned	Fe_3O_4	1.2, 3.2, and 5.2 wt %	Adsorption	[23]
Wound healing	PCL[g]	5-20 wt%	Fe_3O_4	5-15 wt%	Magnetic response	[157]
Retrieval of kidney stone	CS[h]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[100]
Enhanced performance	PVA[b]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[169]
Cargo encapsulation and delivery	GelMA[c]	2 wt%	Fe_3O_4	5 wt%	Magnetic response	[144]
Sewage treatment	PVA[b]	Not mentioned	Fe_3O_4	Not mentioned	Adsorption	[156]
Drug delivery	PLGA[i]	40 mg/2 ml	Fe_3O_4	2 mg/2 ml	Magnetic Navigation	[106]
Anticancer	SA[a]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic hyperthermia	[122]
Drug delivery	SA[a]	2 wt%	Fe_3O_4	20 wt%	Magnetic response	[147]
Enhanced performance	DMAAm[j]	Not mentioned	Fe_3O_4	Not mentioned	Magnetorheological	[160]
Mini-generator	PNIPAm[k]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[99]
Magnetic microrobots	PLGA[i]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic hyperthermia	[101]
Drug delivery	CMC[l]	1.5 % w/v	$CoFe_2O_4$	Not mentioned	Magnetic response	[182]
Drug delivery	PPy[m] and PEG[n]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[102]
Theragnostic applications	DHP[o] 7 and 8	Not mentioned	Fe_3O_4	Not mentioned	Contrast agents	[183]
Drug delivery	SA[a] and XG[p]	Not mentioned	Fe_3O_4	13 wt%	Magnetic response	[103]
Patterning bone tissues	HAP[q] and PDA[r]	Not mentioned	Fe_3O_4	Mentioned	Magnetic response	[111]
3D cell culture	GelMA[c]/PEGDMA[s]	Not mentioned	Fe_3O_4	5 % w/v	Magnetic response	[109]
Drug release	PVA[b]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[104]
Micromotors	SA[a]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic guidance	[88]
Anticancer	Gel[t]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic hyperthermia	[117]
Bone repair	GelMA[c]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[167]
Bending motions	PNIPAm[k] and PAAm[u]	Not mentioned	Fe_3O_4	15 mg/ml	Magnetic hyperthermia	[124]
Adsorption	CG[v]	Not mentioned	γ-Fe_2O_3	Not mentioned	Adsorption	[184]
Adsorption	CS[h]/PPA[w]/EDA[x]	Not mentioned	Fe_3O_4	0.1 to 1.0 wt%	Adsorption	[155]
Enhanced performance	GA[y]/SA[a]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[159]
Anticancer	DMSA[z], PAA[aa], PEG[n], and starch	Not mentioned	Fe_3O_4	Not mentioned	Magnetic hyperthermia	[126]
3D cell culture	PAMA[bb], LA[cc], HAS[dd]	Not mentioned	Fe_3O_4	Not mentioned	Maglev	[185]
Drug delivery	PNIPAm[k]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[105]
Drug delivery	PEG[n]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[186]
Organoids	PEG[n]	Not mentioned	Fe_3O_4	1000 μg/ml	Magnetic response	[110]
PH responsive swelling	AA[d] and VSA[f]	Not mentioned	Fe_3O_4	0.6 g/50 ml	Magnetic response	[171]
Anticancer	PPZ[ee]	10 wt%	Fe_3O_4	10 wt%	Magnetic hyperthermia	[120]
3D assembly	PEDGMA[ff] and GelMA[c]	40 % wt/wt	Fe_3O_4	Not mentioned	Magnetic response	[24]
3D tissue culture	GBI[gg]	Not mentioned	Fe_3O_4/γ-Fe_2O_3	Not mentioned	Maglev	[180]
Drug delivery	PNIPAAm[hh]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[148]
Drug delivery	Gel[t]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[97]
Robotics	GelMA[c]	10 % w/v	Fe_3O_4	2.9 % v/v	Magnetic response	[149]
Robotics	SA[a]/MBAA[ii]	1.08 wt%	Fe_3O_4	Not mentioned	Magnetic response	[187]
Robotics	PEG[n]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[137]
Robotics	PEGDA[e] and PETA[jj]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[139]
Robotics	GelMA[c]	100 mg/ml	Fe_3O_4	6 mg/ml	Magnetic response	[143]
Hydrogel micromotors	SA[a]	2 wt%	Fe_3O_4	10 mg/ml	Magnetic response	[88]
Hydrogel micromotors	SA[a]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[17]
Targeted drug delivery	PLGA[i]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic response	[106]
Anticancer	Gel[t]	Not mentioned	Fe_3O_4	Not mentioned	Magnetic hyperthermia	[117]

Abbreviations: a: Sodium Alginate; b: Polyvinyl Alcohol; c: Methacrylated Gelatin; d: Acrylic Acid; e: Polyethylene Glycol Diacrylate; f: Vinylsulfonic Acid; g: Polycaprolactone; h: Chitosan; i: Poly (Lactic-Co-Glycolic Acid); j: N,N-Dimethylacetoacetamide; k: Poly(N-Isopropylacrylamide) l: Carboxymethylcellulose; m: Polypyrrole; n: Polyethylene Glycol; o: Dehydrodipeptides; p: Xanthan Gum; q: Hydroxyapatite; r: Polydopamine; s: Poly(ethylene glycol) dimethacrylate; t: Gelatin; u: Polyacrylamide; v: Carrageenan; w: Polypropenoic Acid; x: Ethylenediamine; y: Gelatin–Alumina; z: Dimercaptosuccinic Acid; aa: Polyacrylic Acid; bb: Polyacrylic Acid-Co-Maleic Acid: cc: Lauric Acid: dd: Human Serum Albumin; ee: Poly(Organophosphazene); ff: Polyethylene Glycol Dimethacrylate; gg: Gold-Bacteriophage: hh: Poly-N-Isoproprylacrylamide; ii: 6,6′-Diaminodiphenylmethane-3,3′-dicarboxylic acid; jj: Pentaerythritol Triacrylate.

2. Hydrogels

Hydrogels have emerged as a critical material in biomedical applications due to their ability to retain significant amounts of water [25]. These materials, traditionally driven by mechanisms such as osmotic pressure, ionic interactions, and gas-induced responses, undergo volume phase transitions that render them suitable for a wide range of uses including soft actuators and drug delivery systems [26–28].

2.1. Properties and characteristics of hydrogels

Hydrogels are intriguing materials known for their exceptional ability to absorb and retain large amounts of water, often exceeding 90 % by weight [29]. This remarkable water content not only imparts to hydrogels a soft and flexible nature, but also makes them structurally similar to biological tissues. Their ability to mimic the mechanical properties of natural tissues, such as softness and elasticity, allows them to undergo significant deformation without breaking [30]. This makes hydrogels particularly valuable in fields requiring high flexibility and resilience, such as biomedical applications [31,32].

Their high biocompatibility further enhances their utility in medical and biotechnological fields. Hydrogels are often used in drug delivery systems, wound dressings, and tissue engineering because they interact safely with biological systems [33,34]. Their compatibility with living tissues minimizes adverse reactions and promotes effective integration, making them ideal for applications where direct contact with the body is necessary.

In addition to their structural and biological properties, hydrogels exhibit intriguing responsiveness to environmental stimuli [35]. Many hydrogels are engineered to respond to changes in temperature [36], pH [37], or electric fields [38]. This responsiveness is facilitated by the incorporation of specific functional groups or crosslinking agents, which enable the hydrogel to swell or contract in reaction to external conditions [39]. Such adaptive behavior is crucial for the development of smart materials and systems, including advanced drug delivery mechanisms and responsive medical devices [31].

The versatility of hydrogels is further demonstrated by their tunable mechanical properties [40]. Researchers can modify the strength and elasticity of hydrogels through chemical techniques such as polymerization and crosslinking. By adjusting the degree of crosslinking and the composition of the polymer network, hydrogels can be tailored to meet specific performance requirements [41]. This ability to customize their mechanical properties makes hydrogels suitable for demanding applications in soft robotics and artificial muscles [42–44].

Hydrogels, with their exceptional water absorption, flexibility, and biocompatibility, bridge the gap between synthetic materials and biological systems. Their responsiveness to environmental changes and customizable mechanical properties makes them highly versatile, suitable for advanced applications in drug delivery, medical devices, soft robotics, and beyond.

2.2. Hydrogel formation

Hydrogels are retaining large amounts of water and can be formed through a range of mechanisms including temperature changes, non-covalent interactions, chelation, electrostatic interactions, and chemical cross-linking [45,46]. Thermally responsive hydrogels, such as those based on natural polysaccharides and proteins, exhibit gelation phenomena influenced by temperature variations, showing either lower critical solution temperature (LCST) or upper critical solution temperature (UCST) behavior [47]. Protein-based hydrogels often rely on non-covalent self-assembly, utilizing weak interactions such as hydrogen bonds, van der Waals force, and hydrophobic interactions to establish structured scaffolds [48,49], for instance, collagen hydrogels form through hierarchical self-assembly driven by the formation of tropocollagen triple helices [50,51]. Chelation and electrostatic interactions further contribute to gelation, exemplified by alginate gels which form "egg-box" structures in the presence of divalent cations [52], and by electrostatic interactions between oppositely charged polyelectrolytes, such as poly(L-lysine) and polyacrylic acid, leading to complex formation and gelation [53]. Chemical cross-linking, including advanced methods like click chemistry, enhances the stability and control of the gelation process, enabling precise and biocompatible hydrogel formation [54]. The integration of multiple gelation strategies has resulted in hydrogels with superior mechanical properties, injectability, and dynamic modifiability.

2.3. Application scenarios

Hydrogels have found a multitude of applications within the field of biomedicine, primarily due to their unique properties such as high water content, biocompatibility, and tunable mechanical characteristics [55]. In drug delivery systems, hydrogels are utilized for their capacity to encapsulate therapeutic agents and release them in a controlled and sustained manner [28]. This property not only enhances the efficacy of the treatments but also allows for targeted drug delivery, reducing potential side effects and improving patient outcomes [56].

A notable example of hydrogel application in drug delivery is using nano- or microgels as drug carriers [57]. These tiny gel particles can efficiently encapsulate or mix with therapeutic agents, forming a stable and protective matrix for the drugs [58]. When administered, the nano- or microgels can effectively navigate through blood vessels into the inner circulation or enter the digestive system, depending on the route of administration [59,60]. The key advantage of using nano- or microgels for drug delivery is their ability to target specific sites within the body. By modifying the surface properties or incorporating targeting ligands, these particles can be designed to recognize and bind to specific cells or tissues, thereby enhancing the local concentration of the drug and improving its therapeutic effect [61].

For instance, in cancer treatment, hydrogel microspheres loaded with chemotherapy drugs can be injected directly into the tumor site, allowing for a higher drug concentration at the target location while minimizing systemic toxicity [62]. Similarly, in the treatment of inflammatory diseases, nano- or microgels carrying anti-inflammatory agents can be designed to target inflamed tissues, providing localized therapy and reducing side effects associated with systemic drug administration [63].

In tissue engineering, hydrogels serve as essential scaffolds that support cell growth and facilitate tissue regeneration [64]. Their ability to mimic the extracellular matrix makes them ideal for creating environments that promote cellular activities and tissue formation [22]. This characteristic is particularly valuable in the development of engineered tissues and organs, where the structural and biochemical properties of hydrogels play a crucial role in guiding cell behavior and tissue development.

Hydrogels are also employed extensively in regenerative medicine to create conducive environments for healing and repair [65]. Their adaptability allows for the design of hydrogels that can respond to specific biological signals or environmental changes, thereby optimizing the regenerative processes [66]. This includes applications such as wound dressings, which benefit from the hydrogels' capacity to maintain a moist environment and accelerate healing.

Moreover, advancements in 3D bio-printing technology have expanded the use of hydrogels in creating complex structures and scaffolds for various biomedical applications [67,68]. This capability enhances the precision of hydrogel-based constructs and opens new avenues for personalized medicine and tissue engineering [69,70]. For a systematic overview of these applications, refer to Table 2, which categorizes hydrogel uses across biomedical domains, their key properties,

Table 2
Summary of hydrogel applications in biomedicine.

Application Domain	Specific Use	Key Properties	Advantages/Outcomes	References
Drug Delivery	Localized chemotherapy	Nano/microgel encapsulation, targeting	High local drug concentration, reduced toxicity	[57,62]
Drug Delivery	Anti-inflammatory targeting	Ligand-modified carriers	Site-specific release, minimized side effects	[61,63]
Tissue Engineering	Cell scaffolds & regeneration	ECM-mimicking, tunable mechanics	Supports cell proliferation, tissue growth	[22,64]
Regenerative Medicine	Smart wound dressings	Moisture retention, stimuli-responsive	Accelerates healing, prevents infection	[65,66]
3D Bioprinting	Complex organ scaffolds	Biocompatibility, high-resolution printing	Personalized structures, precision medicine	[67–70]

and clinical benefits. In summary, the versatility of hydrogels across drug delivery, tissue engineering, regenerative medicine, and 3D printing underscores their significant role in advancing medical science and technology.

3. SPIONs

3.1. Superparamagnetism

SPIONs represent a remarkable advancement in the field of nanotechnology due to their unique magnetic properties [71]. Due to their intrinsic nanoscale dimensions, SPIONs exhibit superparamagnetism—a behavior distinct from classical ferromagnetism—arising from thermally driven fluctuations of magnetic moments within individual nanoparticles. Superparamagnetic materials can be magnetized in the presence of an external magnetic field, but unlike ferromagnetic materials, they do not retain any net magnetization once the external field is removed [72]. This property is pivotal for various biomedical applications, including imaging and targeted therapy.

The phenomenon of superparamagnetism arises from the magnetic domains within the nanoparticles. At the nanoscale, the thermal energy can overcome the magnetic anisotropy barrier, causing the magnetic moments within each nanoparticle to randomly align. When an external magnetic field is applied, the moments align with the field, leading to a net magnetization [73]. However, once the field is removed, the thermal energy causes the moments to return to a disordered state, resulting in zero net magnetization. This reversible behavior makes SPIONs highly versatile and safe for use in dynamic biological environments [74].

3.2. Synthesis of SPIONs

The synthesis of SPIONs involves a range of methods, each offering control over particle size, shape, and surface characteristics.

Physical synthesis techniques include gas-phase deposition, electron beam lithography, pulsed laser ablation, laser-induced pyrolysis, power ball milling, and combustion. These methods enable the precise tailoring of SPION properties, including their size and magnetic behavior [75].

Chemical synthesis methods, such as co-precipitation, thermal decomposition, microemulsions, and hydrothermal synthesis, also play a critical role. Co-precipitation involves the simultaneous precipitation of iron salts, like ferrous chloride and ferric chloride, under alkaline conditions, producing SPIONs with desirable properties [76]. Thermal decomposition entails the thermal breakdown of iron precursors in the presence of stabilizing agents, offering fine control over particle size and shape [77]. Hydrothermal synthesis dissolves iron salts in a solvent and exposes them to high temperature and pressure, resulting in well-defined nanoparticles with uniform size and shape [78].

To systematically compare the advantages and limitations of these methods, Table 3 summarizes key parameters such as scalability, cost, and suitability for biomedical or industrial applications.

3.3. Applications of SPIONs in biomedicine

The unique properties of SPIONs make them highly valuable in various biomedical applications [79]. One prominent use is in MRI, where SPIONs serve as contrast agents to enhance imaging sensitivity. Their ability to alter the local magnetic field improves the contrast between pathological and healthy tissues, allowing for more detailed and accurate imaging [21]. The high magnetic response of SPIONs facilitates the precise localization and identification of tissues, which is essential for diagnosing and monitoring diseases [80].

Furthermore, magnetic hyperthermia (MHT) utilizes SPIONs to generate localized heat when exposed to an alternating magnetic field (AMF), primarily through Néel rotation rather than Brownian alignment [81]. This heat, generated as the nanoparticles align with the AMF, can effectively destroy cancer cells at the target site. Additionally, SPIONs can be conjugated with anticancer agents to enhance therapeutic efficacy and induce apoptosis in tumor cells.

Another significant application of SPIONs is in drug delivery systems [82]. These nanoparticles can be incorporated into drug delivery systems to act as carriers for therapeutic agents. By embedding SPIONs in hydrogels, researchers achieve targeted drug delivery and controlled release. The application of an external magnetic field can guide these SPION-loaded hydrogels to specific sites within the body, enhancing treatment efficacy while minimizing side effects [83].

SPIONs are also employed in cell separation techniques, particularly in cancer treatment and other cell-based therapies [84]. These nanoparticles enable the selective isolation and separation of specific cell populations, which facilitates more effective treatments and research applications. By harnessing the magnetic properties of SPIONs, researchers can improve the precision and effectiveness of various therapeutic strategies.

A notable applications of SPIONs is in the field of advanced neuromodulation [85]. SPIONs have proven to be crucial in neuromodulatory techniques due to their unique magnetic properties, which allow for precise modulation of neuronal activity and cellular functions. This cutting-edge approach involves conjugating SPIONs with specific cellular receptors or ion channels, enabling the remote and non-invasive manipulation of cellular processes via external magnetic fields. By leveraging this technology, researchers can achieve highly targeted activation or inhibition of neuronal circuits, thereby facilitating detailed investigations into brain function and the development of novel therapeutic strategies for neurological disorders [86,87].

Table 3
Comparison of SPION synthesis methods: key parameters, advantages, and limitations.

Method	Type	Advantages	Disadvantages	Key Applications	References
Co-precipitation	Chemical	Simple, low cost, scalable	Polydispersity, limited crystallinity	Biomedical, wastewater treatment	[76]
Thermal Decomposition	Chemical	Monodisperse, high crystallinity	High cost, organic solvent dependency	Drug delivery, diagnostics	[77]
Hydrothermal	Chemical	Uniform shape, high purity	Energy-intensive, slow process	Energy, catalysis	[78]
Laser Ablation	Physical	No surfactants, clean surfaces	Low yield, expensive equipment	Niche biomedical applications	[75]

4. Superparamagnetic hydrogels

Building upon the Néel relaxation-governed superparamagnetism of isolated nanoparticles, the integration of SPIONs into hydrogel matrices follows three principal strategies to achieve macroscopic functionality: physical blending of pre-synthesized SPIONs during polymer crosslinking [88]; covalent conjugation via surface ligands [89]; and biohybrid internalization where cells preloaded with SPIONs (via endocytosis) are encapsulated within hydrogels [90]. These approaches harness the size-dependent magnetic switching while tailoring hydrogel-SPION interfaces for targeted applications. The resultant hybrids exhibit three synergistic operational modalities (1) tunable actuation through Néel/Brownian relaxation mechanisms, enabling precise mobility control; (2) field-directed anisotropy for programmable alignment of embedded nanostructures; (3) dynamic thermal responsiveness via alternating field-induced eddy currents. These characteristics collectively empower advanced robotics applications while mitigating traditional hydrogel limitations—notably through SPIONs-enhanced mechanical reinforcement. Nevertheless, the iron oxide-polymer interface remains a double-edged sword: while enabling spatiotemporal control, it introduces oxidative degradation pathways requiring careful nanoparticle surface functionalization [91,92]. The following subsections detail how these inherent material properties translate into technological innovations across biomedical, environmental, and mechatronic domains.

4.1. Mobility

Traditional methods for enabling mobility in hydrogels typically involve physical and chemical approaches, such as catalytic reactions generating gases or mechanical forces [17,93]. By harnessing the magnetic responsiveness of superparamagnetic hydrogels, a new realm of possibilities emerges, allowing these hydrogels to respond to magnetic fields dynamically. The motion control of these hydrogels is governed by three key parameters: (1) magnetic field strength and gradient, which determine propulsion force and directionality; (2) SPIONs concentration and spatial distribution within the hydrogel matrix, influencing magnetic susceptibility; and (3) hydrogel viscoelasticity, which modulates deformation response to magnetic torques [94]. With their unique magnetism, superparamagnetic hydrogels can move within magnetic fields. This characteristic opens up various innovative applications, transforming superparamagnetic hydrogels into ballet dancers gracefully moving in the magnetic field.

The use of superparamagnetic hydrogels has led to the development of several technologies. One prominent application is the creation of biodegradable alginate hydrogel micromotors. These micromotors, fabricated using microfluidics and shaped like teardrops, incorporate Pt-coated Fe_3O_4 nanoparticles that provide both catalytic propulsion and magnetic guidance. The microfluidics-generated double emulsion templates and mild Ca^{2+} ion cross-linking method enable precise control over catalyst localization, resulting in high propulsion efficiency and distinctive motion patterns (Fig. 2A). This approach allows for high-throughput production of uniform microscale particles, showcasing the potential for complex biomedical tasks and advanced micromotor development [88].

Further advancements in micromotor technology include the development of multifunctional spherical micromotors made from sodium alginate and magnetic materials. These micromotors are designed for autonomous propulsion through either magnetic guidance or enzymatic catalysis. A key innovation is the gas shearing method, which enables rapid production of multichambered microspheres without the use of organic solvents, photo initiators, chemical crosslinkers, or cytotoxic agents [95]. Integrating biocompatible sodium alginate with magnetic nanoparticles (Fe_3O_4) and enzymatic catalysts like catalase allows for controlled motion through magnetic fields and catalytic decomposition of hydrogen peroxide (H_2O_2). This dual propulsion mechanism provides diverse movement patterns such as rotation, linear motion, rolling, curving, and circular trajectories (Fig. 2B), offering versatile applications in controlled environments and targeted biomedical tasks [17].

In addition to micromotors, superparamagnetic hydrogels are being explored for their potential in drug delivery systems [96]. A notable example is the development of dual-responsive neutrobots, which combine paclitaxel-loaded magnetic nanogels camouflaged with *Escherichia coli* membranes and phagocytosed by neutrophils. These biohybrid systems exhibit exceptional capabilities for magnetically actuated propulsion within intravascular environments (Fig. 2C). This approach facilitates effective blood-brain barrier penetration and targeted therapy for malignant glioma, enhancing precision drug delivery and therapeutic efficacy [97].

Moreover, a soft microrobot assembled with magnetic microsphere scaffold (MMS) beads and mesenchymal stem cells (MSC) has demonstrated responsive behavior to magnetic fields for precise drug delivery. This microrobot, guided by magnetic actuation, showcases remarkable speed and agility. Upon reaching the target site, the MMS beads release their MSC cargo efficiently in response to a phosphate-buffered saline solution, mimicking the extracellular environment (Fig. 2D) [98].

Another significant development is the creation of a novel drug delivery system utilizing superparamagnetic nanoparticles in hydrogels. The chitosan-based in situ forming depot delivery system, specifically the Fe_3O_4-THP-CS/GP system, leverages the magnetic responsiveness of superparamagnetic nanoparticles to enhance the localization and effectiveness of chemotherapy for cancer cells (Fig. 2E). This system allows for precise magnetic targeting and sustained release properties, demonstrating significant potential for improving treatment outcomes [89].

Miniaturized rotors utilizing the Marangoni effect have attracted considerable attention for propulsion and power generation. An innovative approach involving asymmetric porosity in Marangoni rotors composed of poly(N-isopropylacrylamide) (PNIPAm) and hexafluoroisopropanol has been proposed. This design integrates enhanced Marangoni propulsion and drag reduction, resulting in a significant increase in rotation output and fuel economy. The incorporation of iron-powder dopants further enables individual-specific locomotion under magnetic fields, showcasing multifunctional capabilities such as kinetic energy transmission, mini-generator operation, and environmental remediation (Fig. 2F) [99].

Beyond the intrinsic mobility, these superparamagnetic hydrogels can facilitate advanced movement in specific contexts, enabling the transportation of not only the hydrogels themselves but also their therapeutic cargo. This capability allows for targeted drug delivery, where the hydrogels can transport drugs to specific locations within the body, thereby enhancing their therapeutic efficacy and promoting desired biological functions. Such advancements underscore the potential of magnetic hydrogels in improving clinical outcomes through controlled, targeted, and efficient delivery mechanisms.

MagSToNE (Magnetic System for Total Nephrolith Extraction) represents a pioneering approach for optimizing kidney stone fragment removal. By employing a magnetic hydrogel that combines SPIONs with chitosan, this method improves the retrieval process of kidney stones. The SPIONs adhere to the exposed calcium ions on the stone surfaces, making the fragments magnetizable. A magnetic guidewire with alternating polarities is then utilized to efficiently attract and extract these fragments, overcoming the limitations of traditional retrieval techniques such as wire baskets (Fig. 3A). Additionally, the biocompatibility and antimicrobial properties of the hydrogel further enhance the effectiveness of this technique in achieving higher stone-free rates and better patient outcomes [100].

In another study, iron oxide superparamagnetic nanoparticles were encapsulated in a biocompatible polymer, PLGA, to create magnetic microrobots (MMRs) for targeted drug delivery. When injected into the hepatic artery, the MMRs could be directed to specific liver lobes using MRI gradients, demonstrating the ability of SPIONs to enable precise drug delivery within the liver (Fig. 3B) [101].

Superparamagnetic hydrogels have demonstrated remarkable

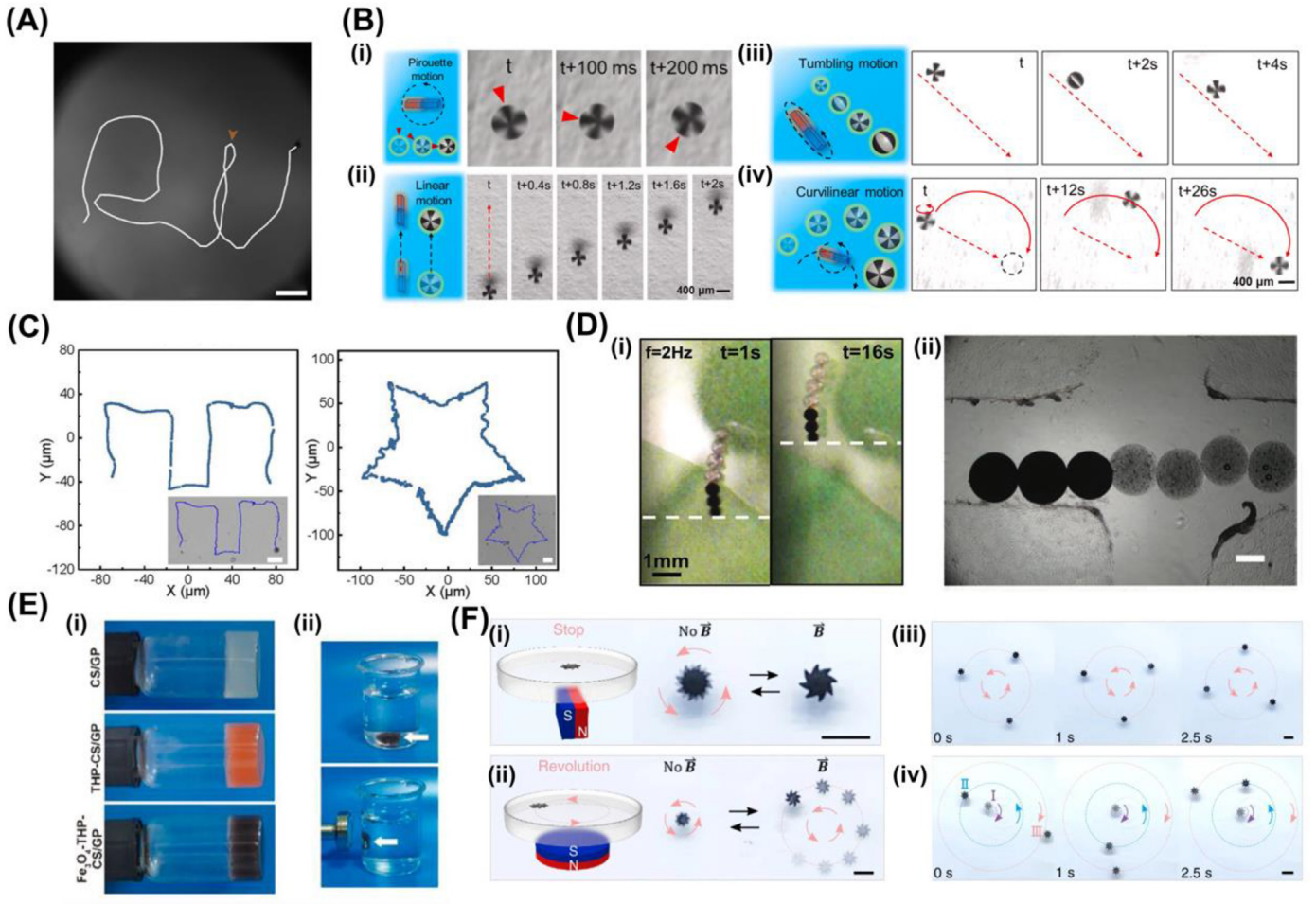


Fig. 2. Superparamagnetic hydrogels can be actuated in response to an external magnetic field. (A) Magnetic guidance of the hydrogel micromotor under the path of "R-shaped and U-shaped path". Scale bars, 500 μm. This figure was adapted from *Advanced Science* 2023,10(34), 2304995 [88]. (B) Hydrogel of the dual propulsion mechanism provides diverse movement patterns such as (i) pirouette motion(ii) linear motion, (iii) tumbling motion, (iv) curvilinear motion. Scale bars, 400 μm. This figure was adapted from *Heliyon* 2023,9(4), e14682. [17]. (C) Controllable magnetic propulsion of hydrogel in a predefined trajectory. Scale bars, 20 μm. This figure was adapted from *Science Robotics* 2021,6(52), eaaz9519 [97]. (D) Controlled locomotion of superparamagnetic hydrogel. (i) movement. Scale bars, 1 mm. (ii) precision mobility to specific locations. Scale bars, 200 μm. This figure was adapted from *Small* 2023,19(32), e2300430 [98].(E) Appearance and characteristics of Fe_3O_4-THP-CS/GP. (i)Liquid gel changes into a solid and stably sticks to the wall of the container. CS/GP gel is milky white, orange with THP, and black with Fe_3O_4-MNP. (ii) When the external magnetic field was applied, the Fe_3O_4-THP-CS/GP gel at the bottom of the container was quickly adsorbed to the sidewall. This figure was adapted from *Frontiers in Bioengineering and Biotechnology* 2022,10958072 [89]. (F) The magnetic rotor can be switched between rotation and stop by removing or applying the magnetic field of a (i) cuboid magnet and (ii) cylindrical magnet. (iii)Three magnetic hydrogel rotors with the same concentration of Fe_3O_4 nanoparticles can revolve along the same orbit, (iv)while those with different concentrations can revolve along different orbits under the magnetic field of a cylindrical magnet, with the revolution direction of the rotors adjustable by turning them over. Scale bars, 5 mm. This figure was adapted from *Advanced Healthcare Materials* 2023,12(28), e2300964 [99].

contributions to precise drug release and drug delivery systems. For instance, the development of multifunctional Fe_3O_4@PPy core-shell nanoparticles integrate near-infrared light-absorbing poly-pyrrole (PPy) with a magnetic Fe_3O_4 core, enabling imaging-guided and remotely controlled cancer therapy (Fig. 3C) [102]. Additionally, hydrogels made from alginate and xanthan gum that are crosslinked with calcium ions and modified with SPIONs, which can efficiently load and release levodopa, a key treatment for Parkinson's disease, in response to magnetic fields (Fig. 3D) [103]. Further advancements include magnetic hydrogels composed of polyvinyl alcohol (PVA) integrated with Fe_3O_4 particles are engineered to control drug release rates via an external magnetic field, allowing for tailored drug delivery profiles (Fig. 3E) [104].

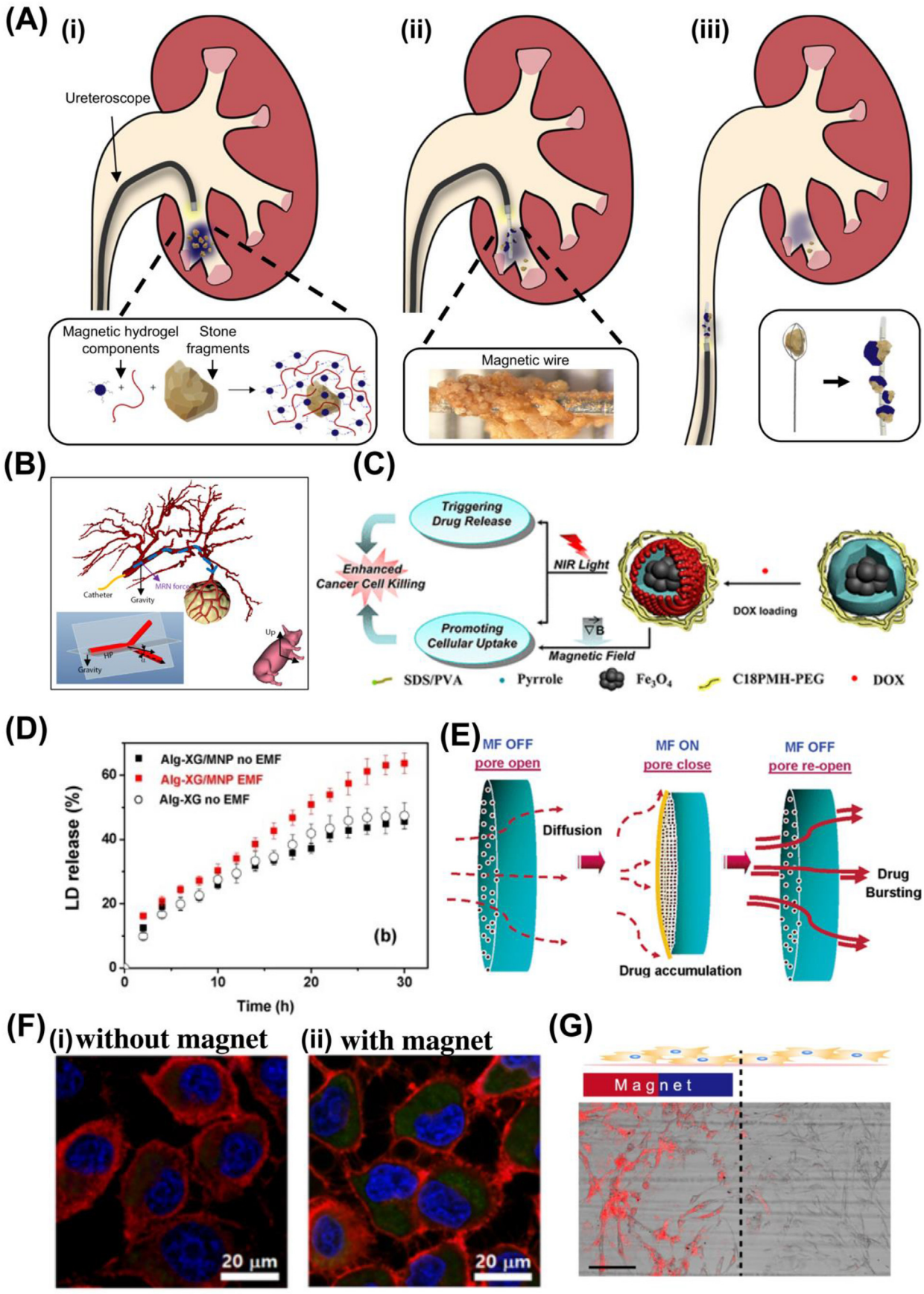
In the realm of targeted drug delivery systems, superparamagnetic magnetite nanoparticles have been integrated into PNIPAm hydrogel cores. By incorporating amine-functionalized copolymer shells and targeting ligands such as folic acid, these multifunctional hydrogels enable site-specific drug uptake by cancer cells through magnetic attraction and receptor-mediated endocytosis. This design enhances the efficacy of drug delivery while minimizing side effects (Fig. 3F) [105].

Another significant development is the dual-targeted drug delivery system using PLGA hydrogels and magnetic nanoparticles. This system effectively targets and inhibits calcification in aortic valves by delivering XCT790 specifically to osteogenically differentiated valvular interstitial cells (Fig. 3G), showcasing its potential for clinical application in treating calcific aortic valve disease [106].

In summary, superparamagnetic hydrogels have emerged as versatile platforms for targeted drug delivery and enhanced clinical outcomes. Their unique properties allow for precise control over drug release rates and targeted delivery to specific locations within the body, thereby improving therapeutic efficacy across a range of medical applications.

4.2. *Magnetoguidance*

In the previous section, we discussed how hydrogels can gain



(caption on next page)

Fig. 3. Superparamagnetism and hydrogel motion in a magnetic field. (A)Schematic of magnetic hydrogel for the retrieval of kidney stone fragments. (i) SPIONs and hydrogels coat kidney stones. (ii) A magnetic wire is introduced to capture the magnetically labeled stone fragments. (iii) The ureteroscope and wire, along with the captured fragments, are removed from the body. This figure was adapted from *Nature Communications* 2023,14(1), 3711 [100]. (B) Schematic of microrobot navigation in vivo. This figure was adapted from *Science Robotics* 2024,9(87), eadh8702 [101]. (C) Schematic of iron oxide @polypyrrole nanoparticles as a multifunctional drug carrier for remotely controlled cancer therapy with synergistic antitumor effect. This figure was adapted from *ACS Nano* 2013,7(8), 6782 [102].(D) Release profiles of Alg and Alg/XG in the presence and absence of a magnetic field. This figure was adapted from *Colloids and Surfaces B: Biointerfaces* 2018,167415 [103].(E) Schematic of drug release can be tunable while the magnetic field was switched from "off" to "on" mode. This figure was adapted from *Langmuir* 2006,22(14), 5974 [104]. (F) Intracellular localization of hydrogels in HeLa cells recorded using CLSM. Without magnet (Left) or with magnet (Right). Scale bars, 20 μm. This figure was adapted from *Scientific Reports* 2017,7(1), 41090 [105]. (G) Fluorescent and bright field images of SK@PFeCy5 cellular uptake within or near the magnetic field. Scale bars, 200 μm. This figure was adapted from *Nature Communications* 2024,15(1), 557[106].

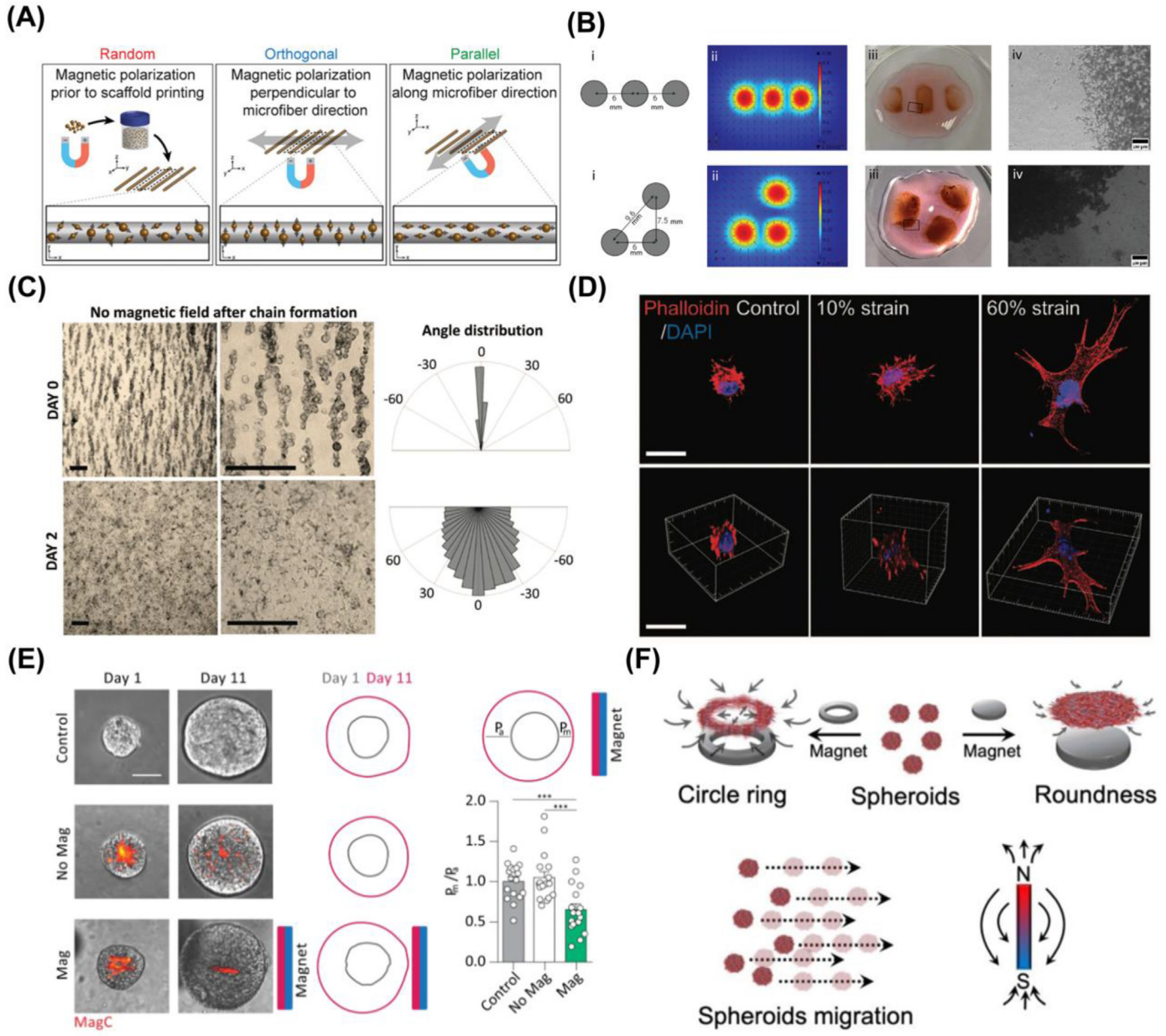


Fig. 4. Alignment of superparamagnetic hydrogels in magnetic field. (A) External magnetic field aligns magnetic domains within lattice to strengthen net particle magnetic field. This figure was adapted from *Advanced Functional Materials* 2023,33(40), 2203715 [107]. (B) Spatial organization patterns and mutual influence of magnetic rods in a 3D MNP-loaded collagen scaffold. (i) Illustration of magnetic rods' locations (ii) Simulation of magnetic flux density in COMSOL software. (iii) MNP-loaded collagen gel solidified under the influence of the magnet array. (iv) Light microscope images of the areas marked in iii. Scale bars, 100 μm. This figure was adapted from *Advanced Functional Materials* 2022,32(50), 2204925 [90]. (C) Evolution of the directionality of cell chains over time. Scale bars, 200 μm. This figure was adapted from *Advanced Functional Materials* 2022,32(50), 2204850 [108]. (D) 3D reconstructions of confocal slices of fibroblasts in the strained μMACs. Scale bars, 30 μm. This figure was adapted from *NPG Asia Materials* 2016,8(1), e238 [109]. (E) Representative images and schematic representation of day 1 and day 11 hNTmO contours. Growth ratio of hNTmOs for various actuation conditions. Scale bars, 50 μm. This figure was adapted from *Nature Communications* 2023,14(1), 5281 [110].(F) Schematic diagram of the patterning bone tissue by applying a circle ring/round magnet. This figure was adapted from *BMEMat* 2024,2(1), e12059 [111].

magnetic responsiveness by integrating with superparamagnetic nanoparticles, thereby enabling their spatial movement. Building on this capability, the following section explores how the incorporation of SPIONs into hydrogels not only facilitates mobility but also enhances the ability to guide, align, and direct cellular behaviors. This innovative strategy leverages the magnetic properties of SPIONs to precisely manipulate cellular behaviors within 3D biomaterials. This enables external control over the spatial arrangement of these cells, facilitating their controlled organization and alignment. This capability is particularly evident in several studies focusing on the use of magnetic particles in tissue engineering applications.

A notable development involves the incorporation of magnetic particles, including SPIONs and ferromagnetic microparticles (FMPs), into polycaprolactone (PCL) microfibers. This incorporation was achieved via fiber and solution electrospinning techniques, revealing that varying magnetic particle concentrations affect fiber diameter and deposition patterns. The resultant FMP-doped fibers exhibit controllable morphology and magnetic properties, enabling precise magnetic pole manipulation and suggesting potential applications in tissue engineering (Fig. 4A) [107]. This development underscores the utility of magnetic materials in facilitating alignment within these biocompatible scaffolds.

In another study, the integration of SPIONs with hydrogels enabled dynamic control over neural network organization within 3D biomaterials. The use of R-γ-Fe2O3-human serum albumin (HSA) SPIONs facilitated the internalization of magnetic properties within neurons, allowing the cells to respond to external magnetic fields. Consequently, these neurons were precisely guided and organized within multi-layered collagen scaffolds through the application of external magnetic fields, leading to patterned cellular arrangements (Fig. 4B) [90]. This method not only facilitated the creation of customized, layered 3D tissue architectures but also enhanced our understanding of cellular and tissue behaviors.

The innovative application of magnetic nanoparticles for the remote manipulation of cells in tissue engineering represents a significant advancement in the field. By making cells magnetic and applying remote forces, researchers have effectively created size-controlled magnetic spheroids and achieved precise spatial organization within 3D scaffolds. This multiscale magnetic approach not only enables high-throughput production of spheroids but also allows for the development of complex tissue structures with controlled alignment. Importantly, when the magnetic field is removed, the cells return to their original unaligned state without compromising their growth and viability, underscoring the reversible nature of this technique (Fig. 4C) [108].

Similar studies have utilized Fe_3O_4 nanoparticles and GelMA hydrogels to precisely control and simulate mechanical stress variations in a biological context through the application of external magnetic fields. By modulating the intensity of magnetic fields, stress variations are controlled, allowing these hydrogels to transmit mechanical strain to embedded cells, thereby effectively promoting their growth, spreading, proliferation, and differentiation. Notably, within the strain range of 40–60 %, NIH-3T3 fibroblasts and C2C12 myofibers exhibited significantly enhanced responses, indicating the considerable potential of superparamagnetic hydrogels to mimic physiological and pathological stress environments (Fig. 4D) [109]. This unique capability provides valuable insights into the interactions between cells and their mechanical environments.

Additionally, the development of “magnetoids” which are organoids with embedded magnetic nanoparticles, has enabled targeted mechanical stimulation within human neural tube organoids. By utilizing global magnetic fields to generate both internal and localized mechanical forces, this technology enhances tissue growth, morphogenesis, and patterning within organoid structures (Fig. 4E) [110]. Magnetoid technology offers valuable insights into mechanotransduction in developmental and disease models, emphasizing the role of local mechanical cues in tissue organization and function.

Lastly, a novel approach combining hydrogels and magnetic nanoparticles has been developed for patterning bone tissue. High-aspect ratio Fe_3O_4-HAp-PDA nanobelts were used to assemble MSCs into 3D hybrid spheroids, facilitating cell aggregation and improving cell-nanobelt interactions through magnetic field manipulation (Fig. 4F). This method effectively promoted osteogenic differentiation of both bone marrow and adipose-derived MSCs, presenting a versatile solution for bone tissue patterning and addressing challenges related to cell survival, differentiation efficiency, and integration of implanted cells [111].

4.3. Magnetothermal

In addition to mobility and directed alignment, magnetothermal properties are gaining attention. This distinctive ability leverages magnetic fields to induce thermal effects, offering significant potential in various applications. It allows precise control over heat generation and distribution within the hydrogel matrix, thereby enabling targeted therapy [112,113], remote control [114], and enhanced material functionalities [115]. Due to their high sensitivity, contrast, and non-ionizing radiation properties, SPIONs are particularly useful in cancer therapy through magnetic hyperthermia [116].

One notable example is the magnetic injectable biomaterial magnetic colloidal hydrogel (MCH), which exhibits excellent biocompatibility and hemocompatibility with negligible cytotoxicity observed in vitro. In vivo studies confirm its safety, as it causes no tissue damage or biochemical abnormalities. Notably, MCH demonstrates significant magnetocaloric effects under AMFs, effectively targeting HepG2 cells and indicating its potential in magnetic hyperthermia for treating hepatocellular carcinoma (HCC) (Fig. 5A) [117]. The integration of hard-magnetic soft materials could further enhance the mechanical adaptability of such hydrogels in dynamic biological environments [118]. This material's capability to penetrate deeper into tissues addresses limitations of conventional near-infrared (NIR) methods, positioning it as a promising tool for advanced hyperthermia therapies. In a similar vein, the CG-IM superparamagnetic hydrogel, which combines iron oxide nanoparticles and mica nanosheets, exhibits magnetic hyperthermia effects (Fig. 5B). It also shows promise in treating unresectable HCC with ultrasound-guided interventions [119].

Another advancement involves SPION-loaded nano-capsule hydrogels (SPION-NHs), which enhance MHT by prolonging retention and enabling multiple treatment sessions at moderate temperatures (Fig. 5C). Monitored by MRI, this method reduces tissue damage compared to single thermal ablation. In U-87 MG tumor studies, multiple MHT cycles led to significant tumor reduction and minimal recurrence, outperforming microwave thermal ablation, which, while effective, carries risks like bleeding and infection [120]. Recent studies highlight that amine-functionalized SPIONs can optimize thixotropic behavior in hydrogels, synergizing with the present design to achieve sustained drug release under magnetic actuation [121].

Research has led to the development of a novel nano-bio-composite combining sodium alginate, silk fibroin, halloysite nanotubes, and SPIONs. This hydrogel shows high blood compatibility and low toxicity while effectively targeting breast cancer cells. With a magnetic saturation of 15.96 emu/g and a specific absorption rate (SAR) of 22.3 W/g under AMFs, it performs efficiently in magnetic fluid hyperthermia, highlighting the potential of SPIONs to enhance hydrogel cancer treatments (Fig. 5D) [122]. The optical phenomena explored in molecule-based magnetic materials may offer future avenues to integrate photothermal-magnetic multimodal responses in such systems [123].

In another innovative approach, combining SPIONs with a thermally responsive comb-type hydrogel matrix has led to the development of light-responsive hydrogels. These hydrogels convert absorbed visible light into thermal energy, resulting in rapid volume changes (Fig. 5E). The free, mobile grafted chains within the comb-type hydrogel facilitate swift responses, enhancing light-induced volume shrinkage and recovery rates. This combination has enabled the creation of a bilayer-type photoactuator capable of rapid bending motions [124].

Looking forward, magnetic polymeric conduits exemplify translational

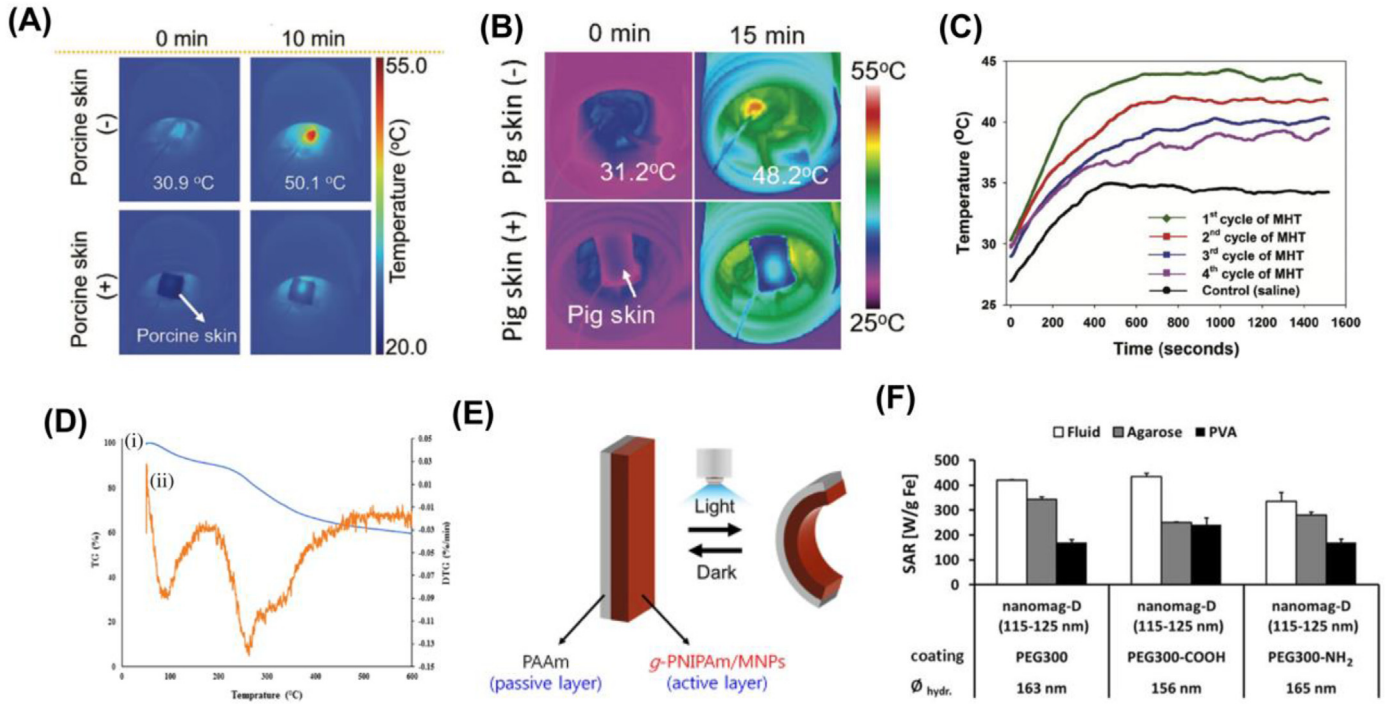


Fig. 5. Magnetothermal of Superparamagnetic Hydrogels (A) Infrared thermal images under alternating magnetic field (AMF) . This figure was adapted from *Advanced Materials* 2024,36(26), e2309770 [117]. (B) Infrared thermal images of mice under AMF. This figure was adapted from *Small* 2024,20(3), 2300733 [119]. (C) The elevated tumor temperature versus time graphs induced by multiple MHT after a single injection of PEGylated SPION aqueous solution. This figure was adapted from *Biomaterials* 2016, 13–23 [120]. (D) The thermogravimetric analysis (i) and DTG curve (ii) of SA/SF/HNTs/Fe_3O_4 bio-composite. This figure was adapted from *Scientific Reports* 2022,12(1), 15431 [122]. (E) Bending motion of the bilayer-type actuator comprising poly(acrylamide) (PAAm) and g-PNIPAm(209)/MNP under visible light irradiation. This figure was adapted from *Scientific Reports* 2015,5(1), 15124 [124]. (F) SAR values of multicore nano-mag-D MNP with differently functionalized PEG300 in water suspension and immobilized in 1 % agar and 10 % PVA. Additionally, hydrodynamic diameters (Øhydr.) for each MNP type are shown. This figure was adapted from *Nanoscale Research Letters* 2014,9(1), 602 [126].

potential, suggesting that current hydrogel platforms could evolve into implantable devices for localized hyperthermia delivery [125]. Research on immobilization methods has highlighted variations in the SAR of magnetic nanoparticles. Different coating materials and synthesis processes result in distinct hysteresis parameters and SAR values (Fig. 5F). For instance, PVA immobilization significantly reduces SAR values, while agarose affects SAR differently, emphasizing the importance of immobilization effects in optimizing tumor therapy [126].

4.4. Robotics

Recent advancements in hydrogel-based soft robotics have expanded the design and functional capabilities of micro-robotic systems, particularly through the integration of stimuli-responsive materials like SPIONs [127–129]. Superparamagnetic hydrogels not only enhance basic functionalities such as movement, magnetoguidance, and magnetic hyperthermia but also enable multimodal responsiveness, a critical feature for adaptive robotics [130,131]. For instance, dual-responsive supramolecular hydrogels that react to both magnetic fields and light have emerged as a breakthrough. These materials exhibit tunable stiffness under magnetic fields and reversible rigidity adjustments via UV/visible light, making them ideal for soft robotic actuators and tissue-mimetic scaffolds [132]. This dual-responsive behavior aligns with broader trends in soft robotics, where multi-stimuli hydrogels are increasingly explored to mimic biological adaptability.

Additionally, these SPION-loaded hydrogels have been effectively utilized in drug delivery systems [133–137]. Microrobots incorporating these hydrogels achieve targeted drug release with low cytotoxicity, as demonstrated in studies where 3T3 fibroblast-compatible devices degraded fully in alkaline environments [138]. Furthermore, microrobots engineered with anticancer drugs like 5-fluorouracil, when exposed to alternating magnetic fields, release the drug and induce localized hyperthermia [139], significantly reducing cancer cell viability. These advancements parallel developments in biohybrid robotics, where living cells or enzymes are integrated into hydrogels for autonomous sensing and actuation [140], though SPION-based systems offer superior remote controllability and scalability.

For future biomedical applications like diagnostics and targeted delivery, the use of mobile micro- and nanorobots is recommended, with an emphasis on ensuring their biocompatibility and biodegradability for successful clinical translation [99]. By creating small robots with non-cytotoxic, biodegradable soft components, device assimilation can be enhanced, tissue interactions optimized, and immune responses minimized [141].

A study demonstrated the fabrication of biodegradable soft helical swimmers using non-toxic gelatin methacryloyl (GelMA) through dual-photon polymerization (Fig. 6A). These GelMA swimmers, decorated with magnetic nanoparticles, exhibit adaptive behavior that surpasses that of rigid microrobots [142]. Another notable innovation in this field is the development of a 20 μm-long, 6 μm-wide hydrogel-based micro--swimmer with a double-helical design, capable of carrying therapeutic cargo and swimming under rotational magnetic fields (Fig. 6B). This micro-swimmer degrades in 118 h into nontoxic byproducts, swells to enhance cargo release, and can deliver anti-ErbB2 antibody-tagged magnetic nanoparticles for breast cancer imaging [143].

Innovations in micro-swimmer technology have produced controllable magnetic hybrid micro-swimmers with hollow helical structures, designed through a simple microfluidic template synthesis and biosilicification method. Incorporating Fe_3O_4 nanoparticles into a biocompatible alginate/protamine/silica shell enhances their mechanical strength and allows for customized structural modifications. For instance, magnetic hybrid micro-swimmers (pitch = 720 μm, CMNPs = 5

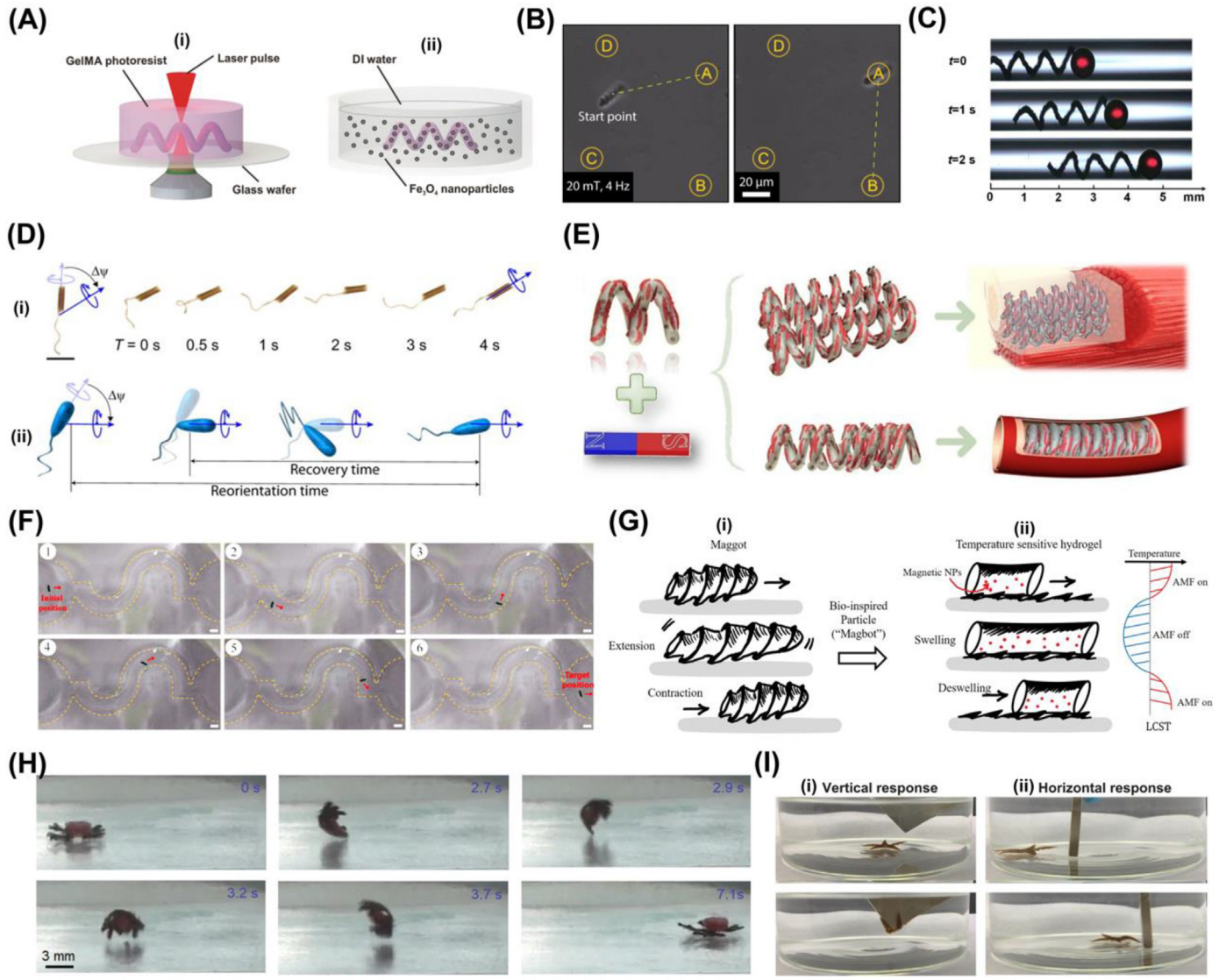


Fig. 6. Superparamagnetic hydrogel robots. (A) Schematic of 3D Printed Enzymatically Biodegradable Soft Helical Micro-swimmers (i) 2 PP is used to print GelMA helical microstructures; and (ii) the printed structures are decorated with magnetic nanoparticles by incubation in water suspensions of Fe_3O_4 nanoparticles. This figure was adapted from *Advanced Functional Materials* 2018,28(45), 1804107 [142]. (B) Magnetic steering control of the micro-swimmer. Scale bars, 20 μm. This figure was adapted from *ACS Nano* 2019,13(3), 3353 [143]. (C) Magnetic hybrid micro-swimmers (pitch = 720 μm, CMNPs = 5 wt%) powered by the rotating magnet with f = 800 rpm, are used to transport the poly-ETPTA microspheres in an aqueous solution with viscosity of 1.03 mPa s. This figure was adapted from *Industrial & Engineering Chemistry Research* 2018,57(29), 9430 [144]. (D) The yaw angle Ψ was instantly changed 45°, while the swimmers were driven at 2 Hz with a field strength of 20 mT in a solution with a viscosity of 3 mPa s. (i) Time-lapse images of a micro-swimmer with a tubular body and helical tail during the reorientation of its swimming direction. (ii) Changing the tail to a planar geometry and ϕ to 30° led to a complete loss of motility. This figure was adapted from *Science Advances* 2019, 5(1), eaau1532 [145]. (E) Schematic illustrations that stack or tube assembly of these helical micromotors under magnetic force and their potential in tissue repair and blood vessel scaffold. This figure was adapted from *ACS Applied Materials & Interfaces* 2020,12(14), 16097 [146]. (F) the movement of GFHM inside an S-shaped microfluidic channel with the guidance of rotating magnetic field. Scale bars, 1000 μm. This figure was adapted from *ACS Nano* 2020,14(12), 16600 [147]. (G) Particle motion and bio-inspiration (i) Schematic showing the crawling motion of a common maggot. (ii) Active particles can be made following similar mechanisms when fabricated with a temperature-sensitive NiPAAm hydrogel loaded with magnetic nano-particles. This figure was adapted from *Scientific Reports* 2017,7(1), 16178 [148]. (H) Snapshots of cargo delivery via rolling locomotion under rotating magnetic fields of 25 mT. Scale bars, 3 mm. This figure was adapted from *Advanced Functional Materials* 2020,30(50), 2004975 [149]. (I) Photos of 3D printed magnetic starfish hydrogels with 1 wt% SPIONs demonstrating response to a magnet. (i) The arms swing towards the magnet and attach to it. (ii) Hydrogel starfish can follow the movement of the magnet. This figure was adapted from *Chemical Engineering Journal* 2021,407127187 [16].

wt%) powered by rotating magnets at 800 rpm successfully transport poly-ETPTA microspheres in an aqueous solution with a viscosity of 1.03 mPa s (Fig. 6C) [144].

Comparatively, origami-inspired hydrogel robots (Fig. 6D) leverage temperature-responsive self-folding for 3D shape-morphing, a strategy gaining traction for minimally invasive surgery. This approach highlights the ingenuity of combining compliant structures and magnetic enhancements to achieve functional autonomy in small-scale devices, drawing parallels to the adaptive mechanics observed in bacteria. Investigating the interplay of hydrodynamic forces and local rheology on low Reynolds number swimming advances our understanding of elasto-hydrodynamic coupling in locomotion and its potential applications in untethered micro-robotics [145]. Additionally, helical micromotors developed via microfluidic spinning technology facilitate cell seeding and cultivation with customizable morphologies and biocompatibility, while magnetic nanoparticles enable responsive motion under fields,

showcasing potential in tissue repair and blood vessel scaffolding (Fig. 6E) [146].

Recent research has advanced soft robotics and biomedical applications with graphene oxide-based helical micromotors (GOFHMs) embedded with superparamagnetic iron oxide (Fe_3O_4) nanoparticles. These micromotors, customizable in pitch, length, and diameter through microfluidic techniques, show promise in water remediation and drug delivery, particularly with doxorubicin (Fig. 6F) [147]. These designs draw inspiration from natural microswimmers, but recent work has further optimized their propulsion efficiency by mimicking helical flagellar structures or ciliary beating.

Another significant advancement is the development of magnetically responsive hydrogel crawlers, which represent a leap forward in soft robotics, particularly for maneuvering within confined spaces. These crawlers, inspired by the peristaltic motion seen in organisms like maggots and earthworms, utilize remote magnetic fields to achieve reversible contraction and elongation (Fig. 6G). This capability allows controlled movement within micro-patterned environments, showing great promise for targeted drug delivery and the creation of active actuators that can navigate through porous biological tissues and materials [148].

Furthermore, the study presents a robust strategy for fabricating biocompatible and fully biodegradable soft millirobots embedded with SPIONs within a collagen-based hydrogel derived from porcine extracellular matrix. This method facilitates precise 3D magnetic anisotropy programming via external magnetic fields, enabling complex shape deformations and functional behaviors such as cargo grabbing and transportation in biologically relevant environments (Fig. 6H). The biocompatibility and degradation profile of these magnetically responsive hydrogels enhance their safety and performance in minimally invasive medical applications [149].

Advancements in 3D printing technology have led to the development of a photosensitive resin infused with uniformly dispersed SPIONs, effectively reducing aggregation during the printing of magnetically responsive hydrogels optimized for stereolithography. The resulting starfish-shaped hydrogels exhibit strong superparamagnetic properties, responding to external magnetic fields and reverting upon field removal (Fig. 6I). This innovation overcomes extrusion printing limitations, presenting opportunities for the creation of soft, flexible hydrogels with

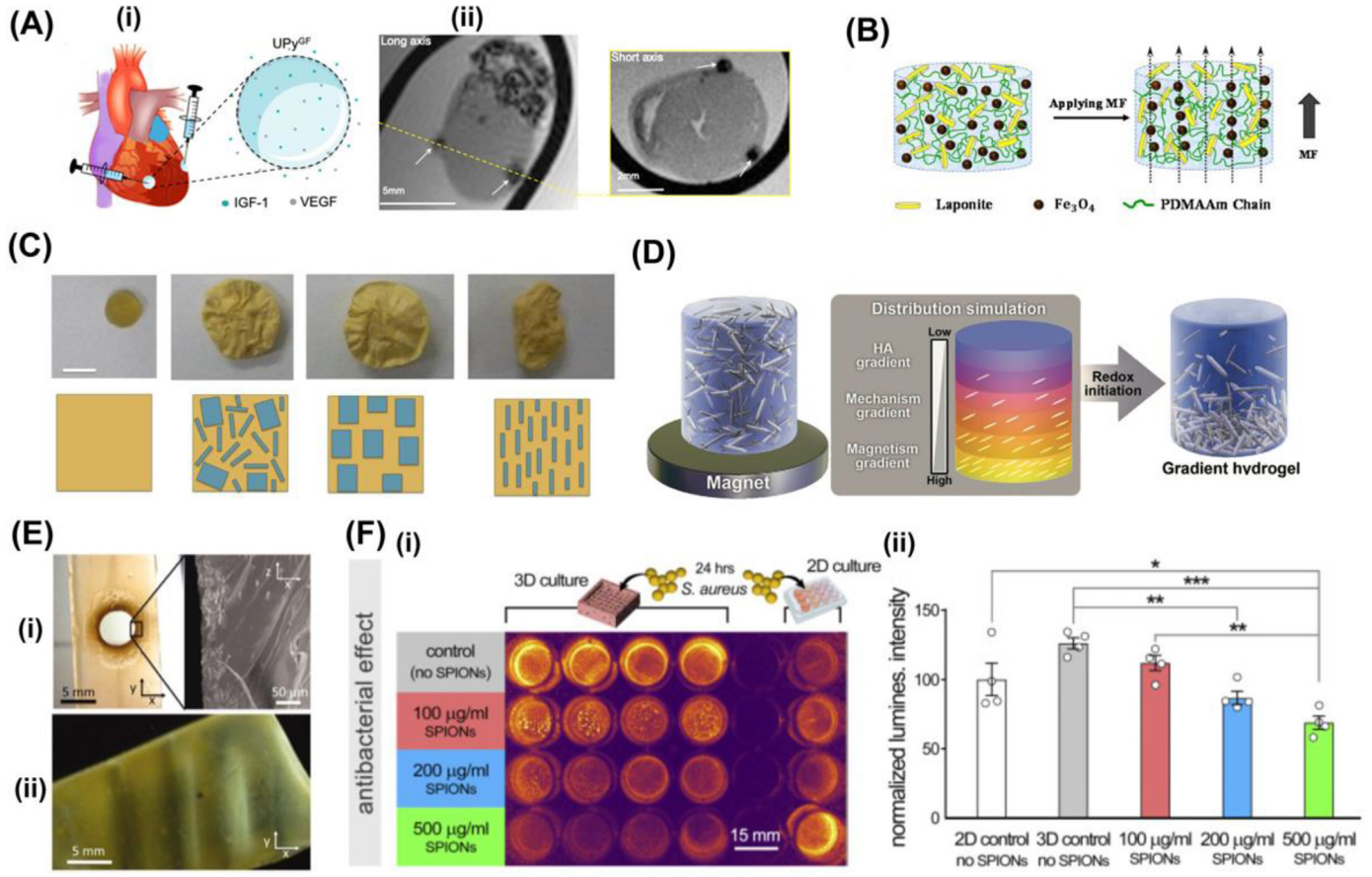


Fig. 7. Advanced functionalities of superparamagnetic hydrogels. (A) UPy^{GF}-hydrogel characterization and in vivo setup.(i) UPy^{GF}-hydrogel slowly released insulin-like growth factor 1 (IGF1) and vascular endothelial growth factor (VEGF). (ii) Proof-of-concept *ex vivo* T_2* MRI to verify intramyocardial UPy^{GF}-hydrogel injections labeled. Scale bars, 5 mm. This figure was adapted from *Scientific Reports* 2019,9(1), 19366 [150]. (B) Schematic illustration of the expected network structure of the PD3L4F2 MR_NCH without (left) and with (right) an applied MF. When an MF is applied, the Fe_3O_4 nanoparticles in the MR_NCH align along the direction to an applied MF, which also changes the arrangement of laponite nanoparticles and PDMAAm chains attaching to the surface of the laponite nanoparticles. This figure was adapted from *Nature Communications* 2013,4(1), 1712 [160]. (C) Alginate-alumina monolayer hydrogel composites with various reinforcement architecture. Scale bars, 1 cm. This figure was adapted from *Scientific Reports* 2019,9(1), 15024 [159]. (D) Scanning electron microscopy (SEM) images of SPIONs, hyaluronic acid (HA), and magnetic hyaluronic acid (MagHA). This figure was adapted from *Advanced Materials* 2023,35(19), 2209565 [167]. (E) Unusual 3D reinforcement architectures through advanced orientational and spatial magnetic control. (i) shows the distribution of UHMR particles in PVA composites under a magnetic field gradient, particularly around weak points in the material. (ii) illustrates the reversible formation of topographical ripples on the polymer surface due to local swelling, which depends on the platelet orientation. Scale bars, 5 mm. This figure was adapted from *Science* 2012,335(6065), 199 [169]. (F) Evaluating the antibacterial effect of varying concentrations of SPIONs in 2D culture (control) and 3D bioprinted GelMA scaffolds, seeded with luminescent *S. aureus* bacteria. Luminescence imaging of 2D controls and 3D printed constructs was performed after 24 h of incubation with bacteria (i) and the signal intensity was quantified and normalized based on the 2D control without SPIONs (ii). Scale bars, 15 mm. This figure was adapted from *Advanced Drug Delivery Reviews* 2011,63(1), 24 [80].

complex structural designs [16]. These developments promise advancements in soft robotic actuators and aquatic grippers, showcasing the potential for sophisticated and functional soft robotic systems.

4.5. Additional advantages

Beyond the remarkable capabilities of superparamagnetic hydrogels in mobility, magnetoguidance, magnetic thermal response, and robotics, there has been significant exploration into their advanced features. These include applications in sustained drug release, MRI localization [150], capacitive properties [151], antibacterial activity [152], adsorption [153,154], water purification [155,156], 3D assembly [24], wound healing [157], suspended cell culture [158], enhanced mechanical performance [159,160], as well as regenerative medicine and electronic devices. The integration of SPIONs into hydrogels has led to substantial advancements across these diverse fields [161,162]. By leveraging the unique properties of SPIONs, researchers have achieved new functionalities and improved performance in various applications, highlighting the transformative potential of these materials in both existing and emerging technologies.

In the realm of medical imaging, superparamagnetic hydrogels have found extensive utility, particularly in MRI, due to their unique properties that enable precise localization and imaging enhancement [163,164]. A study demonstrated that UPy^{GF} hydrogels, embedded with ultrasmall superparamagnetic iron oxide (USPIO) nanoparticles, can sustain the release of IGF1 and VEGF for up to 7 days, which is crucial for effective cardiac repair. The hydrogels' ability to maintain a prolonged release of these growth factors supports ongoing cardiac tissue regeneration. Moreover, MRI imaging confirmed the precise localization of these hydrogels within the myocardium, facilitating targeted delivery (Fig. 7A) [150].

In addition to their precise localization capabilities demonstrated in MRI applications, superparamagnetic hydrogels benefit from significant performance enhancements due to the incorporation of iron oxide nanoparticles. For example, magneto-responsive nanocomposite hydrogels (MR_NCHs) developed with Fe_3O_4 nanoparticles embedded in N,N-dimethylacrylamide (DMAAm) and laponite exhibit remarkable improvements in magnetorheological behavior, mechanical strength, and biocompatibility (Fig. 7B) [160]. These advanced MR_NCHs are well-suited for use as soft actuators in pharmaceutical and biomedical applications. Moreover, the addition of SPIONs enables the creation of self-shaping composites with programmable shape changes. By leveraging ultra-high magnetic responsiveness (UHMR) of anisotropic micro-particles, precise control over particle orientation allows for the design of complex, shape-changing microstructures (Fig. 7C) [159]. This integration of iron oxide nanoparticles thus not only enhances the mechanical and magnetic properties of hydrogels but also expands their versatility and functionality in advanced material design.

Superparamagnetic hydrogels are also being explored for bone repair applications [165,166]. A novel method for repairing hierarchical osteochondral defects involves using a hydrogel with continuous gradients in nano-hydroxyapatite content, mechanical properties, and magnetism (Fig. 7D). This hydrogel incorporates superparamagnetic HA nanorods that respond to a brief magnetic field, allowing for the creation of precise biophysical and biochemical gradients. By optimizing the gradient configuration based on magnetic resonance imaging data from healthy rabbit knees, this approach effectively reconstructs osteochondral tissue and promotes cell infiltration. When applied to rabbit osteochondral defects with a local magnetic field, this multileveled gradient composite hydrogel shows promising outcomes in tissue regeneration, accurately mimicking the natural cartilage-to-subchondral bone transition [167].

Superparamagnetic hydrogels have demonstrated significant advancements in the development of supercapacitors, which are crucial for enhancing the reliability and lifespan of electronic device power supplies [168]. A recent study developed a multi-responsive, healable supercapacitor using Fe_3O_4@Au/polyacrylamide (MFP) hydrogel electrodes with silver nanowire films, which offers high mechanical strength and rapid healing via photothermal and magneto-thermal processes, and achieves triply-responsive healing with integrated electroactive polypyrrole nanoparticles [151]. This enhancement is further complemented by the role of iron oxide nanoparticles, which improve both the mechanical and magnetic properties of the hydrogels. Notably, micrometer-sized reinforcing particles, coated with low concentrations of superparamagnetic nanoparticles (0.01–1 vol percent), can be precisely manipulated using ultralow magnetic fields (1–10 mT) (Fig. 7 E) [169]. This integration not only broadens the functional applications of these hydrogels but also enables the fine-tuning of their structural and performance characteristics in advanced supercapacitor technologies.

In the field of biomedical engineering, recent advancements have focused on developing multifunctional materials that combine antibacterial properties with magnetic resonance imaging visibility [152]. One such innovation involves the integration of SPIONs into various hydrogel scaffolds, including collagen-based cardiac patches and GelMA-based bioinks. These SPION-containing materials have been shown to inhibit bacterial growth, such as that of Salmonella and Staphylococcus aureus, within a specific SPION concentration range of 100–500 μg/mL (Fig. 7F). Below this range, antibacterial effects and MRI contrast are diminished, while concentrations above 500 μg/mL can lead to aggregation and potential cytotoxicity issues [80]. The incorporation of SPIONs into biomaterials not only enhances their antimicrobial capabilities but also enables non-invasive MRI monitoring, opening up new avenues for personalized and precision medicine [170]. This dual functionality represents a significant step forward in the development of antibacterial and MRI-visible materials for biomedical applications.

Recent advancements in magnetic hydrogels, leveraging their unique superparamagnetic properties, have significantly enhanced their applicability in environmental remediation. These hydrogels, particularly those incorporating SPIONs, demonstrate exceptional capabilities in purifying wastewater through their enhanced adsorption capacities [153,154].

For instance, Prussian blue-embedded magnetic hydrogel beads (PB-MHBs), which incorporate in-situ-formed iron oxide nanoparticles as cross-linkers, effectively encapsulate Prussian blue and allow for efficient magnetic separation of radioactive cesium (^{137}Cs) from water (Fig. 8A). The integration of superparamagnetism with robust adsorption characteristics has made these hydrogels highly effective in addressing water pollution and removing hazardous substances [156]. Moreover, a nanocomposite hydrogel (Cs/PPA/EDA/Fe_3O_4-NPs) was synthesized via gamma irradiation, enhancing its superabsorbent and superparamagnetic properties (Fig. 8B). This material demonstrated exceptional capability in adsorbing hazardous dyes from contaminated solutions, showcasing its potential application in environmental remediation [155]. By combining strong adsorption abilities with efficient contaminant removal, these materials are poised to play a pivotal role in enhancing water quality and mitigating the impact of pollutants in aquatic environments.

pH-sensitive hydrogels often have a wide range of applications. A recent study focuses on the synthesis and characterization of pH-sensitive superparamagnetic hydrogel nanocomposites, specifically AA-VSA-P/SPIONs, optimized with varying concentrations of SPIONs at 1.2 %, 3.2 %, and 5.2 % by weight. These hydrogels efficiently adsorb cationic dyes such as methylene blue (MB) from aqueous solutions, particularly under alkaline conditions (pH = 9). They exhibit excellent magnetic responsiveness, facilitating easy separation of dye-loaded hydrogels using a 180 mT bar magnet [23]. This pH-sensitive system shows significant potential for sustainable wastewater treatment due to its high adsorption capacity, recyclability, and eco-friendly nature. Furthermore, Similar studies underscores the dual functionality of these pH-sensitive magnetic hydrogels in biomedical applications, where their superparamagnetism is leveraged for diagnostic purposes (Fig. 8C) [171]. The effective water treatment and advanced diagnostic capabilities of these materials highlight their broad applicability and substantial utility.

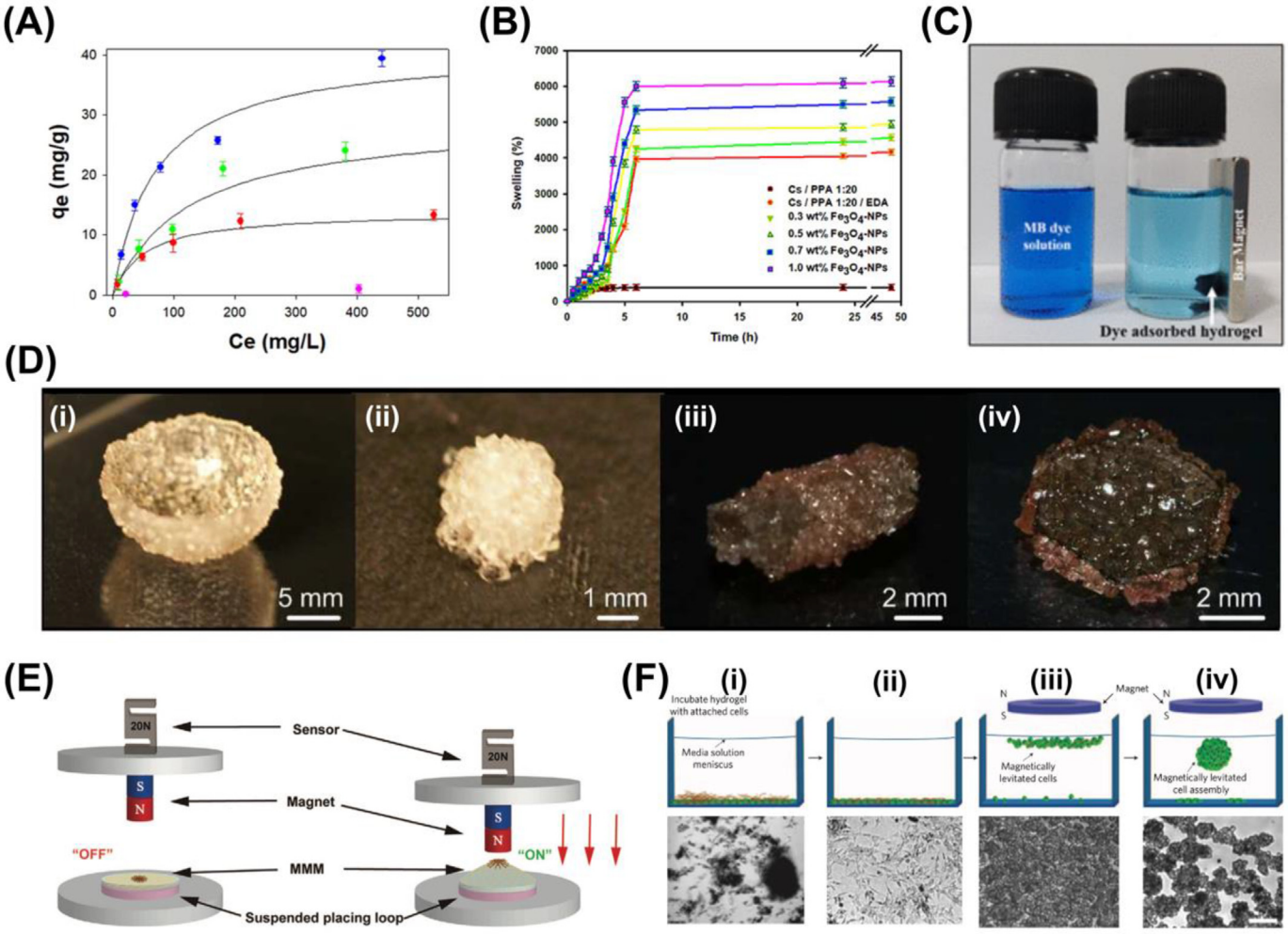


Fig. 8. Advanced functionalities of superparamagnetic hydrogels. (A) Adsorption isotherm data obtained from the various PB-MHBs (red: PB-MHBs-1, green: PB-MHBs-2, blue: PB-MHBs-3, pink: MHBs) . This *f*igure was adapted from *Carbohydrate Polymers* 2022,283119149 [156]. (B) Swelling percentage as a function of time for Cs/PPA/EDA copolymer hydrogel and Cs/PPA/EDA/Fe_3O_4 -NPs nanocomposite hydrogel. This *f*igure was adapted from *Scientific Reports* 2018,8(1), 11476 [155]. (C) Photograph of dye adsorption and subsequent magnetic separation phenomena before and after dye adsorption by AA-VSA-P/SPIONs-I at pH 9 and the dye-adsorbed hydrogel magnetically separated by a bar magnet (180 mT) . This *f*igure was adapted from *ACS Omega* 2020,5(34), 21768 [171]. (D) Schematics describing magnetic assembly of 3D structures: (i) dome, (ii) sphere, (iii) tube, (iv) hexagon. Scale bars, 5, 1, 2, 2 mm, respectively. This *f*igure was adapted from *Advanced Materials* 2011,23(37), 4254 [24]. (E) Schematic diagram of the testing process of MMM. This *f*igure was adapted from *Small* 2024,20(28), 2400644 [157]. (F) 3D cell culture with magnetic-based levitation. (i) Hydrogel is dispersed over cells and the mixture is incubated. The dark blotches are fragments of hydrogel. (ii) Washing steps remove non-interacting hydrogel fragments. Fractions of phage, gold and MIO nanoparticles enter cells or remain membrane-bound. (iii) Application of an external magnet causes cells to rise to the air–medium interface. (iv) After 12 h of levitation, characteristic multicellular structures form (a single structure is shown in the schematic). Scale bars, 30 mm. This *f*igure was adapted from *Nature Nanotechnology* 2010,5(4), 291 [180].

In the field of 3D assembly, the integration of superparamagnetic Nanoparticles and hydrogels is also indispensable [172–174]. A newly developed biomaterial, termed M-gel, integrates magnetic nanoparticles into microscopic hydrogels, thereby preserving their inherent biocompatibility while introducing novel functionalities for both cell culture and magnetic manipulation. This advancement allows for the precise construction of 3D multilayer structures through the application of external magnetic fields. The inclusion of SPIONs enables M-gels to replicate complex in vivo anatomical geometries, including domes, spheres, tubes, and hexagons (Fig. 8D). These features highlight M-gels' potential for advanced biomedical applications, particularly in tissue engineering and related fields [24].

In the realm of wound repair and healing, hydrogels make significant contributions that cannot be overlooked [34,175]. Recent study highlights the development of a magneto-responsive massage membrane (MMM) that integrates an elastic GelMA hydrogel, reinforced fibers with a negative Poisson's ratio, and Fe_3O_4 nanoparticles. The MMM enables precise mechanical stimulation through magnetic activation, demonstrating significant improvements in wound contraction and re-epithelialization in both in vitro and in vivo models (Fig. 8E), showcasing its potential for advanced wound healing applications [157].

Suspension is a distinctive feature of magnetic materials, and superparamagnetic materials, in particular, can impart this property to hydrogels, enabling exceptional performance in various applications [176,177]. These materials are frequently explored for suspension-based cell culture techniques due to their excellent anti-gravitational properties, which allow for precise control over cell positioning and movement in suspension [178]. This control is vital for biomedical applications such as drug delivery systems and tissue engineering [179]. Additionally, the magnetic responsiveness of superparamagnetic Nanoparticles facilitates non-invasive manipulation under external magnetic fields, providing a versatile method for achieving uniform cell distribution and enhancing cellular interactions within the suspension environment [158]. A study introduces a novel, cost-effective 3D tissue culture technique using magnetic levitation with a hydrogel containing gold, magnetic iron oxide nanoparticles, and filamentous bacteriophage, which enables precise cell

control and multicellular clustering, offering a simpler and more adaptable alternative to traditional methods (Fig. 8F) [180].

5. Future prospects and strategic directions

The integration of SPIONs into hydrogels has established a transformative platform that merges the remote controllability of magnetic materials with the biocompatibility and structural versatility of hydrogels. These systems enable precise spatiotemporal manipulation of material properties, including programmable drug release, dynamic mechanical adaptation, and targeted thermal therapy—capabilities that are reshaping approaches to precision medicine and environmental remediation. However, the translation of these laboratory innovations into real-world applications requires overcoming fundamental limitations rooted in material design constraints and interdisciplinary knowledge gaps.

A primary concern lies in the inherent compromises observed in existing SPION-hydrogel designs. High concentrations of magnetic nanoparticles often enhance actuation efficiency and thermal responsiveness but exacerbate biological risks, such as accelerated immune recognition and cellular stress. Conversely, strategies prioritizing biocompatibility through reduced SPION loading frequently sacrifice mechanical stability and controlled drug release kinetics. These contradictions highlight the necessity of rethinking material architectures to decouple performance parameters traditionally viewed as mutually exclusive. Furthermore, while magnetic actuation enables precise spatiotemporal control, the physical constraints of field penetration depth and targeting accuracy limit applicability in deep-tissue therapies, necessitating the development of multimodal stimulation platforms that synergize magnetic guidance with complementary energy modalities.

The field stands at a crossroads, where three transformative pathways could redefine its trajectory. First, the convergence of stimuli-responsive materials and biomolecular computing may yield intelligent systems capable of context-dependent decision-making, such as microenvironment-sensitive drug release or self-adapting mechanical properties. Second, advances in scalable manufacturing technologies could bridge the gap between bench-scale innovation and industrial production, addressing critical issues like batch-to-batch consistency and long-term stability. Third, the integration of sustainability principles into material design—through renewable precursors, energy-efficient synthesis, and closed-loop recyclability—could unlock environmentally responsible applications beyond biomedical domains.

Despite this potential, significant barriers persist. The lack of standardized protocols for assessing long-term biocompatibility and environmental impact poses regulatory challenges, particularly regarding nanoparticle biodistribution and ecosystem interactions. Moreover, the field suffers from fragmented interdisciplinary collaboration, where material innovations often progress in isolation from clinical needs and engineering realities. This disconnects manifests in promising laboratory achievements that fail to meet practical requirements for clinical translation or large-scale implementation.

Interdisciplinary collaboration emerges as a critical driver for progress. Clinically oriented research must prioritize the co-design of SPION-hydrogel systems with surgical applications, such as magnetically deployable barriers for tumor margin sealing or minimally invasive cardiac patch delivery. Environmental applications, meanwhile, demand scalable manufacturing techniques that align with circular economy principles—for instance, UV-degradable hydrogels enabling magnetic recovery and reuse of SPIONs in water purification systems. Emerging green synthesis methods, including solvent-free magnetic crosslinking, exemplify how sustainable production can coexist with high-performance material engineering.

The path forward requires reimagining innovation cycles to integrate application-specific validation at every development stage. By coupling advances in magnetic material science with rigorous biological and environmental testing, researchers can transform SPION-hydrogels from experimental platforms into robust solutions for global healthcare and sustainability challenges. Success will depend not only on technological breakthroughs but also on cultivating ecosystems where material scientists, clinicians, and engineers collaboratively address real-world constraints. Through this holistic integration of design, validation, and implementation, SPION-hydrogel systems may ultimately fulfill their potential as adaptive therapeutic tools and environmental stewardship technologies.

CRediT authorship contribution statement

Huaibin Wang: Writing – review & editing, Writing – original draft. **Yingying Hou:** Writing – original draft. **Long Chen:** Writing – review & editing, Writing – original draft. **Weihong Mo:** Writing – original draft, Visualization. **Leyan Xuan:** Writing – original draft, Project administration, Investigation. **Jialin Wu:** Data curation. **Jie Wang:** Formal analysis, Conceptualization. **Maobin Xie:** Writing – review & editing, Funding acquisition. **Shufang Wang:** Writing – review & editing. **Guosheng Tang:** Writing – review & editing, Funding acquisition, Data curation.

Ethical approval

Our review did not require further ethics committee approval as it did not involve animal or human clinical trials and was not unethical.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (NSFC) Program (No.32201183), the Science and Technology Program of Guangzhou (SL2022A04J00774) and the Guangdong Basic and Applied Basic Research Foundation (2021A1515220174).

References

[1] Y.S. Zhang, A. Khademhosseini, Advances in engineering hydrogels, Science 356 (2017) eaaf3627.
[2] L. Xuan, Y. Hou, L. Liang, J. Wu, K. Fan, L. Lian, J. Qiu, Y. Miao, H. Ravanbakhsh, M. Xu, G. Tang, Microgels for cell delivery in tissue engineering and regenerative medicine, Nano-Micro Lett. 16 (2024) 218.
[3] X. Xue, Y. Hu, Y. Deng, J. Su, Recent advances in design of functional biocompatible hydrogels for bone tissue engineering, Adv. Funct. Mater. 31 (2021) 2009432.
[4] K.J. De France, F. Xu, T. Hoare, Structured macroporous hydrogels: progress, challenges, and opportunities, Adv. Healthcare Mater. 7 (2018) 1700927.
[5] H. Fan, J.P. Gong, Fabrication of bioinspired hydrogels: challenges and opportunities, Macromolecules 53 (2020) 2769–2782.
[6] M.A. Kuzina, D.D. Kartsev, A.V. Stratonovich, P.A. Levkin, Organogels versus hydrogels: advantages, challenges, and applications, Adv. Funct. Mater. 33 (2023) 2301421.
[7] A. Pardo, M. Gómez-Florit, S. Barbosa, P. Taboada, R.M.A. Domingues, M.E. Gomes, Magnetic nanocomposite hydrogels for tissue engineering: design concepts and remote actuation strategies to control cell fate, ACS Nano 15 (2021) 175–209.
[8] S. Pathak, H. An, S.-K. Kim, Dual-cross-linked superparamagnetic hydrogels with tailored viscoelasticity for soft robotics, ACS Appl. Nano Mater. 7 (2024) 17482–17492.
[9] Y. Xiao, J. Du, Superparamagnetic nanoparticles for biomedical applications, J. Mater. Chem. B 8 (2020) 354–367.
[10] A. Figuerola, R. Di Corato, L. Manna, T. Pellegrino, From iron oxide nanoparticles towards advanced iron-based inorganic materials designed for biomedical applications, Pharmacol. Res. 62 (2010) 126–143.
[11] A. Hanini, A. Schmitt, K. Kacem, F. Chau, S. Ammar, J. Gavard, Evaluation of iron oxide nanoparticle biocompatibility, Int. J. Nanomed. 6 (2011) 787–794.
[12] J. Riegler, A. Liew, S.O. Hynes, D. Ortega, T. O'brien, R.M. Day, T. Richards, F. Sharif, Q.A. Pankhurst, M.F. Lythgoe, Superparamagnetic iron oxide

nanoparticle targeting of MSCs in vascular injury, Biomaterials 34 (2013) 1987–1994.
[13] A.J. Cole, V.C. Yang, A.E. David, Cancer theranostics: the rise of targeted magnetic nanoparticles, Trends Biotechnol. 29 (2011) 323–332.
[14] Z. Wang, Q. Ye, S. Yu, B. Akhavan, Poly ethylene glycol (PEG)-Based hydrogels for drug delivery in cancer therapy: a comprehensive review, Adv. Healthcare Mater. 12 (2023) 2300105.
[15] Y. Jung, K. Kwon, J. Lee, S.H. Ko, Untethered soft actuators for soft standalone robotics, Nat. Commun. 15 (2024) 3510.
[16] A.A. Mohammed, J. Miao, I. Ragaisyte, A.E. Porter, C.W. Myant, A. Pinna, 3D printed superparamagnetic stimuli-responsive starfish-shaped hydrogels, Heliyon 9 (2023) e14682.
[17] G. Tang, L. Chen, L. Lian, F. Li, H. Ravanbakhsh, M. Wang, Y.S. Zhang, C. Huang, Designable dual-power micromotors fabricated from a biocompatible gas-shearing strategy, Chem. Eng. J. 407 (2021) 127187.
[18] L.F. Santos, A.S. Silva, J.F. Mano, Magnetic-based strategies for regenerative medicine and tissue engineering, Adv. Healthcare Mater. 12 (2023) 2300605.
[19] W. Zhao, Z. Liu, Z. Sun, Q. Zhang, P. Wei, X. Mu, H. Zhou, C. Li, S. Ma, D. He, P. Ji, W. Zhu, X. Nie, X. Su, X. Tang, B. Shen, X. Dong, J. Yang, Y. Liu, J. Shi, Superparamagnetic enhancement of thermoelectric performance, Nature 549 (2017) 247–251.
[20] A. Kumar, G. Sharma, M. Naushad, S. Thakur, SPION/β-cyclodextrin core–shell nanostructures for oil spill remediation and organic pollutant removal from waste water, Chem. Eng. J. 280 (2015) 175–187.
[21] T. Girardet, E. Bianchi, C. Henrionnet, A. Pinzano, S. Bouguet-Bonnet, C. Boulogne, S. Leclerc, F. Cleymand, S. Fleutot, SPIONs magnetic nanoparticles for MRI applications: microwave synthesis and physicochemical, magnetic and biological characterizations, Mater. Today Commun. 36 (2023) 106819.
[22] S. Kim, S. Min, Y.S. Choi, S.-H. Jo, J.H. Jung, K. Han, J. Kim, S. An, Y.W. Ji, Y.-G. Kim, S.-W. Cho, Tissue extracellular matrix hydrogels as alternatives to Matrigel for culturing gastrointestinal organoids, Nat. Commun. 13 (2022) 1692.
[23] R. Singh, V. Munya, V.N. Are, D. Nayak, S. Chattopadhyay, A. Biocompatible, pH-sensitive, and magnetically separable superparamagnetic hydrogel nanocomposite as an efficient platform for the removal of cationic dyes in wastewater treatment, ACS Omega 6 (2021) 23139–23154.
[24] F. Xu, C.-a.M. Wu, V. Rengarajan, T.D. Finley, H.O. Keles, Y. Sung, B. Li, U.A. Gurkan, U. Demirci, Three-dimensional magnetic assembly of microscale hydrogels, Adv. Mater. 23 (2011) 4254–4260.
[25] A.C. Daly, L. Riley, T. Segura, J.A. Burdick, Hydrogel microparticles for biomedical applications, Nat. Rev. Mater. 5 (2020) 20–43.
[26] Z. Jiang, P. Song, Strong and fast hydrogel actuators, Science 376 (2022) 245.
[27] D. Jiao, Q.L. Zhu, C.Y. Li, Q. Zheng, Z.L. Wu, Programmable morphing hydrogels for soft actuators and robots: from structure designs to active functions, Accounts Chem. Res. 55 (2022) 1533–1545.
[28] J. Li, D.J. Mooney, Designing hydrogels for controlled drug delivery, Nat. Rev. Mater. 1 (2016) 16071.
[29] Z. Zhang, H. Fu, Z. Li, J. Huang, Z. Xu, Y. Lai, X. Qian, S. Zhang, Hydrogel materials for sustainable water resources harvesting & treatment: synthesis, mechanism and applications, Chem. Eng. J. 439 (2022) 135756.
[30] P. Mehta, M. Sharma, M. Devi, Hydrogels: an overview of its classifications, properties, and applications, J. Mech. Behav. Biomed. Mater. 147 (2023) 106145.
[31] Y. Ye, Z. Wan, P.D.S.H. Gunawardane, Q. Hua, S. Wang, J. Zhu, M. Chiao, S. Renneckar, O.J. Rojas, F. Jiang, Ultra-Stretchable and environmentally resilient hydrogels via sugaring-out strategy for soft robotics sensing, Adv. Funct. Mater. 34 (2024) 2315184.
[32] Y. Zhang, Y. Wang, Y. Guan, Y. Zhang, Peptide-enhanced tough, resilient and adhesive eutectogels for highly reliable strain/pressure sensing under extreme conditions, Nat. Commun. 13 (2022) 6671.
[33] G. Chen, F. Wang, X. Zhang, Y. Shang, Y. Zhao, Living microecological hydrogels for wound healing, Sci. Adv. 9 (2023) eadg3478.
[34] Y. Liang, J. He, B. Guo, Functional hydrogels as wound dressing to enhance wound healing, ACS Nano 15 (2021) 12687–12722.
[35] Y. Deng, J. Xi, L. Meng, Y. Lou, F. Seidi, W. Wu, H. Xiao, Stimuli-Responsive nanocellulose Hydrogels: an overview, Eur. Polym. J. 180 (2022) 111591.
[36] S. Guleria, L. Chopra, Manikanika, Temperature responsive hydrogels for biomedical applications, Mater. Today Proc. 92 (2023) 356–363.
[37] R. Cheng, M. Xu, X. Zhang, J. Jiang, Q. Zhang, Y. Zhao, Hydrogen bonding enables polymer hydrogels with pH-induced reversible dynamic responsive behaviors, Angew. Chem. Int. Ed. 62 (2023) e202302900.
[38] Y. Yang, C. Li, L.C. Palmer, S.I. Stupp, Autonomous hydrogel locomotion regulated by light and electric fields, Sci. Adv. 9 (2023) eadi4566.
[39] L. Li, J.M. Scheiger, P.A. Levkin, Design and applications of photoresponsive hydrogels, Adv. Mater. 31 (2019) 1807333.
[40] X. Li, J.P. Gong, Design principles for strong and tough hydrogels, Nat. Rev. Mater. 9 (2024) 380–398.
[41] C. Norioka, Y. Inamoto, C. Hajime, A. Kawamura, T. Miyata, A universal method to easily design tough and stretchable hydrogels, NPG Asia Mater. 13 (2021) 34.
[42] A. López-Díaz, A.S. Vázquez, E. Vázquez, Hydrogels in soft robotics: past, present, and future, ACS Nano 18 (2024) 20817–20826.
[43] N. Park, J. Kim, Hydrogel-based artificial muscles: overview and recent progress, Adv. Intell. Syst. 2 (2020) 1900135.
[44] M. Zhang, A. Pal, Z. Zheng, G. Gardi, E. Yildiz, M. Sitti, Hydrogel muscles powering reconfigurable micro-metastructures with wide-spectrum programmability, Nat. Mater. 22 (2023) 1243–1252.
[45] E.M. Ahmed, Hydrogel: preparation, characterization, and applications: a review, J. Adv. Res. 6 (2015) 105–121.
[46] S. Yang, F. Wang, H. Han, H.A. Santos, Y. Zhang, H. Zhang, J. Wei, Z. Cai, Fabricated technology of biomedical micro-nano hydrogel, Biomed. Technol. 2 (2023) 31–48.
[47] L. Gasperini, J.F. Mano, R.L. Reis, Natural polymers for the microencapsulation of cells, J. R. Soc., Interface 11 (2014) 20140817.
[48] S.H. Zainal, N.H. Mohd, N. Suhaili, F.H. Anuar, A.M. Lazim, R. Othaman, Preparation of cellulose-based hydrogel: a review, J. Mater. Res. Technol. 10 (2021) 935–952.
[49] S. Zhang, Fabrication of novel biomaterials through molecular self-assembly, Nat. Biotechnol. 21 (2003) 1171–1178.
[50] L.E. O'leary, J.A. Fallas, E.L. Bakota, M.K. Kang, J.D. Hartgerink, Multi-hierarchical self-assembly of a collagen mimetic peptide from triple helix to nanofibre and hydrogel, Nat. Chem. 3 (2011) 821–828.
[51] A. Rich, F.H. Crick, The structure of collagen, Nature 176 (1955) 915–916.
[52] I. Braccini, S. Pérez, Molecular basis of C(2+)-induced gelation in alginates and pectins: the egg-box model revisited, Biomacromolecules 2 (2001) 1089–1096.
[53] S.W. Morton, K.P. Herlihy, K.E. Shopsowitz, Z.J. Deng, K.S. Chu, C.J. Bowerman, J.M. Desimone, P.T. Hammond, Scalable manufacture of built-to-order nanomedicine: spray-assisted layer-by-layer functionalization of PRINT nanoparticles, Adv. Mater. 25 (2013) 4707–4713.
[54] W.E. Hennink, C.F. Van Nostrum, Novel crosslinking methods to design hydrogels, Adv. Drug Deliv. Rev. 54 (2002) 13–36.
[55] M. Wang, W. Li, G. Tang, C.E. Garciamendez-Mijares, Y.S. Zhang, Engineering (Bio)Materials through shrinkage and expansion, Adv. Healthcare Mater. 10 (2021) 2100380.
[56] S.J. Buwalda, T. Vermonden, W.E. Hennink, Hydrogels for therapeutic delivery: current developments and future directions, Biomacromolecules 18 (2017) 316–330.
[57] B. Liu, K. Chen, Advances in hydrogel-based drug delivery systems, Gels 10 (2024) 262.
[58] F. Lin, Y. Li, W. Cui, Injectable hydrogel microspheres in cartilage repair, Biomedical Technology 1 (2023) 18–29.
[59] J.N. Chu, G. Traverso, Foundations of gastrointestinal-based drug delivery and future developments, Nat. Rev. Gastroenterol. Hepatol. 19 (2022) 219–238.
[60] G.W. Liu, M.J. Pickett, J.L.P. Kuosmanen, K. Ishida, W.A.M. Madani, G.N. White, J. Jenkins, S. Park, V.R. Feig, M. Jimenez, C. Karavasili, N.B. Lal, M. Murphy, A. Lopes, J. Morimoto, N. Fitzgerald, J.H. Cheah, C.K. Soule, N. Fabian, A. Hayward, R. Langer, G. Traverso, Drinkable in situ-forming tough hydrogels for gastrointestinal therapeutics, Nat. Mater. 23 (2024) 1292–1299.
[61] R. Narayanaswamy, V.P. Torchilin, Hydrogels and their applications in targeted drug delivery, Molecules 24 (2019) 603.
[62] D. Suhag, S. Kaushik, V.B. Taxak, Hydrogels in Drug Delivery//Handbook of Biomaterials for Medical Applications, Volume 1: Fundamentals, Springer Nature Singapore, Singapore, 2024.
[63] Q. Li, X. Shao, X. Dai, Q. Guo, B. Yuan, Y. Liu, W. Jiang, Recent trends in the development of hydrogel therapeutics for the treatment of central nervous system disorders, NPG Asia Mater. 14 (2022) 14.
[64] K.Y. Lee, D.J. Mooney, Hydrogels for tissue engineering, Chem. Rev. 101 (2001) 1869–1880.
[65] T. Guan, J. Li, C. Chen, Y. Liu, Self-assembling peptide-based hydrogels for wound tissue repair, Adv. Sci. 9 (2022) 2104165.
[66] R. Nie, Q.-Y. Zhang, Z.-Y. Feng, K. Huang, C.-Y. Zou, M.-H. Fan, Y.-Q. Zhang, J.-Y. Zhang, J. Li-Ling, B. Tan, H.-Q. Xie, Hydrogel-based immunoregulation of macrophages for tissue repair and regeneration, Int. J. Biol. Macromol. 268 (2024) 131643.
[67] L. Lian, M. Xie, Z. Luo, Z. Zhang, S. Maharjan, X. Mu, C.E. Garciamendez-Mijares, X. Kuang, J.K. Sahoo, G. Tang, G. Li, D. Wang, J. Guo, F.Z. González, V. Abril Manjarrez Rivera, L. Cai, X. Mei, D.L. Kaplan, Y.S. Zhang, Rapid volumetric bioprinting of decellularized extracellular matrix bioinks, Adv. Mater. 36 (2024) 2304846.
[68] M. Xie, L. Lian, X. Mu, Z. Luo, C.E. Garciamendez-Mijares, Z. Zhang, A. López, J. Manríquez, X. Kuang, J. Wu, J.K. Sahoo, F.Z. González, G. Li, G. Tang, S. Maharjan, J. Guo, D.L. Kaplan, Y.S. Zhang, Volumetric additive manufacturing of pristine silk-based (bio)inks, Nat. Commun. 14 (2023) 210.
[69] Z. Luo, L. Lian, T. Stocco, J. Guo, X. Mei, L. Cai, S.M. Andrabi, Y. Su, G. Tang, H. Ravanbakhsh, W. Li, M. Wang, X. Kuang, C.E. Garciamendez-Mijares, D. Wang, Z. Wang, J. Liao, M. Xie, J. Xie, H. Kang, A.O. Lobo, Z. Zhou, Y.S. Zhang, 3D assembly of cryo(Bio)Printed modular units for shelf-ready scalable tissue fabrication, Adv. Funct. Mater. 34 (2024) 2309173.
[70] G. Tang, Z. Luo, L. Lian, J. Guo, S. Maharjan, C.E. Garciamendez-Mijares, M. Wang, W. Li, Z. Zhang, D. Wang, M. Xie, H. Ravanbakhsh, C. Zhou, X. Kuang, Y. Hou, X. Yu, Y.S. Zhang, Liquid-embedded (bio)printing of alginate-free, standalone, ultrafine, and ultrathin-walled cannular structures, Proc. Natl. Acad. Sci. USA 120 (2023) e2206762120.
[71] N. Sezer, İ. Arı, Y. Biçer, M. Koç, Superparamagnetic nanoarchitectures: multimodal functionalities and applications, J. Magn. Magn Mater. 538 (2021) 168300.
[72] B. Gogoi, U. Das, Review on Magnetism in Nanomaterials and Superparamagnetism//**Selected Progresses in Modern Physics**, Springer Singapore, Singapore, 2021, pp. 303–312.
[73] B. Rios, A. Bu, T. Sheehan, H. Kobeissi, S. Kohli, K. Shah, E. Lejeune, R. Raman, Mechanically programming anisotropy in engineered muscle with actuating extracellular matrices, Device 1 (2023) 100097.
[74] T.D. Clemons, R.H. Kerr, A. Joos, D.L. Andrews, R.H. Lipson, T. Nann, 3.10 - multifunctional magnetic nanoparticles: design, synthesis, and biomedical

applications. Comprehensive Nanoscience and Nanotechnology, second ed., Academic Press, Oxford, 2019.
[75] F.E. Kruis, H. Fissan, A. Peled, Synthesis of nanoparticles in the gas phase for electronic, optical and magnetic applications—a review, J. Aerosol Sci. 29 (1998) 511–535.
[76] A. Ali, H. Zafar, M. Zia, I. Ul Haq, A.R. Phull, J.S. Ali, A. Hussain, Synthesis, characterization, applications, and challenges of iron oxide nanoparticles, Nanotechnol. Sci. Appl. 9 (2016) 49–67.
[77] M. Gonzales-Weimuller, M. Zeisberger, K.M. Krishnan, Size-dependant heating rates of iron oxide nanoparticles for magnetic fluid hyperthermia, J. Magn. Magn Mater. 321 (2009) 1947–1950.
[78] H. Hayashi, Y. Hakuta, Hydrothermal synthesis of metal oxide nanoparticles in supercritical water, Materials 3 (2010) 3794–3817.
[79] Z. Yang, L. Zhang, Magnetic actuation systems for miniature robots: a review, Adv. Intell. Syst. 2 (2020) 2000082.
[80] M. Mahmoudi, S. Sant, B. Wang, S. Laurent, T. Sen, Superparamagnetic iron oxide nanoparticles (SPIONs): development, surface modification and applications in chemotherapy, Adv. Drug Deliv. Rev. 63 (2011) 24–46.
[81] M. Sethi, S. Chakarvarti, Hyperthermia techniques for cancer treatment: a review, Int. J. PharmTech Res. 8 (2015) 292–299.
[82] E. Otieno, Y. Huang, N. Li, T. Li, M. Wang, X. Qiu, X. Xiao, Utilization of superparamagnetic iron oxide nanoparticles (SPIONs) as a vector for drug delivery, Appl. Nanosci. 13 (2023) 6191–6216.
[83] G. Kara, B. Ozpolat, SPIONs: superparamagnetic iron oxide-based nanoparticles for the delivery of microRNAi-therapeutics in cancer, Biomed. Microdevices 26 (2024) 16.
[84] X. Wu, S. Ciannella, H. Choe, J. Strayer, K. Wu, J. Chalmers, J. Gomez-Pastora, SPIONs magnetophoresis and separation via permanent magnets: biomedical and environmental applications, Processes 11 (2023) 3316.
[85] X. Yang, E. Mcglynn, R. Das, S.P. Paşca, B. Cui, H. Heidari, Nanotechnology enables novel modalities for neuromodulation, Adv. Mater. 33 (2021) 2103208.
[86] J. Dobson, Remote control of cellular behaviour with magnetic nanoparticles, Nat. Nanotechnol. 3 (2008) 139–143.
[87] H. Huang, S. Delikanli, H. Zeng, D.M. Ferkey, A. Pralle, Remote control of ion channels and neurons through magnetic-field heating of nanoparticles, Nat. Nanotechnol. 5 (2010) 602–606.
[88] J. Luan, P.F. Kuijken, W. Chen, D. Wang, L.A. Charleston, D.A. Wilson, Microfluidic design of streamlined alginate hydrogel micromotors with run and tumble motion patterns, Adv. Sci. 10 (2023) 2304995.
[89] X. Sun, X. Song, P. Guo, D. Zhang, S. Zuo, K. Leng, Y. Liu, H. Zhang, Improvement of the bladder perfusion curative effect through tight junction protein degradation induced by magnetic temperature-sensitive hydrogels, Front. Bioeng. Biotechnol. 10 (2022) 958072.
[90] R. Plen, A. Smith, O. Blum, O. Aloni, U. Locker, Z. Shapira, S. Margel, O. Shefi, Bioengineering 3D neural networks using magnetic manipulations, Adv. Funct. Mater. 32 (2022) 2204925.
[91] Y. Asaad, D. Nemcovsky-Amar, J. Sznitman, P.H. Mangin, N. Korin, A double-edged sword: the complex interplay between engineered nanoparticles and platelets, Bioeng. Transl. Med. 9 (2024) e10669.
[92] D. Maity, G. Kandasamy, A. Sudame, Superparamagnetic Iron Oxide Nanoparticles for Cancer Theranostic Applications//M. RAI, B. JAMIL. Nanotheranostics: Applications and Limitations, Springer International Publishing, Cham, 2019.
[93] Y. Li, G. Huang, X. Zhang, B. Li, Y. Chen, T. Lu, T.J. Lu, F. Xu, Magnetic hydrogels and their potential biomedical applications, Adv. Funct. Mater. 23 (2013) 660–672.
[94] X. He, Y. He, G. Wen, F. Jiao, Evolution and breakup of a ferrofluid droplet neck through a capillary tube, Chem. Eng. Sci. 289 (2024) 119882.
[95] G. Tang, R. Xiong, D. Lv, R.X. Xu, K. Braeckmans, C. Huang, S.C.D. Smedt, Gas-shearing fabrication of multicompartmental microspheres: a one-step and oil-free approach, Adv. Sci. 6 (2019) 1802342.
[96] S. Ganguly, S. Margel, Design of magnetic hydrogels for hyperthermia and drug delivery, Polymers 13 (2021) 4259.
[97] H. Zhang, Z. Li, C. Gao, X. Fan, Y. Pang, T. Li, Z. Wu, H. Xie, Q. He, Dual-responsive biohybrid neutrobots for active target delivery, Sci. Robot. 6 (2021) eaaz9519.
[98] Y. Tian, W. Han, K.L. Yeung, Magnetic microsphere scaffold-based soft microbots for targeted mesenchymal stem cell delivery, Small 19 (2023) e2300430.
[99] Y. Zhang, X. Wu, R.A. Vadlamani, Y. Lim, J. Kim, K. David, E. Gilbert, Y. Li, R. Wang, S. Jiang, A. Wang, H. Sontheimer, D.F. English, S. Emori, R.V. Davalos, S. Poelzing, X. Jia, Submillimeter multifunctional ferromagnetic fiber robots for navigation, sensing, and modulation, Adv. Healthcare Mater. 12 (2023) e2300964.
[100] T.J. Ge, D.M. Roquero, G.H. Holton, K.E. Mach, K. Prado, H. Lau, K. Jensen, T.C. Chang, S. Conti, K. Sheth, S.X. Wang, J.C. Liao, A magnetic hydrogel for the efficient retrieval of kidney stone fragments during ureteroscopy, Nat. Commun. 14 (2023) 3711.
[101] N. Li, P. Fei, C. Tous, M. Rezaei Adariani, M.-L. Hautot, I. Ouedraogo, A. Hadjadj, I.P. Dimov, Q. Zhang, S. Lessard, Z. Nosrati, C.N. Ng, K. Saatchi, U.O. Häfeli, C. Tremblay, S. Kadoury, A. Tang, S. Martel, G. Soulez, Human-scale navigation of magnetic microrobots in hepatic arteries, Sci. Robot. 9 (2024) eadh8702.
[102] C. Wang, H. Xu, C. Liang, Y. Liu, Z. Li, G. Yang, L. Cheng, Y. Li, Z. Liu, Iron oxide @ polypyrrole nanoparticles as a multifunctional drug carrier for remotely controlled cancer therapy with synergistic antitumor effect, ACS Nano 7 (2013) 6782–6795.
[103] S. Kondaveeti, A.T.S. Semeano, D.R. Cornejo, H. Ulrich, D.F.S. Petri, Magnetic hydrogels for levodopa release and cell stimulation triggered by external magnetic field, Colloids Surf. B Biointerfaces 167 (2018) 415–424.
[104] T.-Y. Liu, S.-H. Hu, T.-Y. Liu, D.-M. Liu, S.-Y. Chen, Magnetic-sensitive behavior of intelligent ferrogels for controlled release of drug, Langmuir 22 (2006) 5974–5978.
[105] H. Kim, A. Jo, S. Baek, D. Lim, S.-Y. Park, S.K. Cho, J.W. Chung, J. Yoon, Synergistically enhanced selective intracellular uptake of anticancer drug carrier comprising folic acid-conjugated hydrogels containing magnetite nanoparticles, Sci. Rep. 7 (2017) 41090.
[106] J. Chen, T. Ren, L. Xie, H. Hu, X. Li, M. Maitusong, X. Zhou, W. Hu, D. Xu, Y. Qian, S. Cheng, K. Yu, J.a. Wang, X. Liu, Enhancing aortic valve drug delivery with PAR2-targeting magnetic nano-cargoes for calcification alleviation, Nat. Commun. 15 (2024) 557.
[107] M.E. Jewett, H.L. Hiraki, M. Wojasiński, Z. Zhang, S.S. Xi, A.S. Bluem, E.S. Prabhu, W.Y. Wang, A. Pena-Francesch, B.M. Baker, Rapid magnetically directed assembly of pre-patterned capillary-scale microvessels, Adv. Funct. Mater. 33 (2023) 2203715.
[108] N. Demri, S. Dumas, M.-L. Nguyen, G. Gropplero, A. Abou-Hassan, S. Descroix, C. Wilhelm, Remote magnetic microengineering and alignment of spheroids into 3D cellular fibers, Adv. Funct. Mater. 32 (2022) 2204850.
[109] Y. Li, G. Huang, B. Gao, M. Li, G.M. Genin, T.J. Lu, F. Xu, Magnetically actuated cell-laden microscale hydrogels for probing strain-induced cell responses in three dimensions, NPG Asia Mater. 8 (2016) e238.
[110] A.R. Abdel Fattah, N. Kolaitis, K. Van Daele, B. Daza, A.G. Rustandi, A. Ranga, Targeted mechanical stimulation via magnetic nanoparticles guides in vitro tissue development, Nat. Commun. 14 (2023) 5281.
[111] M. Hao, W. Wang, A. Kumar, W.H.A. Kamaruddin, S. Saidin, N.A.N.N. Malek, J. Claverie, H. Liu, Magnetic hydroxyapatite nanobelt-stem cell hybrid spheroids for remotely patterning bone tissues, BMEMat 2 (2024) e12059.
[112] H. Liu, R. Sun, L. Wang, X. Chen, G. Li, Y. Cheng, G. Zhai, B.H. Bay, F. Yang, N. Gu, Y. Guo, H. Fan, Biocompatible iron oxide nanoring-labeled mesenchymal stem cells: an innovative magnetothermal approach for cell tracking and targeted stroke therapy, ACS Nano 16 (2022) 18806–18821.
[113] N. Pramanik, S. Ranganathan, S. Rao, K. Suneet, S. Jain, A. Rangarajan, S. Jhunjhunwala, A composite of hyaluronic acid-modified graphene oxide and iron oxide nanoparticles for targeted drug delivery and magnetothermal therapy, ACS Omega 4 (2019) 9284–9293.
[114] S. Jeong, W. Shin, M. Park, J.U. Lee, Y. Lim, K. Noh, J.H. Lee, Y.W. Jun, M. Kwak, J. Cheon, Hydrogel magnetomechanical actuator nanoparticles for wireless remote control of mechanosignaling in vivo, Nano Lett. 23 (2023) 5227–5235.
[115] B. Xia, X. Gao, J. Qian, S. Li, B. Yu, Y. Hao, B. Wei, T. Ma, H. Wu, S. Yang, Y. Zheng, X. Gao, L. Guo, J. Gao, Y. Yang, Y. Zhang, Y. Wei, B. Xue, Y. Jin, Z. Luo, J. Zhang, J. Huang, A novel superparamagnetic multifunctional nerve scaffold: a remote actuation strategy to boost in situ extracellular vesicles production for enhanced peripheral nerve repair, Adv. Mater. 36 (2024) e2305374.
[116] Z.W. Tay, P. Chandrasekharan, A. Chiu-Lam, D.W. Hensley, R. Dhavalikar, X.Y. Zhou, E.Y. Yu, P.W. Goodwill, B. Zheng, C. Rinaldi, S.M. Conolly, Magnetic particle imaging-guided heating in vivo using gradient fields for arbitrary localization of magnetic hyperthermia therapy, ACS Nano 12 (2018) 3699–3713.
[117] W.S. Wu, X. Yan, S. Chen, Y. Du, J. Hu, Y. Song, Z. Zha, Y.J. Xu, B. Cao, S.H. Xuan, X. Liu, B. Chen, L. Dong, Y. Lu, S.H. Yu, Minimally invasive delivery of percutaneous ablation agent via magnetic colloidal hydrogel injection for treatment of hepatocellular carcinoma, Adv. Mater. 36 (2024) e2309770.
[118] L. Lu, J. Sim, R.R. Zhao, Mechanics of hard-magnetic soft materials: a review, Mech. Mater. 189 (2024) 104874.
[119] J. Gong, J. Hu, X. Yan, L. Xiang, S. Chen, H. Yang, Z. Chen, Q. Hou, Y. Song, Y. Xu, D. Liu, C. Ji, Q. Qin, H. Sun, J. Peng, B. Cao, Y. Lu, Injectable hydrogels including magnetic nanosheets for multidisciplinary treatment of hepatocellular carcinoma via magnetic hyperthermia, Small 20 (2024) 2300733.
[120] Z.-Q. Zhang, S.-C. Song, Thermosensitive/superparamagnetic iron oxide nanoparticle-loaded nanocapsule hydrogels for multiple cancer hyperthermia, Biomaterials 106 (2016) 13–23.
[121] S. Ganguly, P. Das, S. Srinivasan, A.R. Rajabzadeh, X.S. Tang, S. Margel, Superparamagnetic amine-functionalized maghemite nanoparticles as a thixotropy promoter for hydrogels and magnetic field-driven diffusion-controlled drug release, ACS Appl. Nano Mater. 7 (2024) 5272–5286.
[122] R. Eivazzadeh-Keihan, Z. Sadat, H. Aghamirza Moghim Aliabadi, F. Ganjali, A. Kashtiaray, M. Salimi Bani, S. Komijani, M.M. Ahadian, N. Salehpour, R. Ahangari Cohan, A. Maleki, Fabrication of a magnetic alginate-silk fibroin hydrogel, containing halloysite nanotubes as a novel nanocomposite for biological and hyperthermia applications, Sci. Rep. 12 (2022) 15431.
[123] J.J. Zakrzewski, M. Liberka, J. Wang, S. Chorazy, S.-i. Ohkoshi, Optical phenomena in molecule-based magnetic materials, Chem. Rev. 124 (2024) 5930–6050.
[124] E. Lee, D. Kim, H. Kim, J. Yoon, Photothermally driven fast responding photo-actuators fabricated with comb-type hydrogels and magnetite nanoparticles, Sci. Rep. 5 (2015) 15124.
[125] S. Ganguly, S. Margel, Magnetic polymeric conduits in biomedical applications, Micromachines 16 (2025).
[126] R. Ludwig, M. Stapf, S. Dutz, R. Müller, U. Teichgräber, I. Hilger, Structural properties of magnetic nanoparticles determine their heating behavior - an estimation of the in vivo heating potential, Nanoscale Res. Lett. 9 (2014) 602.
[127] J. Choi, D.I. Kim, J.Y. Kim, S. Pané, B.J. Nelson, Y.T. Chang, H. Choi, Magnetically enhanced intracellular uptake of superparamagnetic iron oxide nanoparticles for antitumor therapy, ACS Nano 17 (2023) 15857–15870.
[128] E. Kim, S. Jeon, Y.S. Yang, C. Jin, J.Y. Kim, Y.S. Oh, J.C. Rah, H. Choi, A neurospheroid-based microrobot for targeted neural connections in a hippocampal slice, Adv. Mater. 35 (2023) e2208747.

[129] F.C. Landers, V. Gantenbein, L. Hertle, A. Veciana, J. Llacer-Wintle, X.Z. Chen, H. Ye, C. Franco, J. Puigmartí-Luis, M. Kim, B.J. Nelson, S. Pané, On-command disassembly of microrobotic superstructures for transport and delivery of magnetic micromachines, Adv. Mater. 36 (2024) e2310084.
[130] Y. Dong, L. Wang, V. Iacovacci, X. Wang, L. Zhang, B.J. Nelson, Magnetic helical micro-/nanomachines: recent progress and perspective, Matter 5 (2022) 77–109.
[131] H. Zhou, C.C. Mayorga-Martinez, S. Pané, L. Zhang, M. Pumera, Magnetically driven micro and nanorobots, Chem. Rev. 121 (2021) 4999–5041.
[132] B.P. Nowak, B.J. Ravoo, Magneto- and photo-responsive hydrogels from the co-assembly of peptides, cyclodextrins, and superparamagnetic nanoparticles, Faraday Discuss 219 (2019) 220–228.
[133] W. Chen, Y. Wen, X. Fan, M. Sun, C. Tian, M. Yang, H. Xie, Magnetically actuated intelligent hydrogel-based child-parent microrobots for targeted drug delivery, J. Mater. Chem. B 9 (2021) 1030–1039.
[134] S. Fusco, M.S. Sakar, S. Kennedy, C. Peters, R. Bottani, F. Starsich, A. Mao, G.A. Sotiriou, S. Pané, S.E. Pratsinis, D. Mooney, B.J. Nelson, An integrated microrobotic platform for on-demand, targeted therapeutic interventions, Adv. Mater. 26 (2014) 952–957.
[135] D.I. Kim, H. Lee, S.H. Kwon, Y.J. Sung, W.K. Song, S. Park, Bilayer hydrogel sheet-type intraocular microrobot for drug delivery and magnetic nanoparticles retrieval, Adv. Healthcare Mater. 9 (2020) e2000118.
[136] Y. Li, D. Dong, Y. Qu, J. Li, S. Chen, H. Zhao, Q. Zhang, Y. Jiao, L. Fan, D. Sun, A multidrug delivery microrobot for the synergistic treatment of cancer, Small 19 (2023) e2301889.
[137] C. Peters, M. Hoop, S. Pané, B.J. Nelson, C. Hierold, Degradable magnetic composites for minimally invasive interventions: device fabrication, targeted drug delivery, and cytotoxicity tests, Adv. Mater. 28 (2016) 533–538.
[138] J.Y. Cha, H.J. Kim, J.H. Yu, J. Xu, D. Kim, B.D. Paul, H. Choi, S. Kim, Y.J. Lee, G.P. Ho, F. Rao, S.H. Snyder, J.W. Kim, Dexras1 mediates glucocorticoid-associated adipogenesis and diet-induced obesity, Proc. Natl. Acad. Sci. USA 110 (2013) 20575–20580.
[139] J. Park, C. Jin, S. Lee, J.-Y. Kim, H. Choi, Magnetically actuated degradable microrobots for actively controlled drug release and hyperthermia therapy, Adv. Healthcare Mater. 8 (2019) 1900213.
[140] Y. Hou, L. Xuan, W. Mo, T. Xie, J.A.R. Lara, J. Wu, J. Cai, F. Nazir, L. Chen, X. Yi, S. Bo, H. Wang, Y. Dang, M. Xie, G. Tang, Anisotropic microcarriers: fabrication strategies and biomedical applications, Adv. Mater. n/a 2416862.
[141] A. Kuntz, M. Emerson, T.E. Ertop, I. Fried, M. Fu, J. Hoelscher, M. Rox, J. Akulian, E.A. Gillaspie, Y.Z. Lee, F. Maldonado, R.J. Webster 3rd, R. Alterovitz, Autonomous medical needle steering in vivo, Sci. Robot. 8 (2023) eadf7614.
[142] X. Wang, X.-H. Qin, C. Hu, A. Terzopoulou, X.-Z. Chen, T.-Y. Huang, K. Maniura-Weber, S. Pané, B.J. Nelson, 3D printed enzymatically biodegradable soft helical microswimmers, Adv. Funct. Mater. 28 (2018) 1804107.
[143] H. Ceylan, I.C. Yasa, O. Yasa, A.F. Tabak, J. Giltinan, M. Sitti, 3D-Printed biodegradable microswimmer for theranostic cargo delivery and release, ACS Nano 13 (2019) 3353–3362.
[144] M.-J. Tang, W. Wang, Z.-L. Li, Z.-M. Liu, Z.-Y. Guo, H.-Y. Tian, Z. Liu, X.-J. Ju, R. Xie, L.-Y. Chu, Controllable microfluidic fabrication of magnetic hybrid microswimmers with hollow helical structures, Ind. Eng. Chem. Res. 57 (2018) 9430–9438.
[145] H.-W. Huang, F.E. Uslu, P. Katsamba, E. Lauga, M.S. Sakar, B.J. Nelson, Adaptive locomotion of artificial microswimmers, Sci. Adv. 5 (2019) eaau1532.
[146] Y. Yu, J. Guo, Y. Wang, C. Shao, Y. Wang, Y. Zhao, Bioinspired helical micromotors as dynamic cell microcarriers, ACS Appl. Mater. Interfaces 12 (2020) 16097–16103.
[147] Y. Dong, L. Wang, J. Wang, S. Wang, Y. Wang, D. Jin, P. Chen, W. Du, L. Zhang, B.-F. Liu, Graphene-based helical micromotors constructed by “microscale liquid rope-coil effect” with microfluidics, ACS Nano 14 (2020) 16600–16613.
[148] T. Shen, M.G. Font, S. Jung, M.L. Gabriel, M.P. Stoykovich, F.J. Vernerey, Remotely triggered locomotion of hydrogel mag-bots in confined spaces, Sci. Rep. 7 (2017) 16178.
[149] S.R. Goudu, I.C. Yasa, X. Hu, H. Ceylan, W. Hu, M. Sitti, Biodegradable untethered magnetic hydrogel milli-grippers, Adv. Funct. Mater. 30 (2020) 2004975.
[150] M. Van Den Boomen, H.B. Kause, H.C. Van Assen, P.Y.W. Dankers, C.V.C. Bouten, K. Vandoorne, Triple-marker cardiac MRI detects sequential tissue changes of healing myocardium after a hydrogel-based therapy, Sci. Rep. 9 (2019) 19366.
[151] H. Qin, P. Liu, C. Chen, H.-P. Cong, S.-H. Yu, A multi-responsive healable supercapacitor, Nat. Commun. 12 (2021) 4297.
[152] A.S. Theus, L. Ning, G. Kabboul, B. Hwang, M.L. Tomov, C.N. Larock, H. Bauser-Heaton, M. Mahmoudi, V. Serpooshan, 3D bioprinting of nanoparticle-laden hydrogel scaffolds with enhanced antibacterial and imaging properties, iScience 25 (2022) 104947.
[153] O. Ozay, S. Ekici, Y. Baran, N. Aktas, N. Sahiner, Removal of toxic metal ions with magnetic hydrogels, Water Res. 43 (2009) 4403–4411.
[154] L. Wei, G. Yang, R. Wang, W. Ma, Selective adsorption and separation of chromium (VI) on the magnetic iron–nickel oxide from waste nickel liquid, J. Hazard Mater. 164 (2009) 1159–1163.
[155] H.E. Ali, S.M. Nasef, Y.H. Gad, Remediation of Astrazon blue and Lerui acid brilliant blue dyes from waste solutions using amphoteric superparamagnetic nanocomposite hydrogels based on chitosan prepared by gamma rays, Carbohydr. Polym. 283 (2022) 119149.
[156] H.-M. Yang, J.R. Hwang, D.Y. Lee, K.B. Kim, C.W. Park, H.R. Kim, K.-W. Lee, Eco-friendly one-pot synthesis of Prussian blue-embedded magnetic hydrogel beads for the removal of cesium from water, Sci. Rep. 8 (2018) 11476.
[157] M. Zhu, Z. Hu, N. Liu, K. Yao, G. Hong, Y. Li, Y. Chen, H. He, W. Wu, Y. Zhou, J. Shi, Y. He, A cyclical magneto-responsive massage dressing for wound healing, Small 20 (2024) 2400644.
[158] K.K. Moncal, S. Yaman, N.G. Durmus, Levitational 3D bioassembly and density-based spatial coding of levitoids, Adv. Funct. Mater. 32 (2022) 2204092.
[159] R.M. Erb, J.S. Sander, R. Grisch, A.R. Studart, Self-shaping composites with programmable bioinspired microstructures, Nat. Commun. 4 (2013) 1712.
[160] J.H. Lee, W.J. Han, H.S. Jang, H.J. Choi, Highly tough, biocompatible, and magneto-responsive Fe3O4/laponite/PDMAAm nanocomposite hydrogels, Sci. Rep. 9 (2019) 15024.
[161] Q. Shi, H. Liu, D. Tang, Y. Li, X. Li, F. Xu, Bioactuators based on stimulus-responsive hydrogels and their emerging biomedical applications, NPG Asia Mater. 11 (2019) 64.
[162] Z. Wei, S. Wang, J. Hirvonen, H.A. Santos, W. Li, Microfluidics fabrication of micrometer-sized hydrogels with precisely controlled geometries for biomedical applications, Adv. Healthcare Mater. 11 (2022) 2200846.
[163] Y. Huang, Z. Ding, Biomaterials for cardiovascular diseases, Biomedical Technology 7 (2024) 1–14.
[164] X. Li, R. Yue, G. Guan, C. Zhang, Y. Zhou, G. Song, Recent development of pH-responsive theranostic nanoplatforms for magnetic resonance imaging-guided cancer therapy, Exploration 3 (2023) 20220002.
[165] M. Rong, D. Liu, X. Xu, A. Li, Y. Bai, G. Yang, K. Liu, Z. Zhang, L. Wang, K. Wang, L. Lu, Y. Jiang, J. Liu, X. Zhang, A superparamagnetic composite hydrogel scaffold as in vivo dynamic monitorable theranostic platform for osteoarthritis regeneration, Adv. Mater. 36 (2024) e2405641.
[166] A. Yang, Y. Wang, Q. Feng, K. Fatima, Q. Zhang, X. Zhou, C. He, Integrating fluorescence and magnetic resonance imaging in biocompatible scaffold for real-time bone repair monitoring and assessment, Adv. Healthcare Mater. 13 (2024) e2302687.
[167] L. Zhang, W. Dai, C. Gao, W. Wei, R. Huang, X. Zhang, Y. Yu, X. Yang, Q. Cai, Multileveled hierarchical hydrogel with continuous biophysical and biochemical gradients for enhanced repair of full-thickness osteochondral defect, Adv. Mater. 35 (2023) 2209565.
[168] X. Cao, C. Jiang, N. Sun, D. Tan, Q. Li, S. Bi, J. Song, Recent progress in multifunctional hydrogel-based supercapacitors, J. Sci. Adv. Mater. Devices 6 (2021) 338–350.
[169] R.M. Erb, R. Libanori, N. Rothfuchs, A.R. Studart, Composites reinforced in three dimensions by using low magnetic fields, Science 335 (2012) 199–204.
[170] M. Mahmoudi, M. Zhao, Y. Matsuura, S. Laurent, P.C. Yang, D. Bernstein, P. Ruiz-Lozano, V. Serpooshan, Infection-resistant MRI-visible scaffolds for tissue engineering applications, Bioimpacts 6 (2016) 111–115.
[171] R. Singh, D. Pal, S. Chattopadhyay, Target-specific superparamagnetic hydrogel with excellent pH sensitivity and reversibility: a promising platform for biomedical applications, ACS Omega 5 (2020) 21768–21780.
[172] S. Ganguly, S. Margel, 3D printed magnetic polymer composite hydrogels for hyperthermia and magnetic field driven structural manipulation, Prog. Polym. Sci. 131 (2022) 101574.
[173] H.-Y. Lin, H.-Y. Huang, S.-J. Shiue, J.-K. Cheng, Osteogenic effects of inductive coupling magnetism from magnetic 3D printed hydrogel scaffold, J. Magn. Magn Mater. 504 (2020) 166680.
[174] N. Marovič, I. Ban, U. Maver, T. Maver, Magnetic nanoparticles in 3D-printed scaffolds for biomedical applications, Nanotechnol. Rev. 12 (2023) 20220570.
[175] M.H. Norahan, S.C. Pedroza-González, M.G. Sánchez-Salazar, M.M. Álvarez, G.T. De Santiago, Structural and biological engineering of 3D hydrogels for wound healing, Bioact. Mater. 24 (2023) 197–235.
[176] T.J. Hinton, Q. Jallerat, R.N. Palchesko, J.H. Park, M.S. Grodzicki, H.-J. Shue, M.H. Ramadan, A.R. Hudson, A.W. Feinberg, Three-dimensional printing of complex biological structures by freeform reversible embedding of suspended hydrogels, Sci. Adv. 1 (2015) e1500758.
[177] A.A. Moud, M. Kamkar, A. Sanati-Nezhad, S.H. Hejazi, Suspensions and hydrogels of cellulose nanocrystals (CNCs): characterization using microscopy and rheology, Cellulose 29 (2022) 3621–3653.
[178] Assembly of a Three-Dimensional Multitype Bronchiole Coculture Model Using Magnetic Levitation, Tissue Eng. C Methods 19 (2013) 665–675.
[179] V. Zablotskii, T. Polyakova, O. Lunov, A. Dejneka, How a high-gradient magnetic field could affect cell life, Sci. Rep. 6 (2016) 37407.
[180] G.R. Souza, J.R. Molina, R.M. Raphael, M.G. Ozawa, D.J. Stark, C.S. Levin, L.F. Bronk, J.S. Ananta, J. Mandelin, M.-M. Georgescu, J.A. Bankson, J.G. Gelovani, T.C. Killian, W. Arap, R. Pasqualini, Three-dimensional tissue culture based on magnetic cell levitation, Nat. Nanotechnol. 5 (2010) 291–296.
[181] R.V. Ramanujan, L.L. Lao, The mechanical behavior of smart magnet–hydrogel composites, Smart Mater. Struct. 15 (2006) 952.
[182] G. Giani, S. Fedi, R. Barbucci, Hybrid magnetic hydrogel: a potential system for controlled drug delivery by means of alternating magnetic fields, Polymers 4 (2012) 1157–1169.
[183] A. Carvalho, J. Gallo, D.M. Pereira, P. Valentão, P.B. Andrade, L. Hilliou, P.M.T. Ferreira, M. Bañobre-López, J.A. Martins, Magnetic dehydrodipeptide-based self-assembled hydrogels for theragnostic applications, Nanomaterials 9 (2019) 541.
[184] D.J. Maciel, M.R. Da Silva, I.L.M. Ferreira, Preparation of a superparamagnetic nanocomposite hydrogel for adsorptive performance in the wastewater treatment, J. Appl. Polym. Sci. 136 (2019) 47705.
[185] M. Kappes, B. Friedrich, F. Pfister, C. Huber, R.P. Friedrich, R. Stein, C. Braun, J. Band, E. Schreiber, C. Alexiou, C. Janko, Superparamagnetic iron oxide

nanoparticles for targeted cell seeding: magnetic patterning and magnetic 3D cell culture, Adv. Funct. Mater. 32 (2022) 2203672.
[186] Z. Mozaffari, M. Hatamzadeh, B. Massoumi, M. Jaymand, Synthesis and characterization of a novel stimuli-responsive magnetite nanohydrogel based on poly(ethylene glycol) and poly(N-isopropylacrylamide) as drug carrier, J. Appl. Polym. Sci. 135 (2018) 46657.
[187] E. Poloni, A. Rafsanjani, V. Place, D. Ferretti, A.R. Studart, Stretchable soft composites with strain-induced architectured color, Adv. Mater. 34 (2022) 2104874.