Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Review on Magnetic Field Responsive Colloids: Synthesis and Applications

Keyur Khatsuriya[1], Hem Bhatt[2], Pratik Lakhani[2], Jaysukh Markna[3], Bharat Kataria[3]

[1]*Research Scholar, Gujarat Technological University, Ahmedabad, Gujarat-382424*
[2]*Shantilal Shah Engineering College, Gujarat Technological University, Ahmedabad, Gujarat-382424*
[3]*Department of Nanoscience and Advanced Materials, Saurashtra University, Rajkot, Gujarat-360005*
Email: keyur.physics@gmail.com

This review paper examines the recent advancements in the field of magnetic field responsive colloids, focusing on their synthesis, characterization techniques, and applications. Magnetic field responsive colloids have gained significant attention due to their unique ability to respond to external magnetic fields, which enables precise control and manipulation of their properties and behavior. This paper discusses various synthesis methods employed to fabricate magnetic field responsive colloids, including chemical and physical approaches. Additionally, the characterization techniques used to assess their structural, magnetic, and rheological properties are discussed. Furthermore, the diverse range of applications of these colloids in fields such as biomedicine, sensing, actuation, and environmental remediation are explored. This comprehensive review aims to provide a thorough understanding of magnetic field responsive colloids and their potential for future technological advancements.
Keywords: magnetic field responsive colloids, synthesis, characterization, applications, biomedicine, sensing, actuation, environmental remediation.

1. Introduction

Magnetic field responsive colloids have emerged as a fascinating class of materials with the ability to respond to external magnetic fields, making them highly versatile and attractive for various technological applications. These colloids, composed of magnetic nanoparticles dispersed in a fluid medium, exhibit unique properties that can be controlled and manipulated through the application of magnetic fields. This review paper aims to provide a comprehensive overview of the synthesis, characterization techniques, and diverse applications of magnetic field responsive colloids.

The synthesis of magnetic field responsive colloids involves the fabrication of colloidal suspensions or gels with embedded magnetic nanoparticles. Various synthesis methods have been developed to achieve controlled and tuneable properties of these colloids. Chemical approaches, such as co-precipitation, sol-gel synthesis, and microemulsion techniques, have been widely employed.[1] Physical methods, including template-assisted synthesis and electrostatic assembly, have also shown promise in achieving colloids with tailored properties.[2] These synthesis methods play a crucial role in determining the size, composition, and magnetic behaviour of the colloids.

Characterizing the structural, magnetic, and rheological properties of magnetic field responsive colloids is essential for understanding their behaviour and performance. Spectroscopic techniques, such as infrared spectroscopy and Raman spectroscopy, provide valuable insights into the chemical composition and bonding within the colloidal system.[3] Electron microscopy, including scanning electron microscopy (SEM) and transmission electron microscopy (TEM), enables the visualization and characterization of the colloidal structure at the nanoscale.[4] X-ray diffraction (XRD) analysis helps identify the crystalline phases present in the colloidal system. Magnetic measurements, such as vibrating sample magnetometry (VSM), offer a comprehensive understanding of the magnetic properties and response of the colloids. Rheological analysis provides information about the flow behaviour and viscoelastic properties of the colloidal suspensions.[5]

The applications of magnetic field responsive colloids span across diverse fields, including biomedicine, sensing, actuation, and environmental remediation. In biomedicine, these colloids have shown great potential for targeted drug delivery, where magnetic fields can guide and concentrate the delivery of therapeutic agents to specific sites within the body.[6] Magnetic hyperthermia, a therapeutic technique that uses magnetic nanoparticles to generate localized heat for cancer treatment, is another promising application.[7] Magnetic field responsive colloids also find applications in biosensing, where they enable sensitive detection of biological analytes through magnetic manipulation and signal transduction.[8] Furthermore, these colloids have been explored for actuation and smart materials applications, such as magnetically controlled valves, microfluidic devices, and responsive coatings. [9] In the field of environmental remediation, magnetic field responsive colloids have been employed for the removal of contaminants from water and soil, offering a potential solution for efficient and selective pollutant capture.[10]

Magnetic field responsive colloids hold tremendous promise for a wide range of applications due to their unique response to external magnetic fields. This review paper aims to provide a comprehensive understanding of the synthesis, characterization techniques, and applications of these colloids, with the goal of advancing research and facilitating their practical implementation in various technological domains.

2. Synthesis Methods

Synthesis techniques play a crucial role in the fabrication of magnetic field responsive. colloids, enabling the control and manipulation of their properties for various applications. Chemical approaches, including co-precipitation, sol-gel synthesis, and microemulsion techniques, have been extensively employed in the synthesis of magnetic nanoparticles. Co-precipitation involves the precipitation of precursor salts to form nanoparticles, while sol-gel synthesis utilizes the hydrolysis and condensation of metal alkoxides to produce colloidal suspensions. Microemulsion techniques, such as reverse micelle and water-in-oil microemulsion, create confined reaction environments for controlled nucleation and growth of nanoparticles. In addition to chemical approaches, physical methods such as laser ablation, template-assisted synthesis and electrostatic assembly have been employed. Template-assisted synthesis utilizes porous templates to control the size and arrangement of magnetic nanoparticles, while electrostatic assembly involves the layer-by-layer deposition of oppositely charged species. These synthesis techniques offer versatility in tailoring the size, composition, and morphology of magnetic field responsive colloids, enabling their customization for specific applications

The synthesis of magnetic colloid involves following steps:

Selecting Magnetic Particles: The first step is to choose magnetic particles that will be suspended in the carrier fluid. Typically, these particles are nanoscale or micron-sized and made from materials like iron oxide (Fe_3O_4) or magnetite.

Preparing the Carrier Fluid: The carrier fluid is the liquid in which the magnetic particles will be suspended. Commonly used carrier fluids include water, kerosene, mineral oil, or organic solvents like toluene or hexane.

Surface Treatment: To prevent the magnetic particles from agglomerating and settling out of the fluid, they are often coated with surfactants or stabilizers. These surface treatments help to maintain the stability and colloidal properties of the magnetic fluid.

Mixing: The magnetic particles are then mixed into the carrier fluid in a controlled environment. Proper mixing ensures that the particles are evenly distributed throughout the fluid.

Purification: After mixing, the magnetic fluid is usually subjected to a purification process to remove any large agglomerates or impurities.

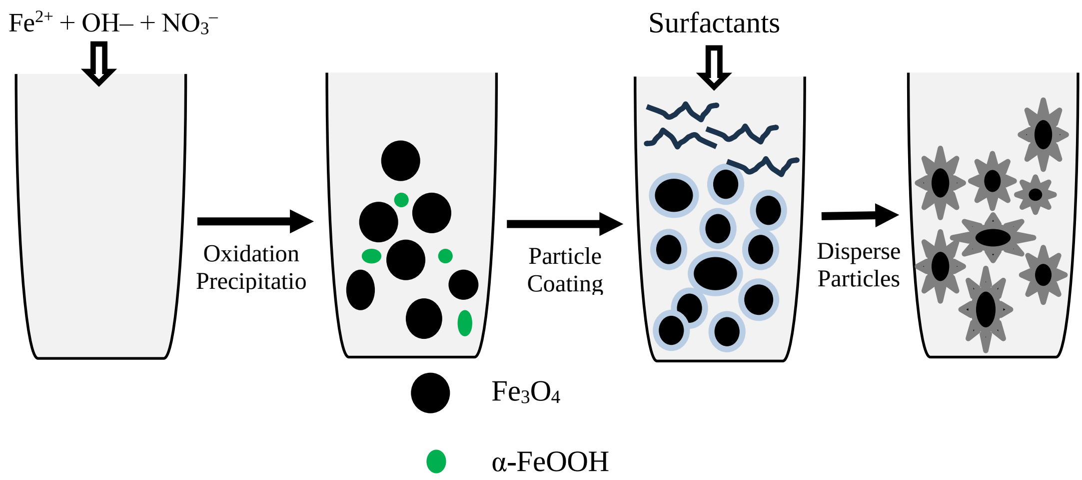
Characterization: The final step involves characterizing the properties of the magnetic fluid, such as its magnetization, viscosity, stability, and other relevant parameters. This step helps ensure that the produced ferrofluid meets the required specifications for its intended application.

This section explores various synthesis methods employed for fabricating magnetic field responsive colloids. It discusses chemical approaches such as co-precipitation, sol-gel synthesis, and microemulsion techniques, as well as physical methods including template-assisted synthesis and electrostatic assembly. The advantages and limitations of each method are addressed, along with recent advancements and emerging techniques.

2.1 Co-precipitation

Co-precipitation is a widely used chemical synthesis method for preparing magnetic nanoparticles. In this method, precursor salts containing the desired magnetic elements are mixed and then precipitated by the addition of a base or a precipitating agent. The resulting precipitate is subsequently subjected to appropriate post-treatment steps to obtain magnetic nanoparticles with desired properties. In the synthesis of iron oxide (Fe_3O_4) nanoparticles, co-precipitation is commonly employed. For instance, in a study by Sun and Zeng[2], Fe_3O_4 nanoparticles with controlled sizes were prepared by mixing Fe (II) and Fe (III) salts in a basic solution. The resulting precipitate was then subjected to washing and drying steps to obtain Fe_3O_4 nanoparticles with tuneable sizes ranging from 4 to 20 nm.

Co-precipitation has also been used for the synthesis of cobalt ferrite ($CoFe_2O_4$) nanoparticles. In a research work by Sharifi et al.[1], a co-precipitation method was employed to synthesize $CoFe_2O_4$ nanoparticles using cobalt and iron salts in the presence of a base. The obtained precipitate was subsequently annealed to obtain well-crystalline $CoFe_2O_4$ nanoparticles suitable for magnetic applications.



(Figure:1 Schematic representation of co-precipitation of magnetic colloids)

Nickel-zinc ferrite ($Ni_{0.5}Zn_{0.5}Fe_2O_4$) nanoparticles have been synthesized using co-precipitation. In a study by Rashad et al.[11], nickel, zinc, and iron salts were co-precipitated by adding a base to form the desired ferrite nanoparticles. The obtained precipitate was washed, dried, and annealed to obtain $Ni_{0.5}Zn_{0.5}Fe_2O_4$ nanoparticles, which exhibited enhanced magnetic properties.

Co-precipitation has also been applied to synthesize magnetic nanoparticles with complex compositions. In a work by Korsakova et al.[12], a co-precipitation method was employed to synthesize manganese-doped magnetite ($Mn_xFe_{3-x}O_4$) nanoparticles. By adjusting the ratio of manganese and iron salts during co-precipitation, they were able to tune the manganese doping level in the resulting nanoparticles.

some unique future directions for the co-precipitation technique in the synthesis of magnetic nanoparticles:

2.1.1 Surface Functionalization:

One future direction is the development of surface functionalization techniques for co-precipitated magnetic nanoparticles. By modifying the surface of the nanoparticles with specific functional groups or coatings, their stability, dispersibility, and compatibility with various applications can be enhanced. Surface functionalization can also enable targeted delivery, bioconjugation, and integration into complex systems like drug delivery vehicles or magnetic resonance imaging (MRI) contrast agents[13].

2.1.2 Coating with organic ligands:

Functional groups such as amines, carboxylates, or thiols can be attached to the nanoparticle surface using ligand exchange or covalent bonding approaches[14].

2.1.3 Polymer encapsulation:

The nanoparticles can be encapsulated within a polymer shell, providing stability, controlled release, and compatibility with biological systems[15].

2.1.4 Silica coating:

Silica shells can be formed around the nanoparticles, offering protection, enhanced dispersibility, and the ability to incorporate additional functional groups[16].

2.1.5 Targeted Delivery and Bioconjugation:

Functionalizing the nanoparticle surface allows for specific targeting and delivery to desired locations within biological systems. It enables the attachment of targeting ligands, antibodies, peptides, or aptamers, facilitating selective interaction with specific cells or tissues[17].

2.1.6 Integration into Complex Systems:

Surface functionalization enables the integration of co-precipitated magnetic nanoparticles into complex systems for various applications, including drug delivery vehicles, MRI contrast agents, biosensors, and catalysis[7].

2.1.7 Size and Shape Control:

Although co-precipitation is known for producing a range of nanoparticle sizes, achieving precise control over the size and shape distribution remains a challenge. Future research could focus on developing strategies to achieve even more precise control over the particle size, shape, and size distribution, including the synthesis of uniform monodisperse nanoparticles or the fabrication of complex morphologies such as core-shell structures or anisotropic shapes[5].

2.1.8 Composite Nanoparticles:

Co-precipitation can be extended to synthesize composite nanoparticles by incorporating additional materials or elements into the magnetic core. For instance, combining magnetic nanoparticles with other functional materials like semiconductors, metals, or polymers can lead to unique properties and multifunctional capabilities. Future research could explore the synthesis of composite nanoparticles with tailored properties for applications such as energy storage, catalysis, or sensing[18].

2.1.9 Controlled Crystallographic Phases:

Co-precipitation typically produces mixed phases of magnetic nanoparticles, such as Fe_3O_4 or $CoFe_2O_4$. Future efforts could focus on developing strategies to control and stabilize specific crystallographic phases, allowing for precise tuning of the magnetic properties and functionalities of the nanoparticles. This could involve optimizing the reaction conditions, post-treatment techniques, or incorporating additives to influence the crystal growth and phase formation[19].

2.1.10 Scalable and Sustainable Synthesis:

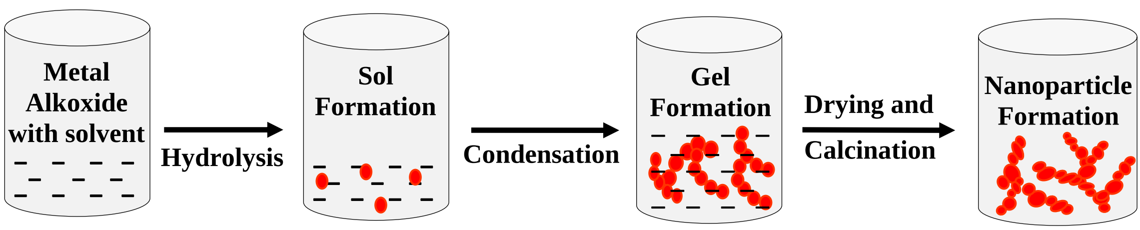
As magnetic nanoparticles find increasing use in various fields, scalable and sustainable synthesis methods become crucial. Future research could explore greener approaches, such as the use of eco-friendly solvents, energy-efficient processes, or waste reduction strategies, while maintaining control over the nanoparticle properties. Developing economically viable and environmentally friendly synthesis routes would facilitate the translation of co-precipitation-based synthesis to industrial-scale production.

These future directions aim to advance the co-precipitation technique in terms of improved nanoparticle properties, expanded functionalities, and sustainable synthesis practices, leading to broader applications in areas such as biomedicine, electronics, and environmental remediation.

2.2 Sol-Gel Synthesis

Sol-gel synthesis is a versatile and widely used method for preparing magnetic field responsive colloids. This technique involves the hydrolysis and condensation of precursor molecules to form a sol, followed by gelation to form a solid network structure. The resulting colloids can exhibit responsive behaviour to external magnetic fields, making them suitable for various applications such as drug delivery, sensing, and actuation.[20][21]

During the sol-gel process, metal alkoxides or metal salts are typically used as precursors. The hydrolysis of these precursors is initiated by the addition of water or a hydrolysing agent, leading to the formation of metal hydroxides or sol. The hydroxide species then undergo condensation reactions, forming a three-dimensional network structure or gel. To introduce magnetic properties, magnetic nanoparticles or magnetic dopants can be incorporated into the sol-gel matrix.



(Figure:2 Schematic representation of Sol-gel Method)

The magnetic responsiveness of the colloids can be attributed to the presence of magnetic nanoparticles within the gel network. These nanoparticles can align in the presence of an external magnetic field, resulting in macroscopic changes in the properties of the colloidal system. The extent of the magnetic response depends on factors such as the concentration and size of the magnetic nanoparticles, the gel structure, and the applied magnetic field strength.

Sol-gel synthesis offers several advantages for the preparation of magnetic field responsive colloids. It allows for precise control over the particle size, composition, and morphology of the colloids. The sol-gel process can be easily scaled up, making it suitable for large-scale production. Additionally, the resulting colloids exhibit good stability and can be functionalized with surface coatings or functional groups to impart specific properties or enable targeted applications.

Fe_3O_4/SiO_2 composite nanoparticles were synthesized via a sol-gel method. The sol-gel process involved the hydrolysis and condensation of metal alkoxides to form a sol, followed by gelation to obtain the composite gel. The resulting Fe_3O_4/SiO_2 colloids exhibited excellent magnetic properties and were investigated for their potential application in magnetic hyperthermia for cancer treatment.[22]

2.3 Microemulsion techniques

In this technique, a microemulsion is formed by mixing water, oil, surfactants, and co-surfactants. The magnetic nanoparticles are then precipitated within the microemulsion, and the resulting ferrofluid is stabilized by the surfactants.

2.4 Laser Ablation

In laser ablation, a high-power laser is used to ablate a solid target containing the desired metal. The ablated material condenses into nanoparticles, which are collected and dispersed in the carrier fluid.

2.5 Chemical Vapor Condensation:

In this method, vaporized metal precursors are rapidly condensed to form nanoparticles, which are then coated and dispersed in the carrier fluid.

2.6 Electrochemical Deposition:

Electrochemical methods involve the electrodeposition of magnetic materials onto a substrate. These deposited materials can be detached from the substrate and dispersed in a carrier fluid.

3. Applications

This section focuses on the diverse range of applications of magnetic field responsive colloids. It explores their use in biomedicine for targeted drug delivery, magnetic hyperthermia, and bioimaging. Additionally, their applications in sensing, actuation, and environmental remediation are discussed, showcasing their potential impact in these fields.

3.1 Drug Delivery Systems:

Magnetic field responsive colloids have gained significant attention in the field of drug delivery due to their ability to be remotely controlled and targeted. These colloids can be functionalized with drugs or therapeutic agents and guided to specific locations in the body using an external magnetic field. The magnetic field can be used to manipulate the colloids, allowing for precise targeting and controlled release of the encapsulated drugs. This approach has the potential to enhance the efficacy and reduce side effects of drug therapies.[23]

3.2 Tissue Engineering:

Magnetic field responsive colloids find applications in tissue engineering for scaffold fabrication, cell manipulation, and tissue regeneration. By incorporating magnetic nanoparticles into the scaffolds or hydrogels, the behaviour and organization of cells can be influenced using an external magnetic field. This allows for controlled cell migration, alignment, and differentiation, promoting tissue regeneration and engineering.[24]

3.3 Biosensing and Diagnostics:

Magnetic field responsive colloids have been utilized in biosensing and diagnostic applications. By functionalizing the colloids with specific biomolecules or receptors, they can be used to capture target analytes or biomarkers from complex biological samples. The captured analytes can then be concentrated and detected using magnetic separation and sensing techniques, enabling sensitive and rapid detection of various diseases and pathogens.[25]

3.4 Actuation and Micro robotics:

Magnetic field responsive colloids have shown promise in actuation and micro robotic applications. By manipulating the magnetic field, the colloids can be remotely controlled to perform desired movements or actions. This capability has potential applications in micro robotics, microfluidics, and microscale assembly, where precise control and manipulation at the microscale are required.[26]

3.5 Magnetic Hyperthermia:

Magnetic field responsive colloids can be used in magnetic hyperthermia, a therapeutic approach that involves heating target tissues using magnetic nanoparticles under the influence of an alternating magnetic field. The magnetic nanoparticles absorb the energy from the magnetic field and convert it into heat, which can selectively destroy cancer cells or treat localized infections.[27]

3.6 Magnetic Separation and Purification:

Magnetic field responsive colloids can be employed for magnetic separation and purification processes. By functionalizing the colloids with specific affinity ligands, such as antibodies or DNA probes, they can selectively bind and capture target molecules or contaminants from complex mixtures. The magnetic field is then used to separate and isolate the colloids along with the bound target molecules, enabling efficient purification.[28]

3.7 Magnetic Responsive Photonic Materials:

Magnetic field responsive colloids can be incorporated into photonic materials to create magnetically tunable optical properties. By controlling the orientation or arrangement of the magnetic nanoparticles within the colloidal structures, the photonic properties, such as reflectance or color, can be dynamically modulated using an external magnetic field. This concept has potential applications in displays, sensors, and optical devices.[29]

Table:1 Synthesis Techniques of Magnetic Colloidal Suspensions

Magnetic Nanoparticle	Synthesis Technique	Application	Main Advantages
Iron oxide (Fe_3O_4)	Co-precipitation	Biomedical imaging, drug delivery, hyperthermia therapy	High magnetization, biocompatibility, tunable size and surface functionalization
Cobalt ferrite ($CoFe_2O_4$)	Sol-gel synthesis	Magnetic data storage, electromagnetic wave absorption, catalysis	High coercivity, chemical stability, tunable magnetic properties
Nickel-zinc ferrite (Ni0.5Zn0.5Fe2O4)	Co-precipitation	Microwave absorption, magnetic sensors, wastewater treatment	Good chemical stability, high electrical resistivity, tunable composition and properties
Manganese-doped magnetite (MnxFe3-xO4)	Co-precipitation	Magnetic resonance imaging (MRI), targeted drug delivery, environmental remediation	Enhanced MRI contrast, tunable magnetic and surface properties, potential for multifunctionality
Nickel nanoparticles (Ni)	Chemical reduction method	Catalysis, magnetic fluids, sensors	High magnetization, catalytic activity, corrosion resistance
Cobalt nanoparticles (Co)	Chemical reduction method	Magnetic recording media, biomedical applications, magnetic fluids	High coercivity, thermal stability, magnetic anisotropy
Iron-platinum nanoparticles (FePt)	Chemical synthesis method	Magnetic data storage, catalysis, biomedical applications	High magnetocrystalline anisotropy, high coercivity, chemical stability
Gadolinium oxide (Gd_2O_3)	Co-precipitation	Magnetic resonance imaging (MRI), contrast agents	High magnetic moment, enhanced MRI contrast, low toxicity
Magnetite-silica core-shell nanoparticles	Sol-gel synthesis	Drug delivery, magnetic separation, environmental sensing	Enhanced stability, biocompatibility, easy surface functionalization
Barium hexaferrite ($BaFe_{12}O_{19}$)	Sol-gel synthesis	Magnetic data storage, microwave devices, magnetic refrigeration	High coercivity, chemical stability, low magnetic losses

4. Challenges and Future Perspectives

The challenges and limitations associated with magnetic field responsive colloids are addressed in this section. The potential avenues for future research and development, such as improving stability, scalability, and biocompatibility, are highlighted. The section concludes with an outlook on the future prospects of magnetic field responsive colloids and their role in advancing various technological domains.

One of the challenges associated with magnetic field responsive colloids is maintaining their stability over time. Colloids may experience agglomeration or sedimentation, leading to loss of their responsive properties. Developing strategies to enhance the stability of colloids, such as surface modifications or encapsulation techniques, is crucial for their practical applications. Another challenge is the scalability of the synthesis methods for magnetic field responsive colloids. Many existing approaches are lab-scale or produce small quantities, hindering their widespread industrial production. Developing scalable synthesis methods that can produce large quantities of colloids while maintaining their desired properties is essential. When considering biomedical applications, ensuring the biocompatibility of magnetic field responsive colloids is crucial. It is essential to assess their cytotoxicity, potential immunogenicity, and long-term biocompatibility to ensure their safe use in biological systems.

Addressing these concerns is essential for advancing biomedical applications such as drug delivery and tissue engineering. Achieving precise targeting and specificity of magnetic field responsive colloids is another challenge. While external magnetic fields can guide the colloids to a specific location, achieving selective binding or interaction with target cells or tissues is crucial for effective and controlled applications. Developing strategies to enhance targeting and specificity will enable improved therapeutic outcomes.

One future direction is the development of multifunctional magnetic field responsive colloids. These colloids can be engineered to possess multiple functionalities, such as combining magnetic response with optical, electrical, or chemical properties. This opens up new opportunities for advanced applications in areas like diagnostics, sensing, and smart materials. Integrating magnetic field responsive colloids with other emerging technologies, such as nanotechnology, microfluidics, and 3D printing, can lead to innovative applications and enhanced performance. For example, combining magnetic colloids with microfluidic systems can enable precise manipulation and analysis of the colloids at the microscale. Magnetic field responsive colloids hold great potential in various biomedical applications. Future research can focus on optimizing their properties for targeted drug delivery, magnetic hyperthermia, biosensing, and tissue engineering. Exploring their compatibility with different biological systems and improving their therapeutic efficacy will be key areas of development. Designing new materials and structures with tailored magnetic response properties is an exciting area for future exploration. By engineering the composition, size, shape, and arrangement of magnetic nanoparticles within colloidal structures, researchers can create materials with customized and tunable magnetic responses. This will enable the development of advanced materials with precise control over their properties and functionalities.

Addressing the challenges of stability, scalability, biocompatibility, and specificity will pave the way for the future development and application of magnetic field responsive colloids. By exploring multifunctionality, integrating with other technologies, and focusing on biomedical applications, these colloids have the potential to revolutionize fields such as medicine, materials science, and biotechnology. Continued research and innovation in this area will unlock new possibilities and drive the advancement of magnetic field responsive colloids.

5. Conclusion

Magnetic field responsive colloids have emerged as versatile and promising materials with a wide range of applications in various fields. The ability to manipulate and control the behaviour of these colloids using an external magnetic field has opened up new avenues for targeted drug delivery, tissue engineering, biosensing, diagnostics, actuation, and other technological advancements. This review paper has provided an overview of the synthesis methods for magnetic field responsive colloids, including sol-gel synthesis and co-precipitation, highlighting their advantages and limitations. We have explored the surface functionalization techniques and coatings that can enhance the stability, dispersibility, and compatibility of these colloids for specific applications. Additionally, we have discussed the challenges associated with magnetic field responsive colloids, such as stability, scalability, biocompatibility, and targeting specificity. Furthermore, we have highlighted the diverse applications of magnetic field responsive colloids in various fields. These include drug delivery systems for controlled and targeted release of therapeutics, tissue engineering for scaffold fabrication and cell manipulation, biosensing and diagnostics for sensitive detection of analytes, and actuation and micro robotics for precise control and manipulation at the microscale.

In considering the future perspectives, we have emphasized the importance of addressing the challenges faced by magnetic field responsive colloids. The development of scalable synthesis methods, enhancement of stability, improvement of biocompatibility, and achieving greater targeting specificity will drive their practical applications. Future research should focus on developing multifunctional colloids, integrating with other emerging technologies, exploring biomedical applications, and designing materials with tailored magnetic response properties. Continued research and development in this field will pave the way for advanced technologies, improved therapeutic outcomes, and the integration of magnetic field responsive colloids into various sectors. With further exploration, optimization, and innovation, magnetic field responsive colloids will continue to contribute to the advancement of science, technology, and medicine.

References

[1] I. Sharifi, H. Shokrollahi, M. M. Doroodmand, and R. Safi, "Magnetic and structural studies on CoFe2O4 nanoparticles synthesized by co-precipitation, normal micelles and reverse micelles methods," J. Magn. Magn. Mater., vol. 324, no. 10, pp. 1854–1861, May 2012, doi: 10.1016/j.jmmm.2012.01.015.

[2] H. Zeng and S. Sun, "Syntheses, Properties, and Potential Applications of Multicomponent Magnetic Nanoparticles," Adv. Funct. Mater., vol. 18, no. 3, pp. 391–400, Feb. 2008, doi: 10.1002/adfm.200701211.

[3] M. J. Banholzer, J. E. Millstone, L. Qin, and C. A. Mirkin, "Rationally designed nanostructures for surface-enhanced Raman spectroscopy," Chem. Soc. Rev., vol. 37, no. 5, p. 885, 2008, doi: 10.1039/b710915f.

[4] Z. L. Wang, "Transmission Electron Microscopy of Shape-Controlled Nanocrystals and Their Assemblies," J. Phys. Chem. B, vol. 104, no. 6, pp. 1153–1175, Feb. 2000, doi: 10.1021/jp993593c.

[5] S. Sun and H. Zeng, "Size-Controlled Synthesis of Magnetite Nanoparticles," J. Am. Chem. Soc., vol. 124, no. 28, pp. 8204–8205, Jul. 2002, doi: 10.1021/ja026501x.

[6] Y. Jun, J. Seo, and J. Cheon, "Nanoscaling Laws of Magnetic Nanoparticles and Their Applicabilities in Biomedical Sciences," Acc. Chem. Res., vol. 41, no. 2, pp. 179–189, Feb. 2008, doi: 10.1021/ar700121f.

[7] D. Kim, K. Shin, S. G. Kwon, and T. Hyeon, "Synthesis and Biomedical Applications of Multifunctional Nanoparticles," Adv. Mater., vol. 30, no. 49, p. 1802309, Dec. 2018, doi: 10.1002/adma.201802309.

[8] O. Veiseh, J. W. Gunn, and M. Zhang, "Design and fabrication of magnetic nanoparticles for targeted drug delivery and imaging," Adv. Drug Deliv. Rev., vol. 62, no. 3, pp. 284–304, Mar. 2010, doi: 10.1016/j.addr.2009.11.002.

[9] R. He, X. Qian, J. Yin, and Z. Zhu, "Preparation of polychrome silver nanoparticles in different solvents," J. Mater. Chem., vol. 12, no. 12, pp. 3783–3786, Nov. 2002, doi: 10.1039/b205214h.

[10] J. Gao, H. Gu, and B. Xu, "Multifunctional Magnetic Nanoparticles: Design, Synthesis, and Biomedical Applications," Acc. Chem. Res., vol. 42, no. 8, pp. 1097–1107, Aug. 2009, doi: 10.1021/ar9000026.

[11] M. M. Rashad, E. M. Elsayed, M. M. Moharam, R. M. Abou-Shahba, and A. E. Saba, "Structure and magnetic properties of NixZn1−xFe2O4 nanoparticles prepared through co-precipitation method," J. Alloys Compd., vol. 486, no. 1–2, pp. 759–767, Nov. 2009, doi: 10.1016/j.jallcom.2009.07.051.

[12] A. S. Korsakova, D. A. Kotsikau, Y. S. Haiduk, and V. V. Pankov, "Synthesis and Physicochemical Properties of MnxFe3–xO4 Solid Solutions," Kondens. sredy i mezhfaznye granitsy = Condens. Matter Interphases, vol. 22, no. 4, pp. 466–472, Dec. 2020, doi: 10.17308/kcmf.2020.22/3076.

[13] R. Mout, D. F. Moyano, S. Rana, and V. M. Rotello, "Surface functionalization of nanoparticles for nanomedicine," Chem. Soc. Rev., vol. 41, no. 7, p. 2539, 2012, doi: 10.1039/c2cs15294k.

[14] G. Baldi et al., "Synthesis and Coating of Cobalt Ferrite Nanoparticles: A First Step toward the Obtainment of New Magnetic Nanocarriers," Langmuir, vol. 23, no. 7, pp. 4026–4028, Mar. 2007, doi: 10.1021/la063255k.

[15] H. Xu, L. Cheng, C. Wang, X. Ma, Y. Li, and Z. Liu, "Polymer encapsulated upconversion nanoparticle/iron oxide nanocomposites for multimodal imaging and magnetic targeted drug delivery," Biomaterials, vol. 32, no. 35, pp. 9364–9373, Dec. 2011, doi: 10.1016/j.biomaterials.2011.08.053.

[16] A. M. Demin et al., "Silica coating of Fe3O4 magnetic nanoparticles with PMIDA assistance to increase the surface area and enhance peptide immobilization efficiency," Ceram. Int., vol. 47, no. 16, pp. 23078–23087, Aug. 2021, doi: 10.1016/j.ceramint.2021.04.310.

[17] B. Almeida, O. K. Nag, K. E. Rogers, and J. B. Delehanty, "Recent Progress in Bioconjugation Strategies for Liposome-Mediated Drug Delivery," Molecules, vol. 25, no. 23, p. 5672, Dec. 2020, doi: 10.3390/molecules25235672.

[18] S. Mourdikoudis, A. Kostopoulou, and A. P. LaGrow, "Magnetic Nanoparticle Composites: Synergistic Effects and Applications," Adv. Sci., vol. 8, no. 12, Jun. 2021, doi: 10.1002/advs.202004951.

[19] S. Layek, A. Pandey, A. Pandey, and H. Verma, "Synthesis of &#947–Fe2O3 nanoparticles with crystallographic and magnetic texture," Int. J. Eng. Sci. Technol., vol. 2, no. 8, Feb. 2011, doi: 10.4314/ijest.v2i8.63778.

[20] D. Bokov et al., "Nanomaterial by Sol-Gel Method: Synthesis and Application," Adv. Mater. Sci. Eng., vol. 2021, pp. 1–21, Dec. 2021, doi: 10.1155/2021/5102014.

[21] E. kianfar, "Magnetic Nanoparticles in Targeted Drug Delivery: a Review," J. Supercond. Nov. Magn., vol. 34, no. 7, pp. 1709–1735, Jul. 2021, doi: 10.1007/s10948-021-05932-9.

[22] J. Li, H. Yao, Y. Lei, W. Huang, and Z. Wang, "Numerical simulation of magnetic fluid hyperthermia based on multiphysics coupling and recommendation on preferable treatment conditions," Curr. Appl. Phys., vol. 19, no. 9, pp. 1031–1039, Sep. 2019, doi: 10.1016/j.cap.2019.06.003.

[23] S. M. Janib, A. S. Moses, and J. A. MacKay, "Imaging and drug delivery using theranostic nanoparticles," Adv. Drug Deliv. Rev., vol. 62, no. 11, pp. 1052–1063, Aug. 2010, doi: 10.1016/j.addr.2010.08.004.

[24] T. Zhu, H. Zhou, X. Chen, and Y. Zhu, "Recent advances of responsive scaffolds in bone tissue engineering," Front. Bioeng. Biotechnol., vol. 11, Nov. 2023, doi: 10.3389/fbioe.2023.1296881.

[25] C. S. S. R. Kumar and F. Mohammad, "Magnetic nanomaterials for hyperthermia-based therapy and controlled drug delivery," Adv. Drug Deliv. Rev., vol. 63, no. 9, pp. 789–808, Aug. 2011, doi: 10.1016/j.addr.2011.03.008.

[26] A. Hsu, A. Wong-Foy, and R. Pelrine, "Ferrofluid Levitated Micro/Milli-Robots," in 2018 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS), Jul. 2018, pp. 1–7, doi: 10.1109/MARSS.2018.8481172.

[27] M. Johannsen et al., "Clinical hyperthermia of prostate cancer using magnetic nanoparticles: Presentation of a new interstitial technique," Int. J. Hyperth., vol. 21, no. 7, pp. 637–647, Nov. 2005, doi: 10.1080/02656730500158360.

[28] J. Ku, K. Wang, Q. Wang, and Z. Lei, "Application of Magnetic Separation Technology in Resource Utilization and Environmental Treatment," Separations, vol. 11, no. 5, p. 130, Apr. 2024, doi: 10.3390/separations11050130.

[29] W. Wang et al., "Magnetochromic Photonic Hydrogel for an Alternating Magnetic Field-Responsive Color Display," Adv. Opt. Mater., vol. 6, no. 4, Feb. 2018, doi: 10.1002/adom.201701093.