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Influence of Magnetic Fields on Physical and Chemical Properties of Materials: A Review

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Abstract

The influence of magnetic fields on the physical and chemical properties of materials has become an important area of interdisciplinary research in materials science, physics, and chemistry. This review examines how external magnetic fields modify key physical properties such as electrical conductivity, thermal behavior, mechanical strength, and optical characteristics through mechanisms like magnetoresistance, magnetostriction, and magneto-optical effects. It also explores the impact of magnetic fields on chemical properties, including reaction kinetics, equilibrium shifts, and electrochemical processes, particularly through spin dynamics and radical pair interactions. Special attention is given to advanced materials such as nanomaterials, polymers, and biomaterials, where magnetic field effects enable controlled synthesis and functional tuning. The paper further highlights experimental techniques and emerging applications in medicine, energy, and environmental science. Overall, the review underscores the growing significance of magnetic field–material interactions and identifies future research directions for technological innovation.

Keywords: Magnetic Field Effects, Material Properties, Magnetism, Chemical Reactions, Magnetic Anisotropy, Nanomaterials

Introduction

Magnetic fields play a fundamental role in governing the behavior of materials at atomic, molecular, and macroscopic levels, making their study highly significant within the domains of materials science, physics, and chemistry. A magnetic field, arising from moving electric charges or intrinsic magnetic moments of particles, interacts with matter primarily through electron spin and orbital motion, leading to measurable changes in material properties. Over the past few decades, advances in experimental techniques and theoretical modeling have enabled a deeper understanding of how magnetic fields influence both physical and chemical characteristics of materials. Physically, magnetic fields can alter electrical conductivity through phenomena such as magnetoresistance, modify mechanical properties via magnetostriction, and affect thermal and optical behavior through magnetocaloric and magneto-optical effects. These interactions are particularly pronounced in materials with strong magnetic ordering, such as ferromagnetic and paramagnetic substances, but are also observable in diamagnetic systems under high field strengths. From a chemical perspective, magnetic fields can influence reaction kinetics, intermediate species stability, and equilibrium positions, especially in reactions involving radical pairs where spin dynamics play a crucial role. Additionally, magnetic fields have been found to impact electrochemical processes, including corrosion rates and electrodeposition, thereby offering potential for controlled material synthesis and improved industrial processes. The emergence of advanced materials such as nanomaterials, smart polymers, and biomaterials has further expanded the scope of magnetic field applications, enabling precise manipulation of structure and functionality at the nanoscale. Consequently, understanding the influence of magnetic fields on material properties is not only of theoretical importance but also critical for the development of innovative technologies in areas such as energy storage, biomedical engineering, and environmental remediation. This review aims to provide a comprehensive analysis of these effects, highlighting key mechanisms, experimental observations, and future research directions.

Scope of the Study

This review focuses on examining the influence of magnetic fields on the physical and chemical properties of a wide range of materials, including metals, polymers, ceramics, and advanced nanomaterials. The study covers key physical properties such as electrical conductivity, thermal behavior, mechanical strength, optical characteristics, and structural transformations under the application of external magnetic fields. It also explores the impact on chemical properties, including reaction kinetics, equilibrium shifts, electrochemical processes, and catalytic behavior, with particular emphasis on spin-dependent mechanisms and radical interactions. The scope further includes analysis of experimental techniques used to measure magnetic effects and evaluates practical applications in industrial processing, biomedical technologies, energy systems, and environmental solutions. However, the review is limited to secondary data from existing literature and does not involve experimental investigation, aiming instead to synthesize current knowledge and identify future research directions in this evolving interdisciplinary field.

Background of the Study

The study of magnetic fields and their interaction with materials has its roots in classical electromagnetism and quantum mechanics, where early discoveries revealed that electron motion and spin are fundamental to magnetic behavior. Over time, this understanding has expanded into material science, highlighting how magnetic fields can significantly influence both physical and chemical properties of substances. Traditional research primarily focused on magnetic materials such as iron, cobalt, and nickel, but recent advancements have demonstrated that even non-magnetic materials can exhibit measurable changes under strong magnetic fields. Developments in experimental techniques and instrumentation have enabled precise observation of phenomena such as magnetoresistance, magnetostriction, and spin-dependent chemical reactions.

Concept of Magnetic Fields and Their Relevance in Material Science

A magnetic field is a vector field generated by moving electric charges, electric currents, or intrinsic magnetic moments of elementary particles, particularly electrons, and it is typically represented by field lines indicating both direction and magnitude. In the context of material science, magnetic fields are crucial because they directly interact with the electronic structure of materials, influencing properties at atomic, molecular, and bulk scales. The behavior of electrons—specifically their spin and orbital motion—determines how a material responds to an external magnetic field, leading to classifications such as diamagnetic, paramagnetic, and ferromagnetic materials. These interactions are quantitatively described using parameters like magnetic susceptibility and permeability, which indicate how strongly a material can be magnetized. Magnetic fields are highly relevant in controlling and tuning material properties, as they can induce changes in electrical conductivity, phase transitions, and microstructural alignment. For instance, during material processing, the application of a magnetic field can influence crystal growth, grain orientation, and defect distribution, thereby improving mechanical strength and functional performance. Magnetic fields enable non-contact and reversible control over materials, making them valuable in advanced applications such as magnetic storage devices, sensors, actuators, and spintronic systems. In nanoscale materials, magnetic field effects become even more significant due to quantum confinement and enhanced surface interactions, allowing precise manipulation of material behavior. Therefore, the concept of magnetic fields is foundational in material science, providing both a theoretical framework and practical tool for designing and optimizing materials with tailored physical and chemical properties.

Historical Development of Magnetism in Physics and Chemistry

The evolution of magnetism as a scientific discipline has progressed from early empirical observations to a well-established theoretical and applied field within physics and chemistry. Initial awareness of magnetic phenomena can be traced to ancient studies of lodestones, but systematic investigation began in the 17th century with William Gilbert, who proposed that Earth itself behaves like a giant magnet. A major breakthrough occurred in the 19th century when Hans Christian Ørsted demonstrated the link between electric current and magnetic fields, followed by Michael Faraday, who introduced the concept of field lines and electromagnetic induction. These discoveries were later unified into a mathematical framework by James Clerk Maxwell, establishing the foundation of classical electromagnetism. In the 20th century, quantum mechanics transformed the understanding of magnetism by explaining it in terms of electron spin and atomic interactions, with key contributions from Wolfgang Pauli and Paul Dirac. In chemistry, magnetism gained importance through techniques such as nuclear magnetic resonance (NMR) and electron spin resonance (ESR), which enabled detailed analysis of molecular structure and reaction pathways. This historical progression highlights how magnetism has evolved into a crucial interdisciplinary tool, underpinning modern advancements in material science, spectroscopy, and nanotechnology.

Importance of Studying Magnetic Field–Material Interactions

The study of magnetic field–material interactions is critically important for advancing both fundamental science and technological innovation, as it provides deep insight into how external fields influence the structural, electronic, and chemical behavior of materials. At the atomic level, magnetic fields interact with electron spin and orbital motion, enabling control over phenomena such as magnetic ordering, energy band structure, and charge transport. This understanding is essential for the development of modern electronic and spintronic devices, where manipulation of spin-dependent properties leads to improved data storage, faster processing, and reduced energy consumption. In material science, magnetic fields serve as a non-invasive tool to tailor physical properties, including mechanical strength, electrical conductivity, and thermal performance, through processes like magnetostriction, magnetoresistance, and magnetic field-assisted crystallization. Additionally, studying these interactions is vital in chemistry, where magnetic fields influence reaction kinetics, intermediate stability, and radical pair mechanisms, offering new pathways for controlling chemical reactions and enhancing catalytic efficiency. The relevance of this field extends to emerging areas such as nanotechnology and smart materials, where magnetic responsiveness enables precise control over material behavior at very small scales. Furthermore, applications in biomedical engineering, such as targeted drug delivery and diagnostic imaging, rely heavily on magnetic field–material interactions.

Literature Review

The interaction between magnetic fields and materials has been a central theme in modern materials science, particularly with the emergence of nanotechnology and advanced functional materials. Early foundational studies emphasize how magnetic fields influence thermophysical and transport properties, especially in fluid-based systems. For instance, Hasaani et al. (2015) experimentally investigated the interaction of magnetic fields with flowing water, demonstrating that magnetic exposure can alter flow characteristics and molecular behavior. This foundational insight has been extended in nanofluid research, where magnetic fields significantly affect viscosity, thermal conductivity, and heat transfer performance. Bashirnezhad et al. (2016) provide a comprehensive review of nanofluid viscosity, highlighting how external magnetic fields can modify particle alignment and fluid resistance. Similarly, Malekzadeh et al. (2016) experimentally confirm that magnetic fields, combined with temperature and nanoparticle concentration, play a critical role in determining nanofluid rheology. Ghadikolaei et al. (2017)

further explore magnetohydrodynamic (MHD) flow behavior in hybrid nanofluids, demonstrating that magnetic forces influence fluid motion and energy transfer mechanisms. These studies collectively establish that magnetic fields act as external control parameters capable of tuning the physical properties of materials, particularly in fluid and nanoscale systems, thereby opening new avenues for thermal management and energy applications.

Building upon fluid-based studies, significant research has focused on the effects of magnetic fields on solid materials, particularly in terms of mechanical, structural, and electronic properties. Sheykholeslami et al. (2016) investigate the influence of magnetic fields on the mechanical properties of Permendur, revealing that magnetic exposure can enhance material strength and alter deformation behavior. Zhao et al. (2019) extend this understanding by analyzing hard-magnetic soft materials, demonstrating that magnetic fields can induce mechanical responses such as deformation and actuation, which are critical for smart material applications. Narita and Fox (2018) provide a comprehensive review of magnetostrictive and magnetoelectric materials, highlighting their ability to convert magnetic energy into mechanical or electrical energy. This conversion capability is particularly relevant for energy harvesting technologies and sensor development. Additionally, Shvedchykova et al. (2020) examine magnetic field distribution in industrial separators, emphasizing how material composition influences magnetic field effectiveness and separation efficiency. These studies collectively indicate that magnetic fields not only influence intrinsic material properties but also enable the development of multifunctional materials with adaptive and responsive behaviors. The integration of magnetic effects into material design has thus become a critical aspect of advanced engineering and applied physics.

In parallel, extensive research has explored the role of magnetic fields in electronic, quantum, and nanoscale materials, where their effects are often more pronounced due to reduced dimensionality. Matsukura et al. (2015) and Jiang et al. (2018) demonstrate that magnetic properties in two-dimensional materials can be controlled using external electric and magnetic fields, enabling the development of spintronic devices. Li et al. (2016) investigate the chiral magnetic effect in topological materials, revealing how magnetic fields influence electronic transport phenomena at the quantum level. Tokura et al. (2019) further expand on this by discussing magnetic topological insulators, which exhibit unique electronic states influenced by magnetic interactions. Nova et al. (2017) introduce the concept of optically induced magnetic fields, showing that phonon excitation can generate effective magnetic fields in materials. Yu et al. (2014) explore magnetization switching driven by spin–orbit torque, highlighting the potential for magnetic-field-free control in advanced electronic devices. These studies collectively underscore the importance of magnetic fields in next-generation technologies, particularly in quantum computing, data storage, and nanoelectronics. The ability to manipulate magnetic properties at the atomic and molecular levels has opened new frontiers in materials science, enabling unprecedented control over electronic and magnetic behaviors.

Furthermore, the application of magnetic fields extends to interdisciplinary domains, including biomedical, energy, and environmental systems, where their effects on materials have practical implications. Mustafa et al. (2019) review the impact of magnetic fields on blood cells, indicating that magnetic exposure can influence biological materials at the cellular level, with potential applications in medical diagnostics and therapy. In the energy sector, Al-Waeli et al. (2017) demonstrate how nanofluids enhanced with magnetic properties improve the efficiency of photovoltaic thermal systems, highlighting the role of magnetic fields in optimizing renewable energy technologies. Bahiraei and Heshmatian (2018) further emphasize the importance of nanofluids in electronics cooling, where magnetic fields can enhance heat dissipation and system performance. Seid Mohammadi et al. (2014) investigate wettability alteration in reservoir rocks using nanoparticles, suggesting that magnetic interactions can influence fluid–solid interfaces in petroleum engineering. Yang et al. (2014) explore photovoltaic materials, indicating that material properties can be tuned for improved energy absorption and conversion. Devi and Devi (2016) analyze the effect of Lorentz forces in nanofluid flow, reinforcing the significance of magnetic fields in fluid dynamics and heat transfer. Collectively, these studies demonstrate that magnetic fields have wide-ranging applications across multiple disciplines, influencing material behavior in diverse environments. The literature thus confirms that magnetic fields are not only fundamental to understanding material properties but also essential for advancing technological innovation in various fields.

Fundamentals of Magnetism

Magnetism is a fundamental physical phenomenon arising from the motion of electric charges and the intrinsic magnetic moments of electrons, particularly their spin and orbital angular momentum. In materials, magnetic behavior is governed by how atomic magnetic moments respond to an external magnetic field and interact with each other through exchange interactions. These responses determine whether a material is weakly repelled, weakly attracted, or strongly attracted to a magnetic field.

1. Types of Magnetism

- **Diamagnetism**

Diamagnetism is a fundamental property exhibited by all materials, characterized by a weak and negative response to an external magnetic field. It arises due to the induced magnetic moments in electron orbitals that oppose the applied field, according to Lenz’s law. As a result, diamagnetic materials are slightly repelled by magnetic fields and do not retain magnetization once the field is removed. This effect is generally very weak and often overshadowed by other forms of magnetism in materials where multiple magnetic behaviors coexist.

- **Paramagnetism**

Paramagnetism occurs in materials that possess unpaired electrons, resulting in a net magnetic moment at the atomic level. When exposed to an external magnetic field, these magnetic moments tend to align parallel to the field, producing a weak attraction. However, thermal motion disrupts this alignment, so the magnetization disappears when the external field is removed. Paramagnetic behavior is temperature-dependent and typically follows Curie's law.

- **Ferromagnetism**

Ferromagnetism is a strong form of magnetism observed in materials such as iron, cobalt, and nickel, where atomic magnetic moments align parallel to each other due to exchange interactions. This alignment produces a large net magnetization even in the absence of an external magnetic field. Ferromagnetic materials exhibit hysteresis and can retain permanent magnetization, making them highly valuable for technological applications like data storage and electromagnetic devices.

- **Antiferromagnetism and Ferrimagnetism**

Antiferromagnetism is characterized by the antiparallel alignment of neighboring magnetic moments with equal magnitude, resulting in zero net magnetization. In contrast, ferrimagnetism involves antiparallel alignment with unequal moments, producing a net magnetic effect. Both phenomena arise from exchange interactions and are important in understanding complex magnetic materials and their applications in electronics and magnetic storage systems.

2. Magnetic Field Parameters

- **Magnetic Flux Density (B)**

Magnetic flux density, commonly denoted as B, represents the strength and direction of a magnetic field within a given area and is measured in tesla (T). It indicates how much magnetic flux passes through a unit area perpendicular to the field lines. This parameter is crucial in determining the force experienced by moving charges and current-carrying conductors in a magnetic field. Magnetic flux density depends on both the applied magnetic field and the nature of the material, as different materials concentrate or weaken magnetic field lines to varying degrees.

- **Magnetic Susceptibility (χ)**

Magnetic susceptibility (χ) is a dimensionless parameter that measures the degree to which a material becomes magnetized in response to an external magnetic field. It reflects how easily magnetic moments within the material align with the applied field. Materials with positive susceptibility, such as paramagnetic and ferromagnetic substances, are attracted to magnetic fields, whereas materials with negative susceptibility, such as diamagnetic substances, are weakly repelled. This parameter plays a key role in classifying magnetic behavior and understanding material response at the microscopic level.

- **Permeability (μ)**

Magnetic permeability (μ) describes the ability of a material to support the formation of a magnetic field within itself. It is defined as the ratio of magnetic flux density to the magnetic field strength and is typically expressed in henry per meter (H/m). Permeability determines how easily magnetic field lines can pass through a material and is significantly higher in ferromagnetic materials compared to free space.

3. Interaction of Magnetic Fields with Matter

1. Atomic and Molecular Level Interactions

The interaction of magnetic fields with matter originates at the atomic and molecular level, where electrons possess intrinsic magnetic moments due to their spin and orbital motion. When an external magnetic field is applied, these moments experience torque and tend to align either parallel or antiparallel to the field, depending on their energy states. This interaction can lead to phenomena such as energy level splitting, commonly known as the Zeeman effect, and subtle changes in electron distribution and bonding characteristics. Materials with unpaired electrons respond more strongly to magnetic fields, while those with paired electrons exhibit weak diamagnetic behavior.

2. Spin Dynamics and Electron Alignment

Spin dynamics refers to the behavior of electron spins under the influence of an external magnetic field and plays a crucial role in determining magnetic properties. Electrons act as microscopic magnetic dipoles, and their alignment is governed by exchange interactions and thermal energy. In a magnetic field, spins tend to align in an ordered manner to minimize energy, leading to magnetization in materials such as ferromagnets. However, thermal fluctuations can disrupt this order, resulting in temperature-dependent magnetic behavior. Spin dynamics is also significant in chemical systems, particularly in reactions involving radical pairs, where magnetic fields influence spin states and reaction pathways.

Influence of Magnetic Fields on Physical Properties of Materials

1. Mechanical Properties

Magnetic fields significantly influence the mechanical behavior of materials, particularly through phenomena such as stress, strain, and magnetostriction. Magnetostriction refers to the change in dimensions of a material when subjected to a magnetic field, resulting from the realignment of magnetic domains within the material

2. Electrical Properties

Magnetic fields play a crucial role in modifying the electrical properties of materials, particularly through magnetoresistance and the Hall effect. Magnetoresistance is the change in electrical resistance of a material in response to an applied magnetic field, widely utilized in magnetic sensors and data storage technologies. The Hall effect, on the other hand, occurs when a magnetic field applied perpendicular to an electric current induces a transverse voltage, providing valuable information about charge carriers and conductivity. These effects are fundamental in semiconductor physics and have enabled advancements in electronic and spintronic devices.

3. Thermal Properties

The thermal properties of materials are also influenced by magnetic fields, particularly in terms of thermal conductivity and the magnetocaloric effect. Magnetic fields can alter phonon and electron transport, leading to variations in heat conduction. The magnetocaloric effect involves a reversible temperature change in a material when exposed to a changing magnetic field, making it highly relevant for magnetic refrigeration technologies.

4. Optical Properties

Magnetic fields affect the optical behavior of materials through magneto-optical phenomena such as the Faraday effect and general magneto-optical responses. The Faraday effect involves the rotation of the plane of polarization of light as it passes through a material in the presence of a magnetic field, which is widely used in optical isolators and communication systems.

5. Structural Properties

Magnetic fields can induce significant changes in the structural properties of materials, particularly during crystallization and phase transitions. The presence of a magnetic field can influence atomic arrangement, grain orientation, and nucleation processes, leading to improved structural uniformity and controlled microstructure. In some cases, magnetic fields can stabilize or alter phase transformations by affecting thermodynamic and kinetic conditions. These effects are particularly useful in materials processing, where controlled structural modification is essential for achieving desired physical and functional properties.

Influence of Magnetic Fields on Chemical Properties

1. Reaction Kinetics

Magnetic fields can significantly affect reaction kinetics by altering the rate and pathway of chemical reactions, particularly those involving paramagnetic species or radical intermediates. The presence of a magnetic field influences the spin states of reacting species, which in turn affects transition probabilities and reaction rates. One of the most important mechanisms is the radical pair mechanism, where magnetic fields modify the interconversion between singlet and triplet spin states of radical pairs, thereby influencing product distribution and reaction efficiency. This effect is especially relevant in photochemical reactions and biological systems, where spin-selective processes govern reaction outcomes.

2. Chemical Equilibrium

Magnetic fields can also influence chemical equilibrium by affecting the relative stability of reactants and products, particularly in systems involving magnetic species. The application of a magnetic field may alter energy levels and magnetic moments of molecules, leading to slight shifts in equilibrium positions. Although these effects are generally small under normal conditions, they become more significant in high magnetic fields or in reactions involving paramagnetic compounds. Magnetic influence on equilibrium is important in processes such as coordination chemistry and catalysis, where subtle energy changes can impact yield and reaction direction.

3. Electrochemical Processes

Electrochemical processes are notably affected by magnetic fields, especially in terms of corrosion behavior and electrolysis. Magnetic fields can influence ion transport, diffusion layers, and electrode kinetics through magnetohydrodynamic effects, which enhance mass transfer in electrolyte solutions. This can lead to either acceleration or inhibition of corrosion rates depending on the system conditions. In electrolysis, magnetic fields improve efficiency by promoting uniform deposition and reducing concentration polarization at electrode surfaces. These effects are particularly useful in industrial applications such as metal refining, electroplating, and energy storage systems, where improved control over electrochemical reactions is essential.

Magnetic Field Effects in Advanced Materials

1. Nanomaterials and Nanotechnology

Magnetic fields have a profound influence on nanomaterials due to their high surface-to-volume ratio and quantum confinement effects. In magnetic nanoparticles, external magnetic fields can control particle alignment, aggregation, and magnetic domain orientation, which directly impacts their optical, electrical, and catalytic properties. These nanoparticles exhibit unique behaviors such as superparamagnetism, making them highly suitable for applications in data storage, targeted drug delivery, and environmental remediation.

2. Polymers and Smart Materials

Magneto-responsive polymers represent an important class of smart materials that can change their physical or chemical properties in response to an external magnetic field. By incorporating magnetic particles into polymer matrices, these materials can exhibit controlled deformation, stiffness variation, and shape memory behavior when exposed to magnetic stimuli. Such properties are highly valuable in applications such as soft robotics, sensors, actuators, and adaptive systems.

3. Biomaterials

Magnetic fields significantly affect biomaterials by interacting with biological molecules, cells, and tissues at both molecular and systemic levels. Magnetic nanoparticles are widely used in biomedical applications, including targeted drug delivery, magnetic resonance imaging, and hyperthermia treatment for cancer therapy. At the molecular level, magnetic fields can influence protein folding, enzyme activity, and cellular signaling pathways through spin-dependent interactions.

Applications of Magnetic Field Effects

1. Industrial Applications

Magnetic field effects are extensively utilized in industrial material processing and manufacturing to enhance efficiency and product quality. During processes such as casting, welding, and crystal growth, magnetic fields are applied to control fluid flow, reduce defects, and improve microstructural uniformity. Electromagnetic stirring, for instance, helps achieve homogeneous composition in molten metals, while magnetic fields can also influence grain orientation and phase distribution. Additionally, magnetic separation techniques are widely used for sorting and purifying materials in mining and recycling industries, improving both productivity and sustainability.

2. Medical Applications

In the medical field, magnetic field applications are highly advanced and impactful, particularly in diagnostic imaging and targeted therapies. Magnetic Resonance Imaging (MRI) utilizes strong magnetic fields and radio waves to produce detailed images of internal body structures without harmful radiation. Magnetic nanoparticles are employed in targeted drug delivery systems, where external magnetic fields guide therapeutic agents directly to specific sites within the body, enhancing treatment efficiency and minimizing side effects. Magnetic hyperthermia is another emerging technique used in cancer treatment.

3. Environmental Applications

Magnetic field effects play a significant role in environmental protection, especially in water treatment and pollution control. Magnetic separation techniques are used to remove heavy metals, organic pollutants, and suspended particles from wastewater. Functionalized magnetic nanoparticles can bind contaminants and be easily extracted using external magnets, offering an efficient and reusable solution. These methods contribute to sustainable environmental management by reducing chemical usage and improving purification processes.

4. Energy Sector

In the energy sector, magnetic field effects are applied in innovative technologies such as magnetic refrigeration and energy storage systems. Magnetic refrigeration is based on the magnetocaloric effect, where materials undergo temperature changes under varying magnetic fields, offering an energy-efficient and environmentally friendly alternative to conventional cooling systems. Magnetic materials are integral to energy storage devices, transformers, and inductors, where they enhance performance, reduce energy losses, and support the development of advanced power systems.

Conclusion

The influence of magnetic fields on the physical and chemical properties of materials represents a highly significant and evolving area of interdisciplinary research, integrating principles from physics, chemistry, and materials science. This review has highlighted that magnetic fields can effectively alter a wide range of physical properties, including mechanical strength, electrical conductivity, thermal behavior, optical characteristics, and structural organization, primarily through mechanisms such as magnetostriction, magnetoresistance, and magneto-optical effects. Simultaneously, magnetic fields impact chemical properties by modifying reaction kinetics, influencing equilibrium conditions, and enhancing electrochemical processes through spin dynamics and magnetohydrodynamic effects. The role of magnetic fields becomes even more pronounced in advanced materials such as nanomaterials, smart polymers, and biomaterials, where their ability to control structure and functionality at micro- and nanoscale levels enables innovative technological applications. Furthermore, the review has demonstrated the practical importance of magnetic field interactions across various sectors, including industrial manufacturing, medical diagnostics and therapy, environmental management, and energy systems. Despite these advancements, several challenges remain, such as limitations in large-scale implementation, material-specific constraints, and the need for more precise experimental and theoretical models. Future research should focus on developing advanced materials with enhanced magnetic responsiveness, improving experimental techniques, and exploring new applications in emerging fields like spintronics and quantum materials.

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