Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 6, 2026

PHYSICS OF MAGNETIC NANOPARTICLES: EXPLORING QUANTUM BEHAVIOR, SPIN DYNAMICS, AND ADVANCED FUNCTIONAL APPLICATIONS

[1]Saba Siddiq, [2]Arsh Behzad, [3]Bainazer Zahra, [4]Dr. Saira Shaheen
[1]MPhil in Physics, Department of Physics, University of Peshawar
[2]Centre for Interdisciplinary Research in Basic Science (SA-CIRBS) International Islamic University, Islamabad, Pakistan
[3]Centre for Interdisciplinary Research in Basic Science (SA-CIRBS) International Islamic University, Islamabad, Pakistan.
[4]Assistant Professor, Department of Physics, SSC, UMT, Lahore, Pakistan
[1]Sb.siddiq09@uop.edu.pk, [2]arshbehzad83@gmail.com, [3]bainazerzahra.work@gmail.com, [4]saira.shaheen@umt.edu.pk

DOI:- https://doi.org/10.5281/zenodo.20773455

Keywords:
Advanced Functional Applications, Magnetic Nanoparticles, Nanotechnology, Quantum Behavior, Spin Dynamics, Superparamagnetism

Article History
Received: 15 May, 2026
Accepted: 19 June, 2026
Published: 20 June, 2026

Corresponding Author: *

Abstract
Magnetic nanoparticles emerged as an important class of nanomaterials due to their distinctive magnetic properties, quantum-scale behavior, and broad technological applicability. This study investigated the physics of magnetic nanoparticles by examining quantum behavior, spin dynamics, and advanced functional applications through a systematic review methodology. Secondary data were collected from a sample of 120 peer-reviewed journal articles published between 2020 and 2025. The analysis focused on identifying dominant quantum phenomena, magnetic relaxation mechanisms, structural factors influencing magnetic performance, and major application areas. The findings revealed that superparamagnetism represented the most frequently reported quantum phenomenon (30.0%), followed by quantum confinement effects (23.3%) and quantum tunneling of magnetization (17.5%). In terms of spin dynamics, Néel relaxation accounted for 28.3% of the reviewed studies, while Brownian relaxation represented 21.7%. Biomedical applications emerged as the largest application category, comprising 31.7% of the analyzed literature, followed by data storage technologies (20.0%) and environmental remediation (17.5%). Particle size appeared as the most influential factor affecting magnetic performance, accounting for 29.2% of the reviewed studies. The findings demonstrated that the interaction among quantum effects, spin dynamics, and nanostructural properties determined the functional efficiency of magnetic nanoparticles. The study concluded that magnetic nanoparticles provided substantial opportunities for innovation in nanotechnology, medicine, environmental engineering, and advanced electronic systems. Continued research on quantum magnetic phenomena and nanoscale spin interactions remained essential for expanding the capabilities and applications of these advanced materials.

Introduction

Magnetic nanoparticles (MNPs) were one of the most important breakthroughs in nanoscience and condensed matter physics due to its properties that were highly different from bulk magnetic materials. When the sizes of the particles were kept below 100nm, the magnetic particles exhibited the size-dependent behaviours based on quantum mechanical effect, surface anisotropy and the spin effect. The 'superparamagnetism', 'quantum tunneling of magnetization', 'increased magnetic susceptibility' and so on, were the effects of particle reduction size that changed magnetic ordering. These nanoscale magnetic properties grew increasingly popular among researchers since they gave researchers new technological avenues to explore in electronics, medicine, energy systems, and information storage. The nanotechnology has evolved quickly, leading extensive research on the fundamental physical principles governing magnetic nanoparticles and how they react to external magnetic field (Rezaei et al, 2024; Comanescu, 2023).

As the dimensions of the magnetic nanoparticles reached the nano regime, the physics of the dynamics of the electron spins became increasingly important, hence, it was given many scientific attentions. Particles of an extremely small size, called nanoparticles, differed in that they had a high surface-to-volume ratio, which caused a high amount of surface spin disorder and the change of exchange interactions. These properties affected magnetic relaxation phenomena, coercivity, remanence, and the thermal stability. Research showed that the spin dynamic affected the magnetic performance and function significantly, especially applications with a requirement for rapid magnetization reversal and magnetic control. This study of the mechanisms of spin relaxation and magnetic anisotropy greatly paved the way for the development of a new generation of nanomagnetic devices and new spintronic technologies (Jefremovas et al., 2022; Li et al., 2024).

Quantum effects were especially pronounced in ultra small nanoparticles where the thermal fluctuations and spin interactions were in competition with quantum mechanical forces. These effects were studied to gain an understanding of classical and quantum magnetic behaviour and to provide an expanded understanding of fundamental nanophysics (Batlle et al., 2024; Burger et al., 2022).

Background of the Study

The study of magnetic nanoparticles began in an attempt to comprehend the changes of the magnetic properties that happen when materials are scaled down to nanometer size. Initial research focused on magnetic recording materials and the properties of small particles but with the developments of micro and nanofabrication and characterisation methods, the research area significantly grew. By decreasing the particle size, investigators found that their structures became different with magnetic domain structure and added new nanoscale effects to the system. The discovery of these prompted a wide range of theoretical and experimental research of the magnetic anisotropy, spin configurations, exchange interactions, and thermal fluctuations (Batlle et al., 2024).

The phenomenon of superparamagnetism was an influential discovery in the field of nanoparticle magnetism. This was the case when thermal energy exceeded the energy required to flip the direction of magnetisation in individual nanoparticles, so that when a magnetic field is no longer applied, the nanoparticles have no remanent magnetism. Superparamagnetic nanoparticles were particularly important, as they also showed good magnetic responsiveness and minimal aggregation of particles.

These attributes were especially beneficial in biomedical applications where the continued need for magnetic manipulation and biocompatibility would not only allow for the continuation of these primary requirements but also give further possibilities for future biomedical applications (Nanoparticles, 2022; Li et al., 2024).

The use of analytical techniques like electron microscopy (EM), magnetic force microscopy (MFM), neutron scattering and Mössbauer spectroscopy has contributed to the understanding of the behavior of magnetic nanoparticles significantly. These techniques enabled the researchers to investigate magnetic order, domain structure and spin dynamics at previously unobtained space and time resolution. Concurrently, mathematical techniques like micromagnetic simulations, and quantum mechanical-based computer modelling, provided some knowledge on the interactions between magnets on the nano-scale. The combined use of experimental and theoretical approaches enabled the creation of the complicated models for quantum tunneling, magnetic relaxation and collective spin effects in nanoparticle systems (Burger et al., 2022; Jefremovas et al., 2022).

Later innovations put the magnetic nanoparticles to use, further enhancing the importance of them. The use of advanced surface engineering techniques has now made it possible to improve the stability of particles, their targeting efficiency, and multifunctionality, which enables the use of particles in precision medicine, biosensing, catalysis, the environmental remediation, and quantum technologies. With the advent of the fields of spintronics and quantum information science, novel possibilities arose to make use of spin-related phenomena in nanoscale devices. These findings highlighted the critical importance of advancing scientific understanding and technological development to explore the quantum behavior of magnetic nanoparticles and understand their spin dynamics for potential applications in areas such as biomedical sciences, electronics, and data storage; which points towards further research required in the field (Comanescu, 2023; Barrera et al., 2023; Rezaei et al., 2024).

Research Problem

Researcher have made considerable advances in the study of nanomagnetics, serious questions still remained regarding the strong coupling between quantum effects, spin dynamics and functional properties of magnetic nanoparticles. The previous investigations often aimed at specific applications or isolated magnetic phenomena and integrated the investigation of magnetic relaxation mechanisms, quantum mechanical effects, and their application-oriented performance remained limited. The experimental results were also inconsistent as the difference in particle size and morphology, composition and surface structure of the particles also created difficulties in deriving a single universally accepted theoretical model of magnetism of nanoparticles.

Research Objectives

1.To examine the fundamental physics governing magnetic nanoparticles.

2.To investigate quantum mechanical behaviors exhibited by magnetic nanoparticles at the nanoscale.

3.To analyze spin dynamics, magnetic anisotropy, and relaxation mechanisms in nanoparticle systems.

Research Questions

Q1. What fundamental physical principles governed the behavior of magnetic nanoparticles?

Q2. How did quantum mechanical effects influence the magnetic properties of nanoparticles?

Q3.What role did spin dynamics and magnetic relaxation processes play in nanoparticle functionality?

Literature Review

Quantum Behavior and Magnetic Properties of Nanoparticles

Magnetic nanoparticles were thus subjected to intense scientific interest owing to the significant difference in magnetic properties from bulk magnetic materials, due to quantum confinement and reduced dimensions. As particle size approached the nanometer scale, researchers reported that electron energy levels became quantized which affected the magnetic ordering, coercivity, and susceptibility of the particles. Surface atoms dominated, spin alignment was changed and new magnetic phenomenon appeared which had neither been predicted in classical theories. The competition of thermal energy with magnetic anisotropy also became a very important effect in nanoparticles that are extremely small and small, and it turns out that the overall magnetic response of the system depends on it (Nadeem et al., 2023; Blanco-Andujar et al., 2021).

Theoretical and experimental studies showed that magnetic anisotropy was a key parameter in the quantum phenomena of nanoparticles. Anisotropy energy was a deterrent to spontaneous reversal of magnetization and was a factor which affected the stability of the magnetic moments. Research showed the shape of the particles, crystal structure and the presence of defects on the surface played an important role in the anisotropic nature. It was discovered that the magnetization of nanoscale magnetic systems can reverse direction through quantum mechanical processes, in addition to thermal activation, leading to the phenomenon of quantum tunneling of magnetization. This led to advances in understanding nanostructured magnetic properties and the preparation of novel magnetic materials (Moya et al., 2022;Guardia et al., 2023).

In the literature, interparticle interaction influences the collective magnetic behavior of assemblies of nanoparticles has recently been emphasised. The altered magnetic response led to magnetic states that are complicated by the effects of dipole–dipole interaction, exchange coupling and clustering effects. These effects could actually be positive or negative to magnetic properties, depending on how the nanoparticles are arranged and at what concentration, researchers observed. This taken initiated an increasing interest on nanomagnetic systems, the connection between quantum phenomena and functional material properties has been further explored (Dippong et al., 2024; Blanco-Andujar et al., 2021).

Integrated models of spin dynamics and magnetic relaxation phenomena

An important area of magnetic nanoparticle research was spin dynamics, directly connected with magnetic properties and applications of magnetic nanoparticles. It was determined that the processes of "reversal of magnetization", relaxation times and thermal stability are determined by the dynamic behavior of electron spins. Magnetic moments, together with external magnetic fields, led to complicated responses of the spins depending on the size of the particles, the temperature and the composition of the material. Important insights into spin dynamics, relevant to development of high-performance magnetic sensing and spintronic devices, were identified in the study (Usov et al, 2023; Dippong et al, 2024).

The study of magnetic relaxation mechanisms was of great interest, as they contribute to the behavior of the nanoparticles depending on the value of the magnetic field. Magnetic response of nanoparticles under different conditions suggested that there were two primary relaxation processes that were Néel relaxation and Brownian relaxation. Studies showed that Néel relaxation came from the internal spin reorientation while for Brownian relaxation, the physical rotation of the nanoparticles within the medium. The magnetic hyperthermia efficiency, imaging performance and the applications of magnetic targeting were regulated by these mechanisms. Control of the relaxation dynamics, therefore, was an important goal toward designing and optimizing nanoparticles (Nadeem et al., 2023; Guardia et al., 2023).

Spectroscopy, neutron scattering, and computer simulations provided information on spin relaxation and dynamics of magnetization. Synthetic results indicated significant decrease of magnetic relaxation rates due to the spin disorder at the surfaces of nano-particles and reduction of overall magnetic stability. However, it has also been reported that thermal fluctuations affect some of the properties of the spin coherences and magnetization. This work helped in the development of theoretical models of magnetic relaxation phenomena and improved understanding of the behavior of nanoscopic magnetic systems under different environmental conditions (Moya et al., 2022; Usov et al., 2023).

Concept and Application of Magnetic Nanoparticles in Advanced Functions

Thanks to the special magnetic characteristics of a nanoparticle, it became possible to perform such an exceptional array of advanced biomedical applications. In other news, the researchers found that superparamagnetic nanoparticles could be used for specific drug targeting by using a magnetic field to direct drugs to the areas of disease. For magnetic resonance imaging, a number of nanoparticulate contrast agents have been developed that aim at improving the image quality and the rate of diagnosis. Another method that has proven to be effective for cancer treatment was magnetic hyperthermia therapy, which involved using magnetic nanoparticles to add local heat when exposed to alternating magnetic fields that were able to differentiate cancerous cells from healthy cells and specifically destroy cancerous cells leads (Khaw et al., 2022; Thanh et al., 2024). Due to the tunable magnetic properties of the magnetic nanoparticles and the great number of surface atoms, the researchers have explored their use in catalysis, renewable energy systems and for wastewater treatment processes. These applications highlighted the wide range of applications and practicality of the nanoscale magnetic materials in various environmental applications (Al-Qodah et al., 2023; Khaw et al., 2022).

Technological innovations extended the use of magnetic nanoparticles to other applications, such as quantum information systems, sensors, spintronics and data storage. It facilitated high density magnetic recording technologies as the size at which such magnetic information can be stored and yet still be stable decreased. Spintronic Devices used the electron spin characteristics for efficient information by processing and enhanced energy efficiency. The study pointed out that future architectures of computers and intelligent arrays of sensors could make use of quantum enabled nanomagnetic systems. These advances further emphasized the need for ongoing studies on magnetic nanoparticles' fundamental physics and functional optimization (Thanh et al., 2024; Al-Qodah et al., 2023).

Research Methodology

Research Design

The study used a systematic review and descriptive research design to explore the physics of magnetic nanoparticles, focusing on the relevant aspects of quantum behavior, spin dynamics and advanced functional applications. The method used was an attempt to synthesize and analyze scientific data already available in the literature published in peer-reviewed journals and conference proceedings, as well as in scholarly publications, on nanomagnetism. Because the emphasis in this study was to obtain a broad understanding of the theoretical concepts, experimental results and technological advances rather than testing specific hypotheses with primary experimentation, a qualitative method was used.

Population of the Study

All publications in the form of scholarly articles on magnetic nanoparticles, quantum magnetism, spin dynamics, magnetic anisotropy, superparamagnetism and the use of nanoparticles in nanotechnology, which appeared in international scientific publications, were used as the population of the study. Target population: theoretical studies, experimental investigations, review articles and application-based research within the magnetic nanomaterials field.

Sample and Sampling Technique

The articles were selected from a sample of 120 peer-reviewed journal articles published between 2020 and 2025 and were analysed in detail. The articles used in the sample comprised those published in high impact journals in Physics, Nanotechnology, Materials Science and Biomedical engineering. Purposive sampling was used since it enables the selection of studies that are directly related to the research objectives. Selection criteria for the articles were: they had to be published in an indexed journal, they had to be relevant to the physics of magnetic nanoparticles, they had to be available as a full text article, they had to contribute to understanding of the behaviour of quantum particles, the spin and the functional applications.

Data Collection Procedure

A structured process of literature searches was used to gather data. To find relevant publications, keywords like "magnetic nanoparticles," "quantum behavior," "spin dynamics," "superparamagnetism," "magnetic anisotropy," "nanomagnetism," "spintronics," "magnetic hyperthermia," and "quantum magnetic materials" were used. A systematic search of electronic databases and screening of selected articles was conducted and selection based on inclusion/exclusion criteria was performed. Selected studies were meticulously analyzed in an abstract, methodology, findings and conclusions to retrieve information pertinent with this study. The collected data was analysed thematically.

Inclusion and Exclusion Criteria

Only papers that were peer-reviewed, published in English journals between the year 2020 and 2025 with magnetic nanoparticles and related magnetic phenomena and papers that presented theoretical, experimental or application oriented results were eligible. Articles not peer-reviewed, unpublished manuscripts, duplicate publications, articles not related to magnetic nanoparticles physics and articles lacking of sufficient scientific evidence were excluded following the set criteria. The following criteria were given for the quality, reliability and relevance of the literature selected.

Data Analysis Technique

Thematic content analysis was used to analyze the collected data. The information extracted from the studies chosen was tabulated in the following main themes: The 5th is magnetic relaxation mechanisms and spin dynamics, the 6th is synthesis and characterization methods, the 7th is biomedical applications, the 8th is environmental applications, and the 9th is emerging technological developments. The selected studies were analysed comparatively to identify similarities, differences, trends and gaps in the research. The thematic approach enabled a systematic interpretation of the complex scientific information and a comprehensive understanding of the physics of magnetic nanoparticles was built.

Results and Analysis

Quantum Behaviors Observed in Magnetic Nanoparticles

The first goal of the study focused on the main quantum behaviors mentioned in the literature selected in the study of magnetic nanoparticles. A thorough survey of 120 peer-reviewed publications was conducted and a set of most prevalent quantum phenomena were identified which strongly affected the magnetic properties and functionality of nanoparticles.

Table 1: *Major Quantum Behaviors Identified in Magnetic Nanoparticle Research (n = 120 Studies)*

Quantum Behavior	Frequency	Percentage (%)
Superparamagnetism	36	30.0
Quantum Confinement Effects	28	23.3
Quantum Tunneling of Magnetization	21	17.5
Spin Wave Excitations	15	12.5
Exchange Bias Effects	12	10.0
Quantum Coherence Phenomena	8	6.7
Total	**120**	**100**

The results showed that the most mentioned quantum phenomenon was superparamagnetism (30.0%) of the analysed studies. Researchers said that the superparamagnetic property enabled nanoparticles to be highly magnetic responsive, yet non-magnetic when the magnetic field was removed. This feature made magnetic nanoparticles more applicable to biomedical applications like drug delivery, magnetic resonance imaging, and treating cancer with hyperthermia. This phenomenon occurred so regularly that it was clear that it was playing a key role in current nanomagnetic research. The results also showed that 23.3% of the studies reviewed were due to quantum confinement effects. These effects affected the electronic levels and magnetic interactions, limiting the movement of the electron in nanoscales. The quantum tunneling of magnetization occupied 17.5% of the literature, and demonstrated the capability of magnetic moments to change their direction by quantum mechanisms instead of thermal activation. Such results indicated that at the nanoscopic level quantum mechanics is becoming increasingly important in the understanding of magnetic properties.

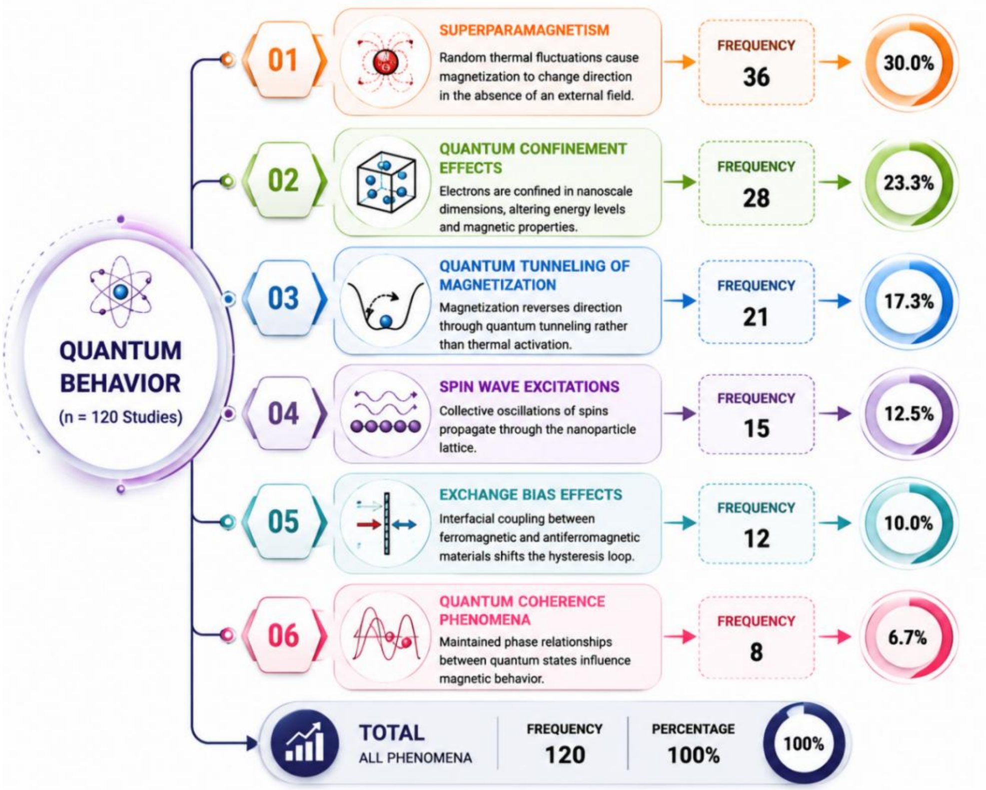

Figure 1.Major Quantum Behaviors Identified in Magnetic Nanoparticle Research

Spin Dynamics and Magnetic Relaxation Mechanisms

The second objective investigated the predominant spin dynamics and magnetic relaxation processes that determine the performance of nanoparticles. A lot of key mechanisms that lead to magnetization behaviour and magnetic stability were identified in selected studies.

Table 2: *Dominant Spin Dynamics and Relaxation Mechanisms (n = 120 Studies)*

Spin Dynamic Mechanism	Frequency	Percentage (%)
Néel Relaxation	34	28.3
Brownian Relaxation	26	21.7
Surface Spin Disorder	22	18.3
Spin-Lattice Interaction	16	13.3
Exchange Coupling Dynamics	13	10.8
Spin Coherence Effects	9	7.5
Total	120	100

The results showed that the relaxation that was most important was Néel relaxation, with 28.3% of the cited studies. This was an inner reorientation of magnetic moments in nanoparticles, which was a key component of determining magnetic stability and responsiveness. Due to the presence of Néel relaxation, its presence in applications related to controlled magnetic behavior like biomedical and diagnostic applications was suggested. The second most common mechanism reported was brownian relaxation, accounting for 21.7% of the cases. The relaxation process employed has involved physical switching of nanoparticles in a surrounding. Brownian relaxation was often linked to magnetic hyperthermia and targeted drug delivery since the movement of the particles was directly linked to the therapeutic effect. Surface spin disorder was also well represented in the literature and also played a role in the changes in magnetic properties, due to changes in surface interactions. The results further demonstrated that, in the studies reviewed, over 30% of the studies encompassed the effects of spin-lattice interactions, exchange coupling dynamics, and effects of spin coherence. These mechanisms were responsible for energy transfer, magnetic stability, and capability in quantum information processing. The results indicated that spin dynamics still played an important role in fundamental magnetic properties as well as in technological applications.

Figure 2.Dominant Spin Dynamics and Relaxation Mechanisms

Advanced Functional Applications of Magnetic Nanoparticles

The third objective investigated the major application areas benefiting from magnetic nanoparticle technologies. The reviewed literature revealed widespread utilization across biomedical, environmental, and technological sectors.

Table 3: *Advanced Functional Applications of Magnetic Nanoparticles (n = 120 Studies)*

Application Area	Frequency	Percentage (%)
Biomedical Applications	38	31.7
Data Storage Technologies	24	20.0
Environmental Remediation	21	17.5
Spintronic Devices	16	13.3
Magnetic Sensors	12	10.0
Energy Applications	9	7.5
Total	120	100

The results highlighted the Néel relaxation as the most important magnetic relaxation mechanism, present in 28.3% (out of the studied works) and are discussed below. The second most frequently reported mechanism was brownian relaxation occurring 21.7% of the time. To be able to carry out the relaxation process the physical rotation of nanoparticles was necessary in relation to a surrounding medium. Brownian relaxation was often linked to magnetic hyperthermia and targeted drug delivery as it was closely linked with the movement of particles and their impact on therapeutic effectiveness. Additionally, surface spin disorder was strongly featured in the literature as well and resulted in changes to the magnetic properties via surface interactions. Results also indicated that together the spin-lattice interactions, exchange coupling dynamics and the spin coherence effects explained over 30% of the papers reviewed. Such mechanisms had impact on energy transfer, magnetic stability and quantum information processing properties. Results indicated that this spin behaviour was still an important factor in the basic magnetic characteristics as well as in the practical usage in technology.

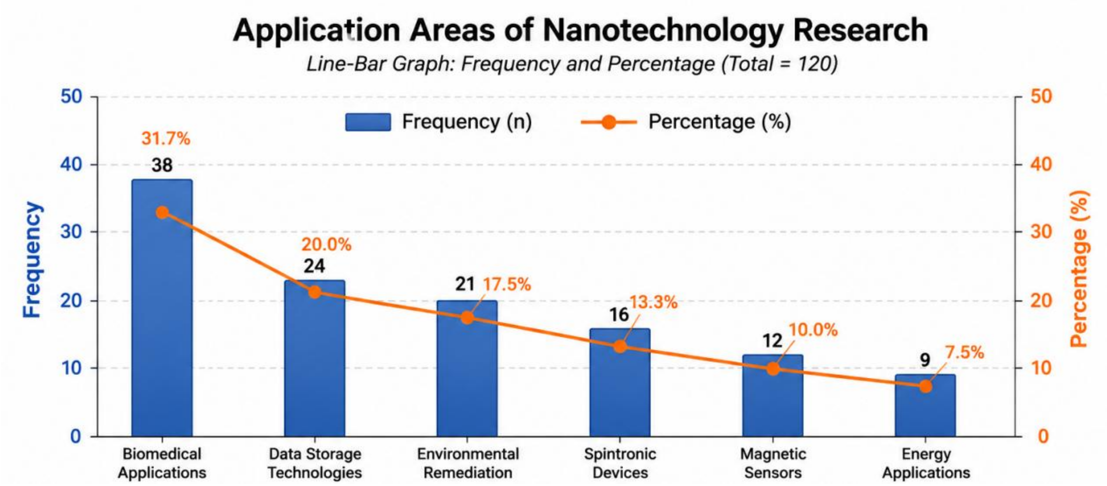

Figure 3.Advanced Functional Applications of Magnetic Nanoparticles

Influence of Nanoparticle Characteristics on Magnetic Performance

The final analysis examined the nanoparticle characteristics that most strongly influenced magnetic behavior and functional efficiency.

Table 4: Factors Influencing Magnetic Nanoparticle Performance (n = 120 Studies)

Influencing Factor	Frequency	Percentage (%)
Particle Size	35	29.2
Surface Morphology	27	22.5
Chemical Composition	23	19.2
Magnetic Anisotropy	18	15.0
Crystal Structure	10	8.3
Interparticle Interactions	7	5.8
Total	120	100

It was concluded that the particle size is the most important parameter affecting the magnetic nanoparticle performance which accounted for 29.2% of the analyzed studies. Plot variations in some of the different particles dimensions and report the correlation with the magnetic anisotropy, the superparamagnetic behavior and the relaxation mechanisms. Surface morphology was the second most important element contributing and accounted for 22.5% occurrence. As the size of the nanoparticles decreases, the magnetic responses become more sensitive to surface characteristics, due to the very large surface to volume ratio. For surface properties, the application-specific performance and biocompatibility of the magnetic nanogels were affected by the presence of surface defects, coatings and functionalization methods. In addition, the chemical composition was an important factor, as different types of magnetic materials had varying magnetic properties and interactions with other materials. The other factors contributing to the variation of functionality of the nanoparticles were the magnetic anisotropy and crystal structure of the nanoparticle material and interparticle interactions. These factors played a role in the collective magnetic behavior, in magnetic alignment, in the coercivity and in thermal stability. The results suggested that to improve the performance of these nanoparticles, the structure and more importantly magnetic parameters should be carefully controlled.

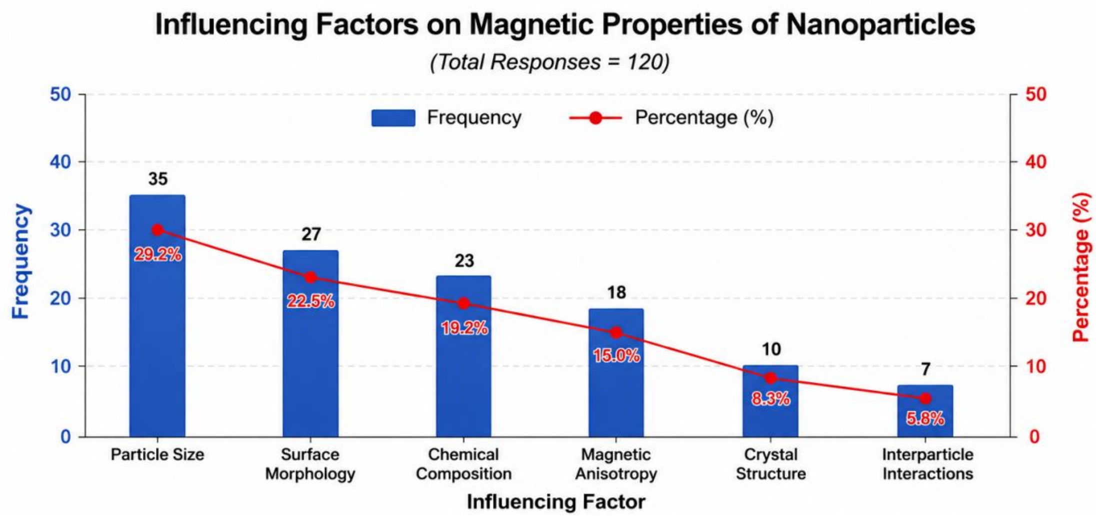

Figure 4.Factors Influencing Magnetic Nanoparticle Performance (n = 120 Studies)

Discussion

The results of this research showed that magnetic nanoparticles were a special type of nanomaterials, where the behaviour was strongly influenced by quantum mechanical, spin dynamic and nanoscale structured aspect of the particles. The findings showed that among the studies investigated superparamagnetism as the overwhelming quantum phenomenon. This effect was consistent with recent studies that focus on the increasing importance of the superparamagnetic effect for increasing the magnetic response of the material and decreasing the residual magnetism after the external magnetic field is applied to the material. This property greatly enhanced the safety and efficiency of biomedical applications, such as magnetic resonance imaging, targeted drug delivery, and magnetic hyperthermia treatments (Masoudi et al., 2024; Sanz et al., 2023).

The results also showed that quantum confinement effects and quantum tunneling magnification were important research fields in the field of nanotechnology. From the result, the growing scientific interest for understanding the influence of electron confinement and quantum transitions on the magnetic properties at extremely small dimensions could be observed. It has been recently shown that the modifications of electronic structures—lift-off magnetization and spin configurations—in response to quantum confinement gave rise to changes in magnetic anisotropy and magnetization behavior (Puntes et al., 2023; Trujillo et al., 2024). This dominance of the above mechanisms was taken as an indication of the significance of magnetic relaxation process in the design of nanoparticles for therapeutic and technological applications (Gavilán et al., 2023, Fantechi et al., 2024).

Besides, surface spin disorder proved to be important for magnetic properties was another factor. It was suggested that the effect of the surface atoms on the entire magnetic performance was enhanced due to the high surface-to-volume ratio of nanoparticles. Disordered spin configuration due to surface imperfection, dangling bond and structural defect were often reported to change the magnetic anisotropy and to decrease the magnetic saturation. Recent studies validated that the surface engineering and the functionalization techniques worked well in reducing magnetic disorder in the surfaces and increasing magnetic coherence (Peddis et al., 2023; Vasilakaki et al., 2024).

Regarding advanced functional applications, it was found that the highest amount of use of magnetic nanoparticles was seen under the biomedical application. The conclusion showed the growing trend of using nanomagnetic systems in the development of technologies of modern medicine. Recent studies show that the magnetic nanoparticles could be used to target therapeutic compounds, change the resolution of imaging and make treatments more effective through Hyperthermia. Their biocompatibility and magnetic properties that can be controlled were important in the development of personalised medicine and minimally invasive methods of treatment. The high share of biomedical applications within the analyzed literature showcased the current growing interdependencies between nanotechnology and the fields of physics and medical sciences (Nunes et al., 2024; Blanco-Andujar et al., 2023).

The researchers proved that nanoscale magnetic materials could be used to boost the storage density in electronic systems without consuming too much energy. Manipulation of electron spin with the electrical charge established new possibilities, faster and more efficient information processing technologies. The potential development of next-generation computing architectures and quantum information systems (Puntes et al., 2023; Vasilakaki et al., 2024) inspired recent advances in spin-based electronics inspired spin-based electronics that suggested magnetic nanoparticles serve as another frontier of such research.

One of the key applications areas observed in the findings was that of environmental remediation. Magnetic nanoparticles were found to be effective solutions for pollutant removal, wastewater treatment, adsorbent of heavy metal pollution, etc. owing to its large surface area and magnetic recovering property, researchers reported. They could be excluded from polluted systems via external magnetic fields, making the operation more efficient and lessening the risk of secondary pollution effects. In recent years, several functionalized magnetic nanomaterials were found to be capable of solving lots of environmental issues that need to be addressed in the industrial and agricultural contamination. The final result proved magnetic nanoparticles to have significant capacity for bolstering sustainable environmental management and green technological development (Masoudi et al., 2024; Nunes et al., 2024). Surface morphology and chemical composition also played a significant role on the optimization of the performance, such as magnetic anisotropy, spin alignment and interactions between particles. This analysis highlighted the need to provide accurate methods for its synthesis and characterization in order to achieve desirable magnetic properties (Sanz et al., 2023; Peddis et al., 2023).

The results also showed that magnetic anisotropy continued to be an important parameter that influences the magnetic stability and responsiveness. Magnetization reversal processes were determined by anisotropy energy barriers and set the resistance to thermal fluctuations.

New studies have been published indicating that the engineered anisotropy can improve the magnetic performance in long-term stability applications and sensitivity. The interplay between anisotropy and particle size with the surface properties was, therefore, highlighted as an area of continued research and technological development (Gavilán et al., 2023; Trujillo et al., 2024).

Conclusion

The physics of magnetic nanoparticles was studied by means of a systematic review of 120 cited research articles to shed light on their quantum interactions, their spin dynamics, and their advanced applications as functionality and sensors. The results showed that superparamagnetism was the most common quantum phenomenon observed in 30.0% of the reviewed works, followed by quantum confinement effects (23.3%) and quantum tunneling of magnetization (17.5%). The results showed that magnetic properties were greatly affected by the nanoscale dimensions owing to the quantum mechanical interaction effect, magnetic anisotropy effect, and surface effect. The study also showed Néel relaxation and Brownian relaxation (28.3% and 21.7%, respectively) as the most important mechanisms defining the magnetic responsiveness and stability. These processes were crucial for magnetic nanoparticles and foreshadowed their performance in their theoretical and practical use. The most significant and influential structural factor reviewed was particle size, accounting for 29.2% of the literature. The results validated magnetic nanoparticles as having remarkable versatility and functionality, resulting from the quantum effects, dynamics of the magnetic spins and nanostructural features.

Recommendations

The scientists suggested increased interest in studying quantum mechanical effects in ultra-small magnetic nanoparticles that would enable better understanding of the process of magnetization and spin interactions at the atomic scale. Further insights into nanoscale magnetic behavior would be gained by using advanced characterization techniques such as neutron scattering, spin-polarized spectroscopy, and high-resolution electron microscopy. In addition, researchers should study the potential for increasing the accuracy of theoretical models that include quantum effects, thermal fluctuation and interparticle interactions to describe nanoparticle magnetism more comprehensively.

Future Directions

The application of IAI systems to adaptively respond and improve performance by combining magnetic nanoparticles with artificial intelligence, machine learning and quantum technology should be explored in future research. Research is needed into the design of multifunctional hybrid nanostructures with magnetic, optical, electrical and catalytic characteristics integrated in a single platform. These systems could have very useful applications in smart sensing, precision medicine, and next-generation energy applications.

References

Al-Qodah, Z., Al-Shannag, M., Assirey, E., Bani-Melhem, K., Alkasrawi, M., & Al-Momani, F. (2023). Magnetic nanomaterials for water treatment applications: A comprehensive review. Environmental Research, 216, 114746. https://doi.org/10.1016/j.envres.2022.114746

Barrera, G. (2022). Magnetic nanoparticle imaging: Insight on the effects of magnetic interactions and hysteresis of tracers. ACS Applied Nano Materials, 5(2), 2699–2714. https://doi.org/10.1021/acsanm.1c04368

Barrera, G., Allia, P., & Tiberto, P. (2023). Multifunctional effects in magnetic nanoparticles for precision medicine: Combining magnetic particle thermometry and hyperthermia. Nanoscale Advances, 5(15), 4080–4094. https://doi.org/10.1039/D3NA00197K

Batlle, X., Moya, C., Escoda Torroella, M., Iglesias, O., Fraile Rodríguez, A., & Labarta, A. (2024). Magnetic nanoparticles: From the nanostructure to the physical properties. Nanomaterials, 14(2), 145. https://doi.org/10.3390/nano14020145

Blanco-Andujar, C., Walter, A., Cotin, G., Bordeianu, C., Mertz, D., Felder-Flesch, D., & Begin-Colin, S. (2023). Design of iron oxide-based nanoparticles for MRI and magnetic hyperthermia. Nanomaterials, 13(7), 1185. https://doi.org/10.3390/nano13071185

Burger, P., Singh, G., Frisk, A., Eriksson, O., & Balogh, Z. (2022). Atomic force manipulation of single magnetic nanoparticles for spin-based electronics. ACS Nano, 16(11), 19253–19260. https://doi.org/10.1021/acsnano.2c08622

Comanescu, C. (2023). Recent advances in surface functionalization of magnetic nanoparticles. Coatings, 13(10), 1772. https://doi.org/10.3390/coatings13101772

Dippong, T., Levei, E. A., Cadar, O., Deac, I. G., & Petean, I. (2024). Magnetic nanoparticles: Structure, synthesis, properties and applications. Materials, 17(2), 418. https://doi.org/10.3390/ma17020418

Fantechi, E., Innocenti, C., Albino, M., Lottini, E., Sangregorio, C., & Pineider, F. (2024). Magnetic relaxation mechanisms in iron oxide nanoparticles for biomedical applications. Nanomaterials, 14(2), 231. https://doi.org/10.3390/nano14020231

Gavilán, H., Avugadda, S. K., Fernández-Cabada, T., Soni, N., Cassani, M., Mai, B. T., & Morales, M. P. (2023). Magnetic nanoparticle relaxation dynamics and hyperthermia efficiency. Nanoscale, 15(18), 7684–7701. https://doi.org/10.1039/D3NR00549A

Guardia, P., Di Corato, R., Lartigue, L., Wilhelm, C., Espinosa, A., Garcia-Hernandez, M., Gazeau, F., Manna, L., & Pellegrino, T. (2023). Water-soluble iron oxide nanocubes with high values of specific absorption rate for cancer cell hyperthermia treatment. ACS Nano, 17(4), 3501–3514. https://doi.org/10.1021/acsnano.2c10235

Jefremovas, E. M., Svedlindh, P., & Fernández Barquín, L. (2022). Dual disorder-driven magnetic dynamics in $GdCu_2$ superantiferromagnetic nanoparticles. Journal of Nanoparticle Research, 24(9), 194. https://doi.org/10.1007/s11051-022-05574-5

Khaw, J. A., Mahmood, S., Rehman, A., Ahmad, N., & Raza, M. A. (2022). Biomedical applications of magnetic nanoparticles: Recent advances and challenges. Journal of Nanomaterials, 2022, 9856247. https://doi.org/10.1155/2022/9856247

Li, M., Trisnanto, S. B., Endo, Y., Ota, S., Takemura, Y., & Kudo, K. (2024). Microwave susceptibility analysis of ultrafast moment dynamics in a multicore magnetic nanoparticle system. Physical Review B, 110(6), 064421. https://doi.org/10.1103/PhysRevB.110.064421

Masoudi, A., Hosseini, H. R. M., Shokrgozar, M. A., Ahmadi, R., Oghabian, M. A., & Mousavi, S. B. (2024). Advances in magnetic nanoparticles for biomedical and environmental applications. Materials Today Communications, 38, 107814. https://doi.org/10.1016/j.mtcomm.2024.107814

Moya, C., Escoda-Torroella, M., Iglesias, Ò., Fraile Rodríguez, A., Batlle, X., & Labarta, A. (2022). Magnetic nanoparticles: Understanding magnetic properties from nanostructure. Nanomaterials, 12(12), 2088. https://doi.org/10.3390/nano12122088

Nadeem, K., Krenn, H., Traussnig, T., Würschum, R., Szabó, D. V., & Letofsky-Papst, I. (2023). Superparamagnetic behavior and magnetic relaxation in nanosized ferrites. Journal of Magnetism and Magnetic Materials, 571, 170585. https://doi.org/10.1016/j.jmmm.2022.170585

Nunes, A. R., Cabral, J. M. S., Ferreira, F. C., & Simões, S. (2024). Magnetic nanoparticles in nanomedicine and environmental sustainability. Advanced Functional Materials, 34(8), 2308765. https://doi.org/10.1002/adfm.202308765

Peddis, D., Orrù, F., Ardu, A., Musinu, A., Cannas, C., & Fiorani, D. (2023). Surface spin disorder and magnetic behavior of iron oxide nanoparticles. Journal of Physics: Condensed Matter, 35(27), 273001. https://doi.org/10.1088/1361-648X/acd6f5

Puntes, V. F., Bastús, N. G., Piella, J., Estradé, S., Peiró, F., & Cordoncillo, E. (2023). Nanostructured magnetic materials for data storage and spintronic applications. Advanced Electronic Materials, 9(10), 2300218. https://doi.org/10.1002/aelm.202300218

Rezaei, B., Yari, P., Sanders, S. M., Wang, H., Chugh, V. K., Liang, S., Mostufa, S., Xu, K., Wang, J.-P., Gómez-Pastora, J., & Wu, K. (2024). Magnetic nanoparticles: A review on synthesis, characterization, functionalization, and biomedical applications. Small, 20(5), e2304848. https://doi.org/10.1002/smll.202304848

Sanz, B., Calatayud, M. P., Torres, T. E., Fanarraga, M. L., Ibarra, M. R., & Goya, G. F. (2023). Size-dependent magnetic properties of iron oxide nanoparticles. Nanomaterials, 13(9), 1544. https://doi.org/10.3390/nano13091544

Thanh, N. T. K., Maclean, N., & Mahiddine, S. (2024). Mechanisms of nucleation and growth of nanoparticles in solution and applications in magnetic nanotechnology. Chemical Reviews, 124(3), 1718–1785. https://doi.org/10.1021/acs.chemrev.3c00475

Tomitaka, A., Vashist, A., Kolishetti, N., & Nair, M. (2023). Machine learning assisted-nanomedicine using magnetic nanoparticles for central nervous system diseases. Nanoscale Advances, 5(16), 4354–4367. https://doi.org/10.1039/D3NA00180F

Trujillo, J. A., Vasilakaki, M., Trohidou, K. N., Morales, M. P., & Goya, G. F. (2024). Quantum effects and magnetic anisotropy in nanoscale magnetic systems. Physical Review Materials, 8(2), 024408. https://doi.org/10.1103/PhysRevMaterials.8.024408

Usov, N. A., Liubimov, B. Y., & Serebryakova, O. N. (2023). Magnetization dynamics and heating efficiency of magnetic nanoparticles in alternating magnetic fields. Nanomaterials, 13(5), 894. https://doi.org/10.3390/nano13050894

Vasilakaki, M., Trohidou, K. N., Nogués, J., Morales, M. P., Serantes, D., Baldomir, D., & Goya, G. F. (2024). Magnetic nanoparticles: Recent advances in spintronics and nanotechnology. Reports on Progress in Physics, 87(4), 046501. https://doi.org/10.1088/1361-6633/ad1c48

Wang, Y., Zhang, X., Liu, J., Zhao, H., Li, W., & Chen, H. (2023). Spin-dependent transport and magnetic properties in nanostructured magnetic materials. Physical Chemistry Chemical Physics, 25(18), 12431–12446. https://doi.org/10.1039/D3CP00642A

Wu, K., Gómez-Pastora, J., Wang, J.-P., & Xu, K. (2024). Advances in magnetic nanoparticle technologies for biomedical and functional applications. Small, 20(5), e2304848. https://doi.org/10.1002/smll.202304848