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COMPARISON OF DIAMAGNETIC, PARAMAGNETIC, AND FERROMAGNETIC MATERIALS

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Abstract: This review article presents a comprehensive comparison and analysis of diamagnetic, paramagnetic, and ferromagnetic materials. Magnetic materials play a crucial role in modern physics and technological advancements; therefore, a clear understanding of their properties is essential. The main objective of this study is to examine the fundamental characteristics, differences, and practical applications of these three categories of magnetic materials. This review is based on an analysis of various scientific articles, textbooks, and previously published research studies. The findings reveal that the primary distinctions between these materials lie in their magnetic susceptibility(χ), atomic magnetic moments, and thermal stability. Diamagnetic materials exhibit weak negative magnetism and are repelled by an external magnetic field, showing a susceptibility that is independent of temperature. In contrast, paramagnetic materials show weak positive magnetism and are slightly attracted to the field, following Curie's Law. Furthermore, ferromagnetic materials demonstrate strong magnetic behavior, characterized by domain formation and the ability to retain magnetization even after the removal of the external field (remanence).these materials are also uniquely distinguished by their non-linear hysteresis loops and their transition to a paramagnetic state above the Curie temperature (T_c). These differences are primarily attributed to the alignment of electron spins and the nature of magnetic moments. In conclusion, these materials have wide-ranging applications in scientific, industrial, and technological fields, and their detailed study is essential for the continued development of advanced technologies.

Keywords: Diamagnetism, Paramagnetism, Ferromagnetism, Magnetic Susceptibility, Hysteresis Loop, Curie-Weiss Law, Magnetic Domains Solid-State Physics.

1. Introduction

Magnetism is one of the most complex and fundamental properties of matter, originating from the motion of atomic particles. In the modern era, the introduction of magnetic materials is not just a theoretical discussion, but a fundamental pillar of the industrial revolution. From large-scale wind turbine generators to micro-storage components in modems and telephones, magnetism forms the backbone of modern electronic devices (Gutfl et al., 2011).The development of new generations of electric vehicles and data storage devices is directly dependent on the quality and type of magnetic materials (K. K. Sharma, 2018; Rasaili & Sharma, 2022). Furthermore, without magnetism, we would lack essential tools such as marine navigation, molecular research, and medical imaging (MRI), as well as electrical motors and generators (Coronado, 2020; Holgate, 2010).

Historically, this journey began with ancient Chinese mariners who utilized magnetite (lodestone) as the earliest forms of the magnetic compass, paving the way for global trade(Jackson, 2014). In modern physics, this phenomenon is explained by the orbital motion of electrons and their spin, which results in the magnetic moment of matter(Kittel & Johnson, 2005). Particularly during the 19th century, the experiments of Faraday and Maxwell proved that magnetism is an integral part of electromagnetic properties, transitioning it from a metaphysical concept into a precise field of mathematical physics (Coey et al., 2023).

Diamagnetism is a fundamental property of all matter, most observable in substances with paired electrons. When placed in an external magnetic field, the orbital velocity of electrons is modified in accordance with Lenz's Law, inducing a small magnetic moment that opposes the applied field(Kittel & Johnson, 2005). The magnetic susceptibility $(\chi)$of diamagnetic materials is negative and independent of temperature$(\chi = \frac{M}{H} < 0)$, The Langevin theory describes the atomic diamgnetic susceptibility as $\left(\chi = -\frac{Nze^2\mu_0}{6m} < r^2 > \right)$(Galsin, 2013; Srivastava, 2009). Common examples include water, copper, and gold, with applications ranging from magnetic levitation to magnetic shielding(Holgate, 2010; Thompson, 2011).

Paramagnetic materials are characterized by unpaired electrons, resulting in permanent but randomly oriented atomic magnetic moments. in an external field, these moments align weakly with the field(M.A.Wahab, 2005).Their susceptibility is positive and follows Curie's Law, meaning it decreases as temperature increases $\left(\chi = \frac{C}{T} \;\; , \; 0 < \chi < 1\right)$(H.P.Myers, 2009). Paramagnets are vital in chemical research and MRI contrast agents to enhance tissue clarity(Wagner & Preschitschek, 2023).

Table 1: *The magnetic susceptibility for some materials (Holgate, 2010)*

Material	Magnetic type	Susceptibility χ
Copper	Diamagnetic	-0.96×10^{-5}
Sodium Chloride	Diamagnetic	-1.41×10^{-5}
Zinc	Diamagnetic	-1.56×10^{-5}
Manganese Sulphate	Paramagnetic	$+3.70 \times 10^{-3}$
Aluminium	Paramagnetic	$+2.07 \times 10^{-5}$
Sodium	Paramagnetic	$+8.48 \times 10^{-6}$

Ferromagnetic materials, such as iron, nickel, and cobalt, exhibit strong magnetic properties due to "exchange interaction," forming spontaneous magnetic domains. Above a specific temperature known as the Curie point T_c,these materials become paramagnetic, following the Curie-Weiss Law $\left(\chi = \frac{C}{T-T_c} \gg 1\right)$(Srivastava, 2009).

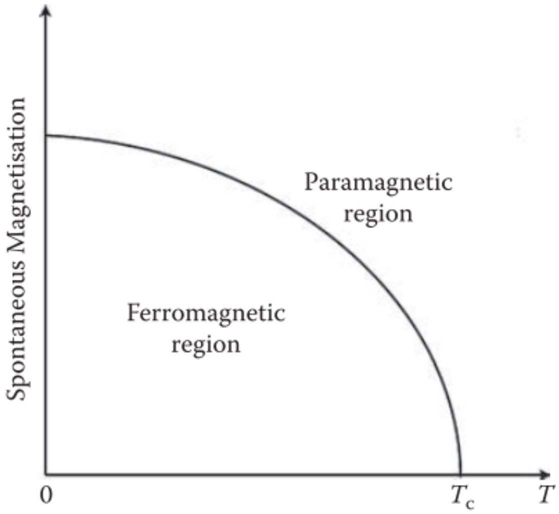

Figure 1: *spontaneous magnetization vs temperature (Holgate, 2010).*

Spontaneous magnetization decreases with increasing temperature and becomes zero at T_c because thermal energy opposes the exchange interaction (Holgate, 2010).

In ferromagnetic materials, **magnetic domains** are defined as microscopic regions within which all atomic magnetic moments are spontaneously and parallelly aligned in a single direction due to the influence of strong **exchange interactions** (Kittel & Johnson, 2005).Under equilibrium conditions, these domains are oriented randomly to minimize the system's total magnetostatic energy, resulting in zero net magnetization for the bulk material. However, Under the influence of an applied magnetic field, the material reaches magnetic saturation either through the rotation of domain vectors toward the field direction or via the expansion of favorable domains through **domain wall motion** as shown in Fig 3 (Naidu, 2010). The irreversible movement of these walls and their 'pinning' against structural defects constitute the fundamental mechanisms responsible for magnetic remanence and the characteristic formation of the **hysteresis loop**(Holgate, 2010; Srivastava, 2009).

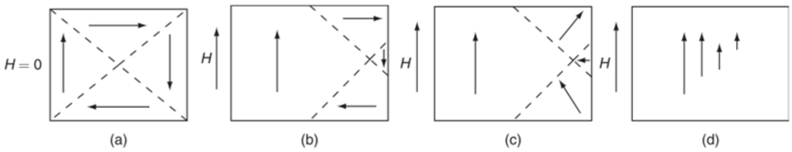

Figure 2: *Schematic illustration of the magnetization process in a ferromagnetic material(Naidu, 2010)*

(a) Randomly oriented domains at zero field. (b) Reversible and irreversible domain wall motion. (c) Rotation of domain magnetization vectors toward the applied field H. (d) Magnetic saturation where all domains are aligned with the external field.

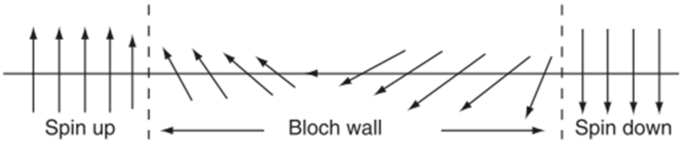

Figure 3: Schematic representation of a Bloch wall, illustrating the gradual transition of magnetic spin orientation between two adjacent domains (Spin up to Spin down) in a ferromagnetic material(Naidu, 2010).

When a ferromagnetic material is subjected to a cyclic magnetic field varying from zero to a maximum positive intensity, returning through zero to a negative saturation point, and finally restoring to its initial state,it exhibits a magnetic hysteresis loop. This non-linear relationship between the magnetization (M) or magnetic flux density (B) and the applied magnetic field intensity (H) is a defining characteristic of ferromagnetic behavior(Srivastava, 2009).

As the external field (H) is initially applied to a demagnetized ferromagnet, it follows the virgin magnetization curve (represented by the dashed line in Figure 2). If the applied field is sufficiently strong, the material reaches a state of saturation magnetization (M_s) (Kittel & Johnson, 2005). At this critical juncture, all magnetic domains are fully aligned with the external field and any further increase in H results in no additional increase in M. This loop not only illustrates the material's 'magnetic memory' but also represents the energy dissipation (hysteresis loss) per unit volume during each cycle, which is a crucial factor in the efficiency of electrical machines (Holgate, 2010; Wang et al., 2012).

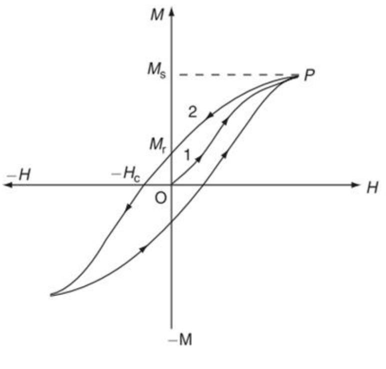

Figure 4: *M vs. H* ***hysteresis loop*** *(Naidu, 2010)*

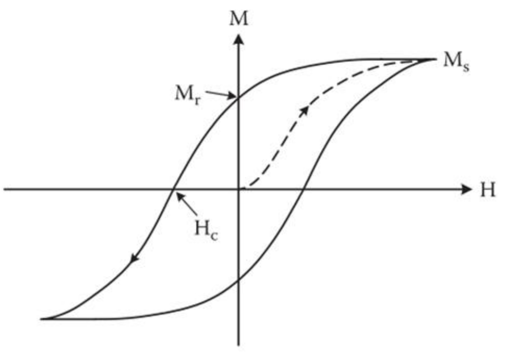

Figure 5: *M vs. H* ***hysteresis loop*** *(Holgate, 2010)*

Paramagnetic materials are characterized by unpaired electrons, resulting in permanent but randomly oriented atomic magnetic moments. In an external field, these moments align weakly with the field(M.A.Wahab, 2005).Their susceptibility is positive and follows Curie’s Law, meaning it decreases as temperature increases $\left(\chi = \frac{C}{T}\ ,\ 0 < \chi < 1\right)$(H.P.Myers, 2009). Paramagnets are vital in chemical research and MRI contrast agents to enhance tissue clarity(Wagner & Preschitschek, 2023).

Ferromagnetic materials, such as iron, nickel, and cobalt, exhibit strong magnetic properties due to "exchange interaction," forming spontaneous magnetic domains. Above a specific temperature known as the Curie point T_c,these materials become paramagnetic, following the Curie-Weiss Law $\left(\chi = \frac{C}{T-T_c} \gg 1\right)$(Srivastava, 2009).

Table 2: *The Curie temperatures for some ferromagnetic materials(Holgate, 2010)*

Metals	Curie Temperature (in K)
Gd	289
Ni	631
Tungsten steel	1033
Fe	1043
Co	1404

Recent studies highlight that the efficiency of ferromagnetic materials is significantly affected by mechanical factors such as plastic deformation, which increases hysteresis losses(Wang et al., 2012). This study provides a vital framework for understanding how structural changes and temperature influence energy dissipation in 21st-century technology(Gutfl et al., 2011; K. K. Sharma, 2018).

2. Significance Of The Study

The significance of this study lies in its systematic comparative analysis of the fundamental classes of magnetic materials-diamagnetic, paramagnetic, and ferromagnetic. Understanding the distinct magnetic susceptibilities and atomic-level behaviors of these materials is crucial for both theoretical physics and contemporary engineering applications. By elucidating the varying responses of these substances to external magnetic fields, this research provides a critical framework for materials scientists and engineers in selecting appropriate materials for specific technological needs, ranging from magnetic shielding and medical imaging (MRI) to high-performance permanent magnets used in renewable energy systems.

Furthermore, this research offers vital insights into the thermal and structural dependencies of magnetic properties, such as the Curie temperature and the mechanisms of energy dissipation. Analyzing the unique hysteresis behavior of ferromagnetic materials in contrast to the linear responses of dia- and paramagnetic substances is essential for improving the energy efficiency of electromagnetic devices like transformers and electrical motors. Ultimately, this work bridges the gap between quantum mechanical spin theory and macroscopic material science, serving as a robust reference for the development of next-generation magnetic sensors and more efficient power infrastructure.

3. Review Of Related Studies

Although extensive information regarding magnetic properties exists in the literature, a significant scholarly gap remains in the comprehensive comparative study of the theoretical foundations governing diamagnetism, paramagnetism, and ferromagnetism (Woolley, 1957). While most researchers tend to focus on specific material groups, a holistic perspective that examines these materials under external factors-such as temperature variations and mechanical stress remains largely fragmented (Rathod, 2024; Wang et al., 2012). For instance, Wang et al. (2012) demonstrated that plastic deformation significantly influences the magnetization processes of ferromagnetic materials by inducing structural dislocations. Therefore, understanding the precise relationship between magnetic susceptibility (χ) and permeability (μ) across different states of matter is vital for the design of next-generation engineering materials(Naidu, 2010; Thompson, 2011).

The theoretical framework of magnetism is deeply rooted in the authoritative works of solid state physics, where the spin and orbital motion of electrons are identified as the primary sources of magnetic moments. in Kitte classic work, he elucidates the quantum mechanical roots of diamagnetism and paramagnetism, noting that diamagnetism arises from the creation of an opposing magnetic field through the orbital motion of electrons. He presented the following formula for diamagnetic susceptibility (χ), which is related to the atomic radius (r^2):

$$\chi = -\frac{Nze^2\mu_0}{6m}\sum < r_i^2 >$$

where $< r_i^2 >$ represents the mean square atomic radius (Kittel & Johnson, 2005).

Furthermore, the complexities of ferromagnetic domains and their structural characteristics have been extensively detailed in the literature (M.A.Wahab, 2005; Srivastava, 2009). The concept of **exchange interaction** is particularly emphasized, demonstrating that as temperature increases, thermal energy disrupts the alignment of magnetic moments. This transition, which describes the shift from ferromagnetic to paramagnetic behavior at the Curie point, follows the **Curie-Weiss Law** (Srivastava, 2009). In parallel, the physical nature of magnetism has been examined through paramagnetic and diamagnetic responses to temperature (H.P.Myers, 2009; Hofmann, 2015). Within these studies, a rigorous explanation of the phenomenon of magnetic anisotropy is also provided (H.P.Myers, 2009).

In recent years, the scope of magnetism has expanded into nanotechnology. Research on manganese-doped ZnO nanoparticles illustrates their significant role in modern optoelectronic devices, where a direct correlation exists between optical properties and magnetic responses (Omri et al., 2013). Additionally, current literature indicates a close correlation between the diamagnetism of metals and their specific chemical compositions(A.Moore, 2005; Rikhter, 2018).

4.Objectives Of The Study

The primary objective of this review is to provide a systematic comparative analysis of magnetic materials based on their fundamental physical properties. The specific objectives are as follows:

- To analyze Magnetic Susceptibility (χ): To evaluate and compare the magnitude and nature (positive/negative) of susceptibility in dia, para and ferromagnetic materials.
- To investigate Atomic Magnetic Moments: To examine the role of electron configuration and spin alignment in determining the permanent or induced magnetic moments of these substances.
- To evaluate Temperature Dependence: To analyze how thermal agitation affects magnetic behavior, specifically focusing on the Curie and Curie-Weiss laws.
- To examine the Removal of External Magnetic Fields: To study the retention or loss of magnetization (remanence) after the external field is withdrawn.
- To characterize the Hysteresis Loop: To contrast the energy dissipation and non-linear magnetization curves unique to ferromagnetic materials.

- To analyze the χ vs. T Relationship: To interpret the graphical representation of susceptibility versus temperature, highlighting the temperature-independent nature of diamagnetism versus the dependent nature of other magnetic states.

5. Methodology

This review article employs a systematic qualitative approach to evaluate the physical characteristics of diamagnetic, paramagnetic, and ferromagnetic materials. The research was conducted by retrieving 50 scholarly sources from Google Scholar using targeted keywords such as magnetic susceptibility, hysteresis loop, and atomic moments, from which 27 high-quality references were meticulously selected for final synthesis. The literature integration includes a strategic blend of four classical textbooks (1957–2005) to establish fundamental laws and contemporary research articles spanning from 2010 to 2025 to capture recent advancements. This methodology focuses on a comparative analysis of electronic structures and temperature-dependent behaviors, ensuring a logical transition from quantum mechanical principles to practical engineering applications.

6. Discussion and Analysis

The review of existing literature indicates that the magnetic response of materials is fundamentally dependent on their atomic structure. Diamagnetic materials, characterized by a weak and opposing magnetic response, follow Lenz's Law. Conversely, paramagnetic materials exhibit weak magnetization that aligns parallel to the external field (Kittel & Johnson, 2005).In sharp contrast, ferromagnetic materials possess exceptionally strong magnetic properties due to the exchange interaction (Srivastava, 2009). Current research further demonstrates that the magnetic susceptibility (χ) of diamagnetic materials is largely independent of temperature. However, the magnetic behavior of paramagnetic and ferromagnetic materials is governed by Curie's Law and the Curie-Weiss Law, respectively (H.P.Myers, 2009).

A significant finding is that above the Curie Point, ferromagnetic materials lose their permanent magnetic properties and transform into paramagnetic materials, posing a substantial challenge in the design and thermal management of electric motors(Rathod, 2024). Our analysis demonstrates that not only temperature but also mechanical stress and plastic deformation significantly reduce magnetic permeability. This process widens the hysteresis loop, consequently increasing energy dissipation (hysteresis losses) in generators and transformers (Wang et al., 2012). This is a critical insight that is less frequently addressed in traditional physics textbooks. For further clarity, a comparative evaluation of the physical properties of these materials is presented in Table 1.

Table 3: *Comprehensive comparison of physical and magnetic properties of diamagnetic, paramagnetic, and ferromagnetic materials*

Property	Diamagnetic	Paramagnetic	Ferromagnetic	Reference
Magnetic susceptibilty χ	Negative and very small $\chi < 0$	Positive and small $\chi > 0$	Positive and very large $\chi \gg 0$	(K. K. Sharma, 2018; Kittel & Johnson, 2005)
Relative Permiability μ_r	Less than unity $\mu_r < 1$	Slightly greater than unity $\mu_r > 1$	Much greater than unity$\mu_r \gg 1$	(Naidu, 2010; Srivastava, 2009)
Relation with temperture	Independent of temperature	Follows Curie's Law $\chi \propto \frac{1}{T}$	Follows Curie-Weiss Law $\chi = \frac{C}{T-\theta}$	(H.P.Myers, 2009; Rathod, 2024)
Atomic magnetic moment	Zero (paired electrons)	Permanent but randomly oriented	Permanent and aligned (Domains)	(Galsin, 2013; M.A.Wahab, 2005)
Response to external magnetic field	Weakly repelled	Weakly attracted	Strongly attracted	(Rikhter, 2018; Thompson, 2011)
Hysteresis Effect	Not have	Not have	Exhibits significant Hysteresis Loop	(M.A.Wahab, 2005; Wang et al., 2012)
State of matter	May be found in solids, liquids or gases	May be found in solids, liquids or gases	Normally found only in solids	(Verma, 2020)
Examples	Copper, Water(H_2O), Bismuth, Silver,etc (Kittel & Johnson, 2005)	Aluminum, Platinum, Magnesium, Oxygen, Manganese,etc(M.A.Wahab, 2005)	Iron, Cobalt, Nickel, Gadolinium,etc (Srivastava, 2009)	
Apllications	Magnetic shielding in electronics, MRI diagnostics, Superconductors(A.Moore, 2005; Holgate, 2010; Kittel & Johnson, 2005)	MRI contrast agents, Optoelectronic devices, specialized sensors(K. K. Sharma, 2018; M.A.Wahab, 2005; Omri et al., 2013)	Transformers, Electric motors, Generators, Magnetic memory (Rathod, 2024; Srivastava, 2009; Wang et al., 2012)	

7. Recommendations and future scope

Based on the findings of this review, the following recommendations are proposed for researchers, engineers, and science enthusiasts:

- Future research should focus on the magnetic behavior of materials at the nanoscale. Controlling magnetic domains in nanoparticles can lead to revolutionary breakthroughs in medical diagnostics, particularly in enhancing the precision of MRI contrast agents.
- There is a critical need to develop new alloys with higher Curie Points. This is essential for maintaining magnetic stability in electric motors and aerospace components that operate under extreme thermal conditions.
- For industrial applications, engineers should prioritize materials with narrow hysteresis loops in the design of transformer cores and generators. Minimizing energy dissipation as heat is vital for developing sustainable and energy-efficient electrical machines.
- Designers must account for the effects of mechanical stress and plastic deformation on magnetic permeability. Further studies are recommended to quantify how structural fatigue influences the long-term magnetic performance of industrial sensors and actuators.
- Enthusiasts and material scientists are encouraged to explore smart materials whose magnetic properties can be dynamically tuned by external stimuli (such as pressure or temperature) for use in soft robotics and advanced switching technologies.

8. Conclusion

The distinction between diamagnetic, paramagnetic, and ferromagnetic materials is not an inexplicable phenomenon; rather, it is entirely explicable through mathematical formulations based on atomic structure and the orbital and spin motion of electrons. These differences are fundamentally governed by atomic configurations and environmental conditions.While diamagnetism and paramagnetism remain critical in fundamental scientific research and Magnetic Resonance Imaging (MRI), ferromagnetic materials have historically served as the driving force behind the industrial revolution. Our analysis concludes that when selecting materials for engineering applications, it is imperative to consider not only Curie's Law and thermal stability but also mechanical stress and plastic deformation. These factors serve as critical determinants, as they exert a direct influence on energy efficiency and the operational lifespan of technical devices.

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