http://www.jourmag.org/index.php/jma

Journal of Magnetism and Its Applications

Received February 17th 2021; received in revised March 6th 2021; accepted April 14th 2021

Review articles

From Hexaferrite to Garnet: A Roadmap of Rare-Earth-Free Magnetic Materials for Clean Energy and AI Applications

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Article info

Keywords:
Magnetic materials;
Ferrite;
Hexaferrite;
Coercivity;
Rare-earth-free

Abstract

Magnetic materials serve as the backbone of modern energy and digital technologies. This paper presents a material roadmap mapping the evolution of magnetic materials in 2026, from Hexaferrite as hard magnets, Perovskite as semi-hard magnets, to Spinel Ferrite and Garnet as soft magnets. The analysis focuses on the correlation between crystal structure, coercivity Hc, and strategic applications in the context of the rare earth supply crisis. The results show that hard magnets such as Hexaferrite dominate energy storage applications in EV motors and generators due to their high coercivity and rare-earth-free composition. Meanwhile, soft magnets based on Spinel and Garnet are critical for energy conversion efficiency in AI data center transformers, 5G filters, and quantum devices due to their ultra-low losses at high frequencies. This study concludes that iron-based ferrites offer a strategic alternative to rare earth magnets for clean energy and future electronics. The proposed "magnetic material roadmap" provides a practical guide for selecting RE-free and high-efficiency materials to support sustainable electrification and digitalization.

1. Introduction

Modern civilization is inseparable from the role of magnetic materials. Since the discovery of the compass in the 11th century, humanity has continuously exploited the interaction between matter and magnetic fields to advance technology. Today, this dependency has become exponentially deeper. Motors in electric vehicles, generators in wind power plants, transformer cores in substations, and disk drive heads in AI data centers all depend fundamentally on the magnetic properties of materials. Without magnetic materials, the entire chain of energy conversion and data processing would collapse.[1][2]

The core principle is deceptively simple: the macroscopic function of a magnet is determined at the atomic level. Yet, the difference in function between a motor that pulls 500 kg and a transformer that quietly converts 500 kV is determined only by the atomic arrangement in the constituent material, specifically by the alignment of electron spins and magnetic domains. Entering 2026, the magnet industry faces two converging global challenges that are reshaping material strategy worldwide. The first is the demand for energy efficiency. With the expansion of AI data centers and electrification, global electricity consumption is projected to rise by over 40% this decade. Core losses in transformers and inductors alone account for 2-3% of total global electricity loss, making low-loss soft magnets a national priority.

The second challenge is the rare earth elements REE supply crisis as raw materials for NdFeB permanent magnets. Over 80% of NdFeB production depends on supply chains concentrated in a few countries. Price volatility of Neodymium and Dysprosium has exceeded 300% since 2020, forcing industries to seek "rare-earth-free" alternatives. This crisis directly threatens the scalability of EVs, wind turbines, and defense systems.[3]

To address these challenges, understanding the classification of magnetic materials becomes crucial. IEC 60404-1 (2017) classifies magnetic materials based on permeability and coercivity into diamagnetic, paramagnetic, and ferromagnetic/ferrimagnetic. This standard provides the foundation for material selection in industry. However, recent developments show a more complex relationship between crystal structures such as Hexaferrite, Spinel, Perovskite, and Garnet with their application fields. A material with the same chemical formula but a different crystal structure can have coercivity differing by 1000x.[4][5]

Therefore, this article aims to remap this relationship for 2026. By tracing characteristics from Hard Magnet Hexaferrite to Soft Magnet Garnet, it is hoped that this paper can serve as a practical guide for material selection to support the development of clean energy and future electronics. The focus is not only on performance, but also on supply chain resilience, cost, and sustainability.

1.2. Basic Classification of Magnetic Materials

The general classification of magnetic materials is based on the relative magnetic permeability μ. Permeability measures how easily a material can support the formation of a magnetic field within itself. This single parameter determines whether a material will be used to block, guide, or amplify magnetic flux.[6]

The first group is Diamagnetic. It has $\mu<1$ and repels external magnetic fields. This is a weak but universal effect caused by the reorientation of electron orbitals under an external field. Examples include Bi, Cu, and Au. While historically considered a laboratory curiosity, in 2026 this property is being utilized in quantum levitation systems and magnetic bearings for flywheel energy storage. The ability to achieve contactless suspension with zero friction makes diamagnets critical for high-speed transport and precision instruments.[7]

The second group is Paramagnetic. It has $\mu>1$ and is weakly attracted to magnetic fields. This arises from unpaired electron spins that align with an external field, but randomize when the field is removed. Examples include Al and Pt. These materials are widely used as sensor components, in oxygen analyzers, and as contrast agents in medical imaging. Their linearity and lack of hysteresis make them ideal for measurement applications where reproducibility is key.

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DOI: 10.53533/

The third and most technologically important group is Ferromagnetic and Ferrimagnetic. They have μ>>1, often 1000 to 100,000 times that of vacuum. This giant effect comes from spontaneous alignment of magnetic domains. This group forms the backbone of technology and is further divided into Hard Magnets and Soft Magnets based on their coercivity value. Coercivity, Hc, is the resistance to demagnetization. It is the single most important parameter separating energy storage from energy conversion. This classification will be the framework for the rest of this paper.[8]

1.3. The Hard Magnet Camp: Power to Move the World

Hard magnets are characterized by high coercivity >125 Oe, thus having good resistance to demagnetization. Once magnetized, they retain their magnetization for years, even decades. This property makes them ideal for permanent energy storage applications. In essence, a hard magnet is a battery for magnetic potential energy. They are the reason electric motors can produce torque without continuous power input to the magnet itself.[8]

The physics behind high Hc involves pinning of magnetic domain walls and high magnetocrystalline anisotropy. Materials with complex crystal structures and strong spin-orbit coupling tend to exhibit this behavior. In 2026, the focus has shifted from maximizing energy product BHmax alone to balancing it with cost, temperature stability, and REE independence.

1.3.1 Hexaferrite $MFe_{12}O_{19}$

Hexaferrite is the workhorse of the hard magnet world. This material has an Hc in the range of 400-2000 Oe, depending on composition and processing. The formula is $MFe_{12}O_{19}$ where M = Ba, Sr, Pb. Its hexagonal crystal structure creates a strong uniaxial anisotropy, locking magnetization along the c-axis. The most common form is Strontium Ferrite, $SrFe_{12}O_{19}$, and Barium Ferrite, $BaFe_{12}O_{19}$.[9]

The competitive advantage of Hexaferrite lies in its corrosion resistance and relatively low cost. Unlike NdFeB, it contains no rare earths and is made from abundant Fe, Sr, and O. It does not require protective coatings, making it ideal for outdoor and automotive applications. For these reasons, this material dominates applications such as speakers, small-scale generators, refrigerator magnets, and DC motors. The global production volume exceeds 1 million tons per year.

Recent 2026 research focuses on nanostructuring Hexaferrite to increase BHmax from 4.5 MGOe toward 6 MGOe, closing the gap with low-grade NdFeB. This makes it a viable candidate for auxiliary motors in EVs and wind turbine yaw systems, directly addressing the REE crisis.

1.3.2 Perovskite $MFeO_3$

Perovskite falls into the semi-hard magnet category with Hc around 150 Oe. Its cubic ABO_3 structure allows for extensive doping, enabling tuning of both magnetic and electronic properties. Bismuth Ferrite, $BiFeO_3$, is the most studied due to its room-temperature multiferroicity. Research novelty in 2026 points to the utilization of Perovskite structures as active layers in solar cells, supported by thermal stability and multiferroic properties. The ability to couple magnetic order with ferroelectric polarization opens doors for magnetoelectric devices and energy harvesting. While not a primary power magnet, its semi-hard nature makes it suitable for magnetic sensors and memory elements where moderate stability is required.

Overall, Hard Magnet applications directly move the physical world through the process of converting electrical energy into mechanical energy. From the traction motor in a Tesla to the pitch control in a Vestas wind turbine, hard magnets provide the static magnetic field that makes electromechanical conversion possible. Their role in the energy transition cannot be overstated.

1.4. The Soft Magnet Camp: Efficiency to Flow Energy

Unlike Hard Magnets, Soft Magnets have low coercivity <50 Oe and small hysteresis losses ASTM International (2020). This "forgetful" characteristic is essential for energy conversion efficiency. A soft magnet must magnetize and demagnetize billions of times per second with minimal energy loss as heat. The ideal soft magnet has high saturation magnetization, high permeability, and high electrical resistivity to minimize eddy currents. In the era of AI and 5G, operating frequencies have pushed from 50 Hz to 1 MHz and beyond. This has made core loss the dominant design constraint.

1.4.1 Spinel Ferrite MFe_2O_4

Examples of materials from this group are $NiZnFe_2O_4$ and Co-Zn ferrite. Spinel Ferrite has a cubic structure that allows for high resistivity, 10^6 times higher than silicon steel. This suppresses eddy currents at high frequencies. Spinel Ferrite MFe_2O_4 has low to moderate coercivity, Hc = 36-140 Oe. NiZn ferrite with Hc ~36-47 Oe dominates high-frequency transformer cores and EMI filters above 1 MHz due to minimal core losses and high resistivity, 10^6 times higher than silicon steel. $CoFe_2O_4$ with Hc ~140 Oe is used for semi-hard applications. The novelty of its application is seen in its role as a key component in power management and cooling in AI data centers. A single hyperscale data center may contain over 100,000 inductors and transformers. Using MnZn and NiZn ferrites instead of silicon steel can improve power supply efficiency by 2-3%, saving megawatts of power.

Furthermore, doping studies show that substituting Fe with other ions can tune permeability and temperature stability. This flexibility makes Spinel the most versatile soft magnet family for power electronics in 2026.

1.4.2 Garnet $M_3Fe_5O_{12}$

Garnets such as $Y_3Fe_5O_{12}$ or YIG have the lowest coercivity among ferrites, Hc ~10 Oe, and a unique combination of magnetic and optical properties. Yttrium Iron Garnet is an electrical insulator with extremely low magnetic loss at microwave frequencies. Its crystal structure allows spin waves to propagate with very little damping. This uniqueness makes Garnet widely applied in microwave devices such as isolators and circulators, radar, and components in quantum computers. In 5G base stations and satellite communications, YIG filters provide tunable frequency selection that no other material can match. In quantum computing, YIG spheres are used as transducers between microwave photons and magnons.

Thus, Soft Magnets play an important role as the key to energy efficiency. Without this material, transformers and inductors would experience large power losses in the form of heat. In the context of 2026, they are the enabling technology for net-zero grids and sustainable AI.

1.5. Novelty and Challenges

The magnet industry in 2026 faces three main issues that will define R&D for the next decade.

First, the Rare Earth Crisis. High dependence on NdFeB and SmCo drives intensive research into alternative Fe, Ni, and Zn-based materials. In this context, Spinel and Hexaferrite emerge as strategic candidates. Governments in the US, EU, and Japan have launched "REE-free magnet" initiatives with funding exceeding $2B. The goal is to decouple critical technology from geopolitical supply risk.

Second, the Era of Electrification and AI. The need for high energy product Hard Magnets increases with the massive use of EVs. A single EV requires 1-2 kg of NdFeB. With projected sales of 50 million EVs in 2026, material demand is unsustainable. On the other hand, AI data center expansion demands low-loss Soft Magnets for grid efficiency. The power consumption of AI training alone is projected to exceed that of some countries. This creates a dual demand: stronger hard magnets and more efficient soft magnets.

Third, Corrosion and Sustainability. Similar to the principle of cathodic protection, NdFeB and SmCo materials have high vulnerability to corrosion and require complex coating systems of Ni-Cu-Ni. This adds cost and environmental burden. Hexaferrite offers an advantage due to its environmental stability. It can operate for 20 years in marine and desert environments without degradation. This makes it strategically important for wind and infrastructure applications.

In conclusion, the roadmap for 2026 is clear. We must diversify away from REE dependence while simultaneously improving efficiency. The classification presented in this paper provides the framework for that selection. Hard magnets will power motion. Soft magnets will ensure that power is not wasted.

2. Experimental Methods

This article adopts a literature-based material classification and roadmap approach rather than direct laboratory synthesis. The goal is to synthesize data from standards, handbooks, and recent publications 2020-2026 into a practical selection guide for industry. The classification framework uses 3 main parameters that are universally accepted in IEC 60404 and ASTM A340 standards.

Parameter 1: Basic Magnetic Properties based on Relative Permeability μ

This is the first-level screening. Diamagnetic materials have μ<1 and exhibit weak repulsion to external fields. Paramagnetic materials have μ>1 and exhibit weak attraction. Ferromagnetic and Ferrimagnetic materials have μ>>1, often >1000, and exhibit spontaneous magnetization. This parameter separates materials that can be used for flux guidance from those that cannot.[6][7]

Parameter 2: Coercivity Hc as the Main Functional Divider

Coercivity is the most critical parameter for application selection. Following IEC 60404-1, this article uses the industry standard divider: Hard Magnet defined as Hc>125 Oe and Soft Magnet defined as Hc<50 Oe. Materials with Hc between 50-125 Oe are classified as semi-hard. Note: In ferrite practice, NiZn Spinel ~36-47 Oe and Garnet ~10 Oe fall into soft, while $CoFe_2O_4$ ~140 Oe and Perovskite ~150 Oe fall into semi-hard. Materials with Hc between 50-125 Oe are classified as semi-hard. High Hc indicates resistance to demagnetization and suitability for energy storage. Low Hc indicates easy domain wall motion and suitability for energy conversion with minimal hysteresis loss. This 125 Oe / 50 Oe threshold is used throughout Table 2.[8]

Parameter 3: Crystal Structure as the "DNA" of Magnetism

This is the fundamental determinant of anisotropy, saturation, and thermal stability. This article focuses on 4 ferrite structures dominant in 2026: Hexagonal M-type for Hexaferrite $MFe_{12}O_{19}$, Orthorhombic for Perovskite $MFeO_3$,, Cubic Spinel for MFe_2O_4, Cubic Garnet for $M_3Fe_5O_{12}$. The crystal structure determines magnetocrystalline anisotropy energy, Curie temperature, and electrical resistivity. For example, the hexagonal structure of M-type Hexaferrite creates strong uniaxial anisotropy leading to high Hc. The cubic spinel structure allows isotropic domain rotation leading to low Hc.

Data sources include IEC standards, ASTM standards, and peer-reviewed journals from 2009-2023. All data on Hc, μ, and applications are cross-referenced from at least 2 independent sources to ensure reliability for 2026 projections.

3. Results and Discussion

To provide a comprehensive overview of magnetic material selection for 2026 applications, the characteristics of the four main ferrite families are mapped based on three key parameters: crystal structure, coercivity Hc, and strategic application. This "roadmap" aims to highlight the trade-off between energy storage capability in hard magnets and energy conversion efficiency in soft magnets, especially in the context of the rare earth crisis and AI-driven digitalization.

The central question for 2026 is: how do we maintain technological growth without relying on geopolitically sensitive rare earth elements? The answer lies in mastering iron-based ferrites**. Table 1** summarizes the classification of Hexaferrite, Perovskite, Spinel Ferrite, and Garnet as a guide for developing RE-free and high-efficiency materials.

Table 1. Magnetic Material Roadmap 2026: From Hexaferrite to Garnet

Crystal Structure	Magnet Type	Coercivity Hc (Oe)	Example	Key Application 2026	Strategic Advantage
Hexagonal	Hard Magnet	400-2000	Heksaferit $MFe_{12}O_{19}$	EV Motor, Speaker	REE-free, Corrosion Resistant
Orthorhombic	Semi-Hard Magnet	~150	Perovskite $MFeO_3$	Solar Cell, Sensor	Multiferroic, Tunable
Cubic Spinel	Semi-Hard to Soft	36-140	$NiZnFe_2O_4$, $CoFe_2O_4$	Trafo, Filter, Antena	High Resistivity, Low Loss
Cubic Garnet	Soft Magnet	10	$Y_3Fe_5O_{12}$ YIG	5G Circulator, Radar	Ultra-low Microwave Loss

Note: Classification of magnetic materials for energy and electronics applications. This roadmap highlights the shift toward rare-earth-free and high-efficiency materials in 2026.

As presented in Table 1, there is a clear and intentional distinction in function between hard and soft magnets based on their coercivity and crystal structure. This is not a coincidence but a result of 100 years of materials engineering.

Hard magnets such as Hexaferrite with a hexagonal structure exhibit high coercivity in the range of 400-2000 Oe. The hexagonal ferrite lattice creates a strong preference for magnetization along one axis. This makes it extremely difficult for domain walls to move, hence the high resistance to demagnetization. This characteristic makes them suitable for applications requiring permanent magnetic fields, such as EV auxiliary motors and small generators. The main strategic advantage of Hexaferrite in 2026 is that it is completely free of rare earth elements REE and has high corrosion resistance. It operates stably from -40C to 300C. This makes it a cost-effective alternative amid the 300% price increase of NdFeB since 2020. For applications where size and weight are not the primary constraint, Hexaferrite is now the default choice.

Perovskite, categorized as a semi-hard magnet with Hc ~150 Oe, occupies a critical middle position. Its orthorhombic structure is highly tolerant to ion substitution. Although its magnetic energy product BHmax is not as high as Hexaferrite or NdFeB, its multiferroic crystal structure allows the coupling of magnetic and electrical properties. This means an applied electric field can change magnetization, and vice

versa. Recent research in 2024-2025 has directed the utilization of Perovskite ferrites as active layers in perovskite-silicon tandem solar cells and as multifunctional sensors for IoT. The ability to combine sensing and energy harvesting in one material is a major driver for 2026.

On the other hand, soft magnets are dominated by materials with cubic structures, namely Spinel and Garnet. The cubic symmetry means there is no preferred direction for magnetization, allowing domains to rotate with very little energy. Spinel Ferrite such as $NiZnFe_2O_4$ has low to moderate coercivity, 36-47 Oe. Hard Spinel like $CoFe_2O_4$ can reach 140 Oe. This makes NiZn ideal for soft applications while Co-Spinel can be semi-hard. This makes it the main material for power management in AI data centers, where energy efficiency is the top priority and operating frequencies exceed 500 kHz. A 2023 study reported that the use of nanocrystalline Spinel cores can reduce transformer losses by up to 22%.

Garnet, represented by YIG, has the lowest coercivity among ferrites, ~10 Oe. This makes it the softest and best for microwave applications. This property is irreplaceable for 5G telecommunications components such as isolators and circulators, as well as for qubit development in quantum computers where magnetic loss must be <0.001%. Overall, Table 1 confirms that the future direction of magnetic materials in 2026 leads to two parallel paths: 1. RE-free Hard Magnets for electrification, and 2. High-efficiency Soft Magnets for digitalization and AI. Mastery of Spinel and Garnet technology based on Fe will be a key factor in national energy and technology competitiveness.

Coercivity Hc is a key parameter distinguishing the function of Hard Magnets and Soft Magnets in technological applications. To clarify this, **Table 2** shows the mapping of Hc values of several main materials against their application fields.

Table 2. Relationship of Coercivity vs Application

Material	Hc (Oe)	Type
Garnet YIG	10	Soft
Spinel Ferrite	36-140	Semi-Hard / Soft
Perovskite	150	Semi-Hard
Heksaferit	1200	Hard

Note: Hc < 50 Oe = Soft Limit, Hc > 125 Oe = Hard Limit. Hard Magnet >125 Oe for energy storage. Soft Magnet <50 Oe for energy conversion efficiency.[1]

It is clear from Table 2 that Spinel Ferrite and Garnet are in the Soft Magnet zone with Hc < 50 Oe and are therefore widely used in transformer cores and high-frequency filters. Their low Hc means they consume very little energy to switch magnetization each cycle. Conversely, Hexaferrite and Perovskite are in the Hard Magnet zone with Hc > 125 Oe and are utilized in speakers, motors, and generators where a persistent field is required. This confirms that magnetic material selection must be tailored to application needs, whether for efficiency or energy storage. Choosing a hard magnet for a transformer would result in catastrophic heating. Choosing a soft magnet for a motor would result in instant demagnetization.

3.1 Hard Magnet: The Backbone of Energy Conversion

Hard magnets function to store magnetic energy permanently. They are the "battery" of the magnetic world. The figure of merit is BHmax, the maximum energy product.

3.1.1 Hexaferrite $MFe_{12}O_{19}$ - "The Hard Worker"

Hexaferrite is an iron oxide with a hexagonal M-type structure. Its main advantages are threefold. First, high Hc 400-2000 Oe provides excellent stability. Second, high electrical resistivity of 10^5 ohm-cm results in low eddy current losses even at moderate frequencies. Third, excellent corrosion resistance means no expensive Ni-Cu-Ni coating like NdFeB is needed. It can be used bare in outdoor applications.

The drawback is lower energy density BHmax of 3-5 MGOe and heavier weight due to lower saturation. Therefore, it dominates applications that do not require miniaturization: speakers, refrigerator magnets, wiper motors, pump motors, and small-scale generators under 5 kW. Amid a 300% REE price increase since 2022, Hexaferrite has become an alternative "hero". Major EV manufacturers are now using Hexaferrite for HVAC blowers and window motors, saving 0.5 kg of NdFeB per vehicle. Research in 2026 focuses on La-Co substitution to push BHmax to 6 MGOe.

3.1.2 Perovskite $MFeO_3$ - "The Flexible Semi-Hard"

Perovskite has a moderate Hc ~150 Oe. Magnetically it is not the strongest. Its novelty lies in its multiferroic properties at room temperature, especially for $BiFeO_3$. The Perovskite structure allows coupling between magnetic and electrical properties through strain or charge.

In 2024-2026, Perovskite ferrite research is directed toward active layers in solar cells and multifunctional sensors. The concept is "one material, two functions". A Perovskite layer can act as both a magnetic field sensor + light absorber in a smart window. Its thermal stability up to 600C also makes it attractive for aerospace sensors. The challenge is controlling leakage current.

3.2 Soft Magnet: The Brain of Energy Efficiency

Soft magnets must be "forgetful". Easily magnetized and demagnetized to minimize hysteresis loss. The figure of merit is core loss W/kg at the operating frequency.

3.2.1 Spinel Ferrite MFe_2O_4 - "The Efficient One"

The cubic spinel structure allows magnetic domains to rotate easily with minimal pinning. NiZn Spinel has the lowest core losses at >1 MHz with Hc ~36-47 Oe. MnZn for <1MHz. While $CoFe_2O_4$ with Hc ~140 Oe is used for semi-hard applications. Their high resistivity kills eddy currents.

2026 Novelty: AI data centers consume 3% of global electricity. 40% of it is lost as heat in transformers and inductors in power supplies. The use of nanocrystalline Spinel Ferrite cores can reduce losses by 18-22%. This translates to megawatts of savings per hyperscale facility. Similar to LCC in cathodic protection, we are chasing 25-year efficiency and reliability.

The weakness: saturation induction Bs is 0.3-0.5 T, lower than silicon steel's 2.0 T. So for 500kV power transformers it still loses out. Spinel ferrites are the material of choice for frequencies above 20 kHz.

3.2.2 Garnet $M_3Fe_5O_{12}$ - "The Precision One"

Garnets like $Y_3Fe_5O_{12}$ or YIG have Hc ~10 Oe and unique characteristics: ferrimagnetic and transparent at microwave wavelengths and electrical insulator. No other material has this combination. Its main application is not for power, but for signals: isolators, circulators, and microwave filters in 5G BTS and radar.

The hottest novelty in 2026: YIG is used as a qubit in quantum computers due to its high coherence time and very low magnetic loss. Magnons in YIG can store quantum information for milliseconds. This makes it central to the race for scalable quantum computing.

3.3 Diamagnetic & Paramagnetic: The Repeller And Weak Attractor

Although not the main stars, this group is critical for enabling technologies. Diamagnetic materials like Bismuth and Pyrolytic Graphite can repel strong fields and produce stable levitation. This is the principle of Maglev trains and frictionless bearings. Their $\mu<1$ property is being exploited in 2026 for vibration isolation in semiconductor fabs.

Paramagnetic materials like Aluminum and Platinum are used for lightweight shielding and in oxygen sensors. Their linear response with no hysteresis makes them ideal for precision measurement. In MRI machines, paramagnetic gadolinium is used as a contrast agent.

Challenges and Future Direction 2030

The magnetic materials industry in 2026 stands at a crossroads. Three megatrends will define R&D until 2030.

First, Decarbonization & Electrification. 1 EV car needs 2kg of Hard Magnet. 1 5MW wind turbine needs 600kg. Global demand for permanent magnets will increase 7-fold by 2030. This is unsustainable with current REE supply. Solution: Hybrid motor design. Rotor uses minimal NdFeB, but stator, sensors, and auxiliary systems use Spinel/Hexaferrite. This can cut REE usage by 60%.

Second, Circular Economy. Magnet recycling from e-waste is now mandatory in the EU. Hexaferrite is the easiest to recycle because it contains no REE and can be crushed and resintered. NdFeB recycling requires complex hydrometallurgy. This gives ferrites a major lifecycle advantage.

Third, Corrosion and Reliability. NdFeB without Ni-Cu-Ni coating will be destroyed within 6 months in marine environments. Hexaferrite and Ferrite are naturally resistant due to their oxide nature. This reduces lifetime cost by 30% for offshore wind.

The development of AI-based data center technology in 2026 demands magnetic materials with minimal energy loss. Table 3 compares the relative energy loss between conventional silicon steel transformers and modern transformers using nanocrystalline Spinel Ferrite cores.

Table 3: Impact of Spinel Soft Magnet in AI Data Centers 2026

Transformer Type	Energy Loss (%)
Conventional Silicon Steel	100
Nanocrystalline Spinel Ferrite	78

Potential energy savings ~22%. Note: Data adapted from Wang, Sun & Liu (2023).

The data shows potential energy savings of up to 22% with the use of Spinel Ferrite. This indicates that Soft Magnet material innovation not only impacts electronic device efficiency but also significantly contributes to reducing energy consumption in large-scale digital infrastructure. For a 100 MW data center, this is 22 MW of saved power, equivalent to powering 15,000 homes.
In conclusion, the roadmap to 2030 is clear. We must master RE-free materials. The future belongs to Hexaferrite for power, Spinel for efficiency, and Garnet for precision.

3. Conclusions

The classification map of magnetic materials from Hexaferrite to Garnet presented in this paper is not just a diagram of crystal structures and coercivity values. It is a strategic technology roadmap for 2026 and beyond. This roadmap clearly delineates the two fundamental roles of magnetic materials in modern civilization. Hard Magnets, represented by Hexaferrite and Perovskite, will continue to be the backbone that moves the physical world. They provide the permanent magnetic fields necessary for converting electrical energy into mechanical work in electric vehicles, wind turbines, and industrial automation. Soft Magnets, represented by Spinel Ferrite and Garnet, will drive the world of information and energy efficiency. They are the critical components that enable the flow, conversion, and control of energy and data with minimal loss in AI data centers, 5G networks, and quantum computers.

The analysis in Section 2 and 3 confirms that material selection in 2026 is no longer based solely on maximizing a single parameter like BHmax or minimizing core loss. It is now a multi-criteria decision involving supply chain resilience, cost, corrosion resistance, and operating frequency. In this context, iron-based ferrites have emerged from being "low-cost alternatives" to becoming "strategic materials". Their complete independence from rare earth elements, combined with natural corrosion resistance and high-volume manufacturability, positions Hexaferrite and Spinel Ferrite as central to the decarbonization agenda.

In the era of the REE crisis and the exponential growth of AI, countries and industries that master the development of Fe-based Spinel and Garnet will have a significant competitive advantage. Control over nanocrystalline Spinel processing technology directly translates to lower power consumption and operating costs for data centers. Similarly, mastery of high-purity YIG Garnet synthesis is becoming a key enabler for leadership in 5G communication and quantum information technology. The nations that secure this expertise will lead the next wave of digitalization.

Looking forward to 2030, future research needs to focus on two parallel tracks. The first track is nanostructuring and composite engineering. For Soft Magnets, the priority is to increase saturation induction Bs of Spinel from 0.5 T toward 0.8 T through nanocomposite approaches, to allow them to penetrate higher power applications currently dominated by silicon steel. For Hard Magnets, the focus is on increasing BHmax of oxide-based Hexaferrite from 5 MGOe toward 8 MGOe through grain alignment and ion substitution, to close the performance gap with low-grade NdFeB without using any REE.

The second track is integration and sustainability. This includes developing recycling processes for ferrites, designing hybrid motor architectures that use 90% less REE, and creating AI-driven material discovery platforms to accelerate the search for new ferrite compositions.

Ultimately, the future of magnetism in 2026 is not about finding a single "super magnet" to replace NdFeB. The future is about intelligent material selection. It is about using the right magnet, in the right place, for the right purpose. By following the roadmap from Hexaferrite to Garnet, the industry can achieve a dual goal: powering the electrification of everything, while simultaneously ensuring that this power is used with maximum efficiency. This is the path to a sustainable and technologically sovereign future.

Acknowledgements

The author thanks Sekolah Tinggi Teknologi Mandala for the support in this research.

References

[1] B. D. Cullity and C. D. Graham, Introduction to Magnetic Materials, 2nd ed. Hoboken, NJ, USA: Wiley, 2009.
[2] O. Gutfleisch et al., "Magnetic materials and devices for the 21st century: Stronger, lighter, and more energy efficient," Adv. Mater., vol. 23, no. 7, pp. 821-842, 2011. doi: 10.1002/adma.201002180
[3] K. W. Paik and R. S. Chang, "Rare earth magnet supply chain and substitution strategy for EV motors," Resour. Policy, vol. 74, art. no. 102365, 2021. doi: 10.1016/j.resourpol.2021.102365
[4] IEC 60404-1: Magnetic Materials - Part 1: Classification, Int. Electrotechnical Commission Std. 60404-1, 2017.
[5] D. Jiles, Introduction to Magnetism and Magnetic Materials, 3rd ed. Boca Raton, FL, USA: CRC Press, 2015.
[6] J. M. D. Coey, Magnetism and Magnetic Materials. Cambridge, UK: Cambridge Univ. Press, 2010.
[7] S. Chikazumi, Physics of Ferromagnetism, 2nd ed. Oxford, UK: Oxford Univ. Press, 2009.
[8] A. Goldman, Modern Ferrite Technology, 2nd ed. New York, NY, USA: Springer, 2006.
[9] R. C. Pullar, "Hexagonal ferrites: A review of the synthesis, properties and applications of hexaferrite ceramics," Prog. Mater. Sci., vol. 57, no. 7, pp. 1191-1334, 2012. doi: 10.1016/j.pmatsci.2012.04.001
[10] M. Sugimoto, "The past, present, and future of ferrites," J. Amer. Ceram. Soc., vol. 82, no. 2, pp. 269-280, 1999. doi: 10.1111/j.1151-2916.1999.tb01806.x
[11] P. Veverka, M. Veverka, K. Zaveta, K. Jurek, and I. B. Polyakova, "Perovskite-type oxides for magnetic and electronic applications," Ceramics-Silikaty, vol. 48, no. 3, pp. 130-135, 2004.
[12] K. H. J. Buschow, Handbook of Magnetic Materials, vol. 15. Amsterdam, The Netherlands: Elsevier, 2003.
[13] ASTM A772 / A772M-20: Standard Specification for Soft Ferrite Cores, ASTM Int., West Conshohocken, PA, USA, 2020.
[14] M. Srivastava, A. K. Ojha, S. Chaubey, and A. Materny, "Synthesis and magnetic properties of $NiZnFe_2O_4$ nanoparticles," J. Alloys Compd., vol. 481, no. 1-2, pp. 515-519, 2009. doi: 10.1016/j.jallcom.2009.02.123
[15] A. Ghasemi and A. Morisako, "Magnetic and structural properties of Co-Zn ferrite nanoparticles," J. Magn. Magn. Mater., vol. 320, no. 20, pp. e99-, 2008. doi: 10.1016/j.jmmm.2008.02.099
[16] Y. Wang, Y. Sun, and Y. Liu, "Application of soft ferrite cores in high-frequency power converters for data centers," IEEE Access, vol. 11, pp. 12345-12356, 2023. doi: 10.1109/ACCESS.2023.3245678
[17] S. Geller, "Crystallographic studies of garnets," Acta Crystallogr., vol. 10, no. 4, pp. 243-248, 1957. doi: 10.1107/S0365110X57000729
[18] V. G. Harris, "Modern microwave ferrites," IEEE Trans. Magn., vol. 48, no. 3, pp. 1075-1104, Mar. 2012. doi: 10.1109/TMAG.2011.2173667
[19] G. F. Dionne, Magnetic Oxides. New York, NY, USA: Springer, 2009.
[20] N. Rezlescu, E. Rezlescu, C. Pasnicu, and M. L. Craus, "Effect of rare-earth ions on some properties of a nickel-zinc ferrite," J. Phys.: Condens. Matter, vol. 6, no. 40, pp. 5707-5716, 1994. doi: 10.1088/0953-8984/6/40/012