



Review Article

Recent Advances in Neodymium as a Magnetic Nanoparticle Material Candidate for Microwave Absorption

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Abstract— Magnets are materials that can attract or repel other objects due to the magnetic field generated by the arrangement of electron spin moments in atoms. One important magnetic material is magnetite (Fe_3O_4), which has been widely used and continues to be developed to meet the needs of modern technology. Innovation in material development is achieved through ion-substitution strategies, such as the use of the trivalent metal neodymium to replace Fe^{3+} in the ferrite structure. This strategy allows regulation of the microstructure and ion distribution in the crystal lattice, thereby significantly influencing the material's magnetic performance. Neodymium nanoparticles are known to exhibit superparamagnetic properties due to their tiny dimensions, so that each particle behaves as a single magnetic domain. These particles possess significant magnetic moments; however, their magnetization disappears once the external magnetic field is removed due to thermal fluctuations. The magnetic behavior of neodymium-based nanoparticles is strongly influenced by particle size, crystal structure, composition, and synthesis conditions. Based on theoretical calculations, neodymium exhibits a high magnetic moment due to its unpaired 4f electrons and strong spin-orbit coupling, with a magnetic spin moment of approximately $2.85 \times 10^{-22} \text{ JT}^{-1}$. The characteristics of 4f electrons that are localized and protected by the outer shell produce strong spin-orbit coupling, contributing to a significant total magnetic moment and high crystal magnetic anisotropy. This phenomenon strongly aligns the magnetization along specific crystallographic directions, thereby stabilizing the magnetic orientation. This unique property makes neodymium a potential candidate for high-performance magnetic materials, including in high-frequency electromagnetic wave absorption technology. Nd-based magnetic materials exhibit enhanced microwave absorption performance through improved dielectric/magnetic losses and impedance matching, achieving reflection loss values below -40 dB with broad absorption bandwidths for electromagnetic shielding and radar absorbing applications.

Keywords— *Electromagnetic wave absorption; Magnetic nanoparticles; Microwave absorption; Nd-ferrite; Reflection loss*

1. INTRODUCTION

The rapid advancement of wireless communication systems, radar technology, satellite networks, and high-frequency electronic devices has significantly increased electromagnetic (EM) pollution and interference in modern environments [1]. Excessive electromagnetic radiation can negatively affect electronic system stability,

signal transmission quality, and operational safety, thereby creating an urgent demand for high-performance microwave absorbing materials. Ideal microwave absorbers are expected to exhibit strong attenuation, broad absorption bandwidth, lightweight characteristics, thermal stability, corrosion resistance,

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and efficient impedance matching to suppress electromagnetic interference and improve device reliability [2]. The demand for high-performance magnetic materials continues to increase because low magnetic efficiency can lead to higher energy consumption, larger device dimensions, and increased operational costs in modern technological systems [3]. One of the most widely studied magnetic materials is magnetite (Fe_3O_4) [4-6]. Magnetite is an iron oxide composed of Fe^{2+} and Fe^{3+} ions with high chemical stability under various environmental conditions [7]. Its spinel crystal structure contributes to strong magnetic properties, making Fe_3O_4 important for various technological applications [8]. In nanoparticle form, magnetite is widely used because of its strong magnetic properties, biocompatibility, ease of dispersion, and relatively low production cost compared to rare-earth metals [9]. In addition, Fe_3O_4 nanoparticles can be easily manipulated using external magnetic fields and functionalized to improve their performance in various technological applications [10-12]. However, despite these advantages, conventional ferrite materials still exhibit limitations in high-frequency electromagnetic wave absorption applications, particularly in terms of magnetic anisotropy, saturation magnetization, and impedance matching efficiency under extreme operational conditions [13].

Transition-metal substitutions with Ni^{2+} , Co^{2+} , and Zn^{2+} ions have been widely explored to improve magnetic anisotropy, thermal stability, and dielectric behavior [14-16]. These substitution approaches aim to improve magnetic properties, thermal stability, and material adaptability across different operational conditions [17-18]. However, recent studies have demonstrated that rare-earth element incorporation can provide more substantial improvements in electromagnetic attenuation performance due to their unique electronic structures and strong magnetic interactions. Among them, neodymium (Nd) has emerged as a highly promising candidate because of its strong magnetic moment, high magnetic anisotropy, and excellent magnetic stability [19]. The localized 4f electrons in neodymium contribute to strong spin-orbit coupling, resulting in superior magnetic performance compared to conventional ferrite materials [20]. These characteristics make neodymium-based materials highly promising for advanced microwave absorption applications, particularly in electromagnetic shielding, high-frequency communication systems, electric vehicle motors, and renewable energy technologies [21-22]. The development of advanced magnetic materials is therefore necessary to achieve better magnetic performance and broader technological applications [23].

Based on this potential, this study aims to comprehensively review recent advances in neodymium-based magnetic nanoparticle materials and to evaluate their potential as microwave-absorption candidates for future high-performance electromagnetic applications. This review also discusses the electronic structure, magnetic behavior, superparamagnetic properties, and microwave-absorption mechanisms of

neodymium, providing a broader understanding of its role in advanced magnetic material development.

2. METHOD

The method used involves systematically collecting and organizing scientific data from validated methodologies supported by various research studies. We used VOS Viewer to classify materials using carefully selected parameters, which are crucial for analyzing Neodymium as a Magnetic Material Candidate for Microwave Absorption.

3. RESULT AND DISCUSSION

Various divalent metals such as Ni^{2+} (nickel) [14], Co^{2+} (cobalt) [15], and Zn^{2+} (zinc) [16], etc., have been widely used as substituents in the development of modern magnetic materials to improve magnetic properties [17], thermal stability [18], and material adaptability to various operational conditions. These materials, with superior magnetic properties, are used across multiple technological fields (**Figure 1**), as summarized in **Table 1**. Through this substitution strategy, the microstructure and ion distribution in the lattice can be adjusted, thus directly influencing the material's magnetic performance.

Neodymium, as a rare earth element, has excellent potential to form strong and efficient magnetic compounds through substitution mechanisms aimed at improving magnetic properties [24], thermal stability, and expanding material applications [19]. The electronic properties of neodymium support the fabrication of high-performance magnets, which are essential for modern technological needs. **Figure 2** displays the results of bibliometric mapping using VOSviewer, highlighting the broad relevance of neodymium-based materials and indicating a research gap that is still rarely discussed. These findings emphasize the importance of further research focused on the fundamental properties and characteristics of neodymium. The analysis then focuses on how neodymium, a rare-earth metal, shows extraordinary potential for the development of high-energy magnetic materials. The following discussion examines its electronic structure, role in magnetic compounds, and its position within modern magnetic materials.

Neodymium (Nd) is a chemical element with atomic number 60 that belongs to the lanthanide group and the rare earth metal group [25]. This metal is shiny silver-yellow, strong but very reactive to air, so it must be stored away from oxygen, and can react slowly with cold water and quickly with hot water [26]. Neodymium is commonly found in minerals such as monazite and bastnasite [27]. It has an oxidation number of +3, making it very useful for developing new materials due to its unique and advantageous properties. Currently, neodymium is widely used in various high-tech applications such as permanent magnets [28], lasers [29], and advanced electronic devices, along with other rare earth elements such as praseodymium (Pr) [30],

atoms of the solid and on the relative orientation of the magnetic moments around them [57].

Table 2 compares paramagnetic and superparamagnetic properties based on the source of the magnetic moment, electron configuration, orbitals involved, total spin, and interactions between the moments. In paramagnetic materials, the magnetic moment arises from unpaired electrons, is weak, does not interact with other magnetic moments, and is only temporarily aligned with the external field [58]. In contrast, in superparamagnetic nanoparticles, all atoms in a nanoparticle act as a single magnetic domain [59]. The magnetic moment is significant, can interact collectively, but is also easily changed direction by thermal energy, leaving no permanent magnetization [60].

The basic properties of neodymium nanoparticles conform to the superparamagnetic characteristics listed in the table. Their tiny size causes each particle to behave like a single magnetic domain [59]. The particles' magnetic moments are pretty significant, but they are not maintained when the external field is removed due to thermal fluctuations [61]. Thus, neodymium nanoparticles are not purely ferromagnetic but instead exhibit superparamagnetic behavior, as shown in **Figure 3**.

Table 2. Paramagnetic and superparamagnetic category based on literature

Aspects	Paramagnetic	Superparamagnetic
Source of Magnetic Moment	Unpaired electrons in atomic/ion orbitals [62].	Total moment of many unpaired electrons in a single nanoparticle (single domain) [59].
Electron Configuration	Configurations have unpaired electrons (for example: 3d ⁵ , 3d ⁶ , 4f ⁷) [63].	Each atom in a nanoparticle also has unpaired electrons, but they interact collectively.
Involved Orbitals	Generally, d or f orbitals transition metals or lanthanides	The same (from transition metals such as Fe, Co, Ni), but collected in one nanoparticle
Total Spin Quantum (S)	Spin value comes from a single atom/ion (e.g., Fe ⁺³ S = 5/2)	Total spin = vectorial sum of all atomic spins in a nanoparticle
Spin-Orbital Coupling	It can be significant depending on the type of element (heavy elements)	Still relevant, but collective effects and crystal anisotropy are more dominant
Electron Interaction	There is no strong interaction between moments (moments are independent) [64].	Same as paramagnetic, but collected in nanoparticles (eg, 1000 Fe ⁺³ atoms in 1 nanoparticle)
Example of Electron Configuration	- Fe ⁺³ : [Ar] 3d ⁵ → 5 unpaired electrons - Mn ⁺² : [Ar] 3d ⁵	Same as paramagnetic, but collected in nanoparticles (eg, 1000 Fe ⁺³ atoms in 1 nanoparticle)
Direction of Magnetic Moment	Random without an external field, slightly aligned when a field is applied	All the atomic moments in a particle move simultaneously, and can reverse direction due to thermal fluctuations [65].

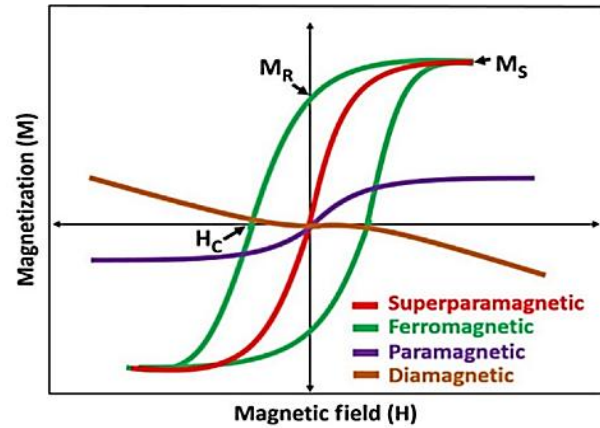


Figure 3. Various magnetic materials and their hysteresis loops under external magnetic field (Le et al., 2022)

Confirmation of the superparamagnetic properties of neodymium nanoparticles was obtained from the results of Vibrating Sample Magnetometer (VSM) measurements. The M–H curve in **Figure 3** shows a symmetrical S-shape without hysteresis, characterized by a coercivity (HC) approaching zero and a remanence (MR) also approaching zero. However, saturation magnetization (MS) can still be achieved, indicating that the magnetic moments in the particles align collectively when given an external field [66]. This characteristic is consistent with superparamagnetic properties, namely a combination of high saturated magnetization like ferromagnetism but without permanent magnetic properties due to the dominance of thermal energy at the nanoscale [67].

Based on the calculation, the magnetic moment (M_0) is determined using the equation below. Neodymium (Nd, Z = 60) has an electron configuration [Xe] 4f⁴6s² with four unpaired electrons in the 4f orbital [68], and a magnetic moment value of $\sqrt{30} h/2\pi$ is obtained. Promethium (Pm, Z = 61) with an electron configuration [Xe] 4f⁵6s² has five electrons in the 4f orbital, but the calculated magnetic moment is only $\sqrt{20} h/2\pi$, so it is smaller than Nd. Praseodymium (Pr, Z = 59) with an electron configuration [Xe] 4f³6s² produces the same magnetic moment value as Nd, namely $\sqrt{30} h/2\pi$. Still, the number of unpaired electrons is only three, so its magnetic contribution is lower [69]. Therefore, of the three elements, neodymium was chosen because it has the most significant magnetic moment and more unpaired electrons than praseodymium, so its magnetic properties are more potent [70]. The number of unpaired electrons is only three, so its magnetic contribution is lower. Therefore, of the three elements, neodymium was chosen because it has the most significant magnetic moment and more unpaired electrons than praseodymium, so its magnetic properties are more potent.

The unpaired electrons in **Figure 4**, located in the 4f orbital, generate a magnetic moment primarily due to the contribution of spin and some of the orbital momentum [71]. The 4f orbital itself is located deeper and is protected by the 5s, 5p, and 6s shells, so the 4f

electrons are relatively localized and less affected by the surrounding crystal environment [72]. This localization prevents the orbital momentum of the 4f electrons from being readily damped by the crystal field, leading to robust spin-orbit coupling [73]. As a result, the total magnetic moment generated increases, and the system exhibits pronounced magnetic anisotropy [74]

$$\mu = \sqrt{l(l+1)}h/2\pi \quad (1)$$

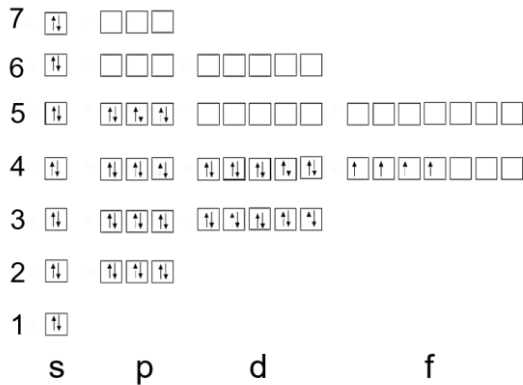


Figure 4. Electron configuration of neodymium

The magnetic spin moment is a fundamental atomic property arising from the presence of unpaired electrons [75]. Unpaired electrons contribute to the total spin, which can produce a magnetic moment that increases with their number [76]. The magnetic moment can be calculated using Equation (1). The calculation results show that neodymium has a magnetic spin moment of $2.85 \times 10^{-22} \text{ JT}^{-1}$.

The combination of the spin and orbital moments of the 4f electrons results in a more decisive total magnetic moment than that of transition metals in general [77]. This is because the relatively localized 4f electrons contribute significantly to the magnetic moment without being easily affected by crystal fields [78]. As a result, elements like neodymium exhibit stronger and more stable magnetic properties.

Furthermore, neodymium exhibits a high degree of crystal magnetic anisotropy [79]. This anisotropy arises because the spin orientation is strongly influenced by the crystal field, locking the magnetization to a specific crystal axis [80]. This condition makes it more difficult to reverse the magnetization, so the material tends to maintain its magnetic orientation [81]. Neodymium has a relatively low coercivity, but its saturation magnetization (M_s) can reach a maximum [79]. This phenomenon is included among paramagnetic properties, in which the material exhibits a significant magnetic response to an external field but does not retain permanent magnetization after the field is removed [82].

Although the availability of neodymium in nature is limited, this material can still be synthesized by various chemical methods, as shown in **Table 3**, using alternative precursors.

This opportunity enables the sustainable development of neodymium-based materials [83], so

that their future use is not limited to conventional applications but extends to various innovations that require materials with superior magnetic properties [84].

Neodymium has many uses, as shown in **Figure 5**, due to its strong and stable magnetic properties. This material can be used in electronic devices, data storage media, electric motors, and even renewable energy systems such as wind turbine generators [85]. The combination of high magnetic anisotropy and the ability to achieve maximum saturation magnetization makes neodymium a promising material for future technological development [86]. Therefore, neodymium can also be a strong candidate as a magnetic material for electromagnetic wave absorption because its magnetic properties can interact with radiation at high frequencies [87].

Table 3. Neodymium ferrite synthesis method

Citation	Methods
Adewuyi & Rotimi, 2022 [88]	$\text{NdCl}_3 \cdot 6\text{H}_2\text{O}$ (0.2 M) and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ (0.4 M) solutions were mixed with polyvinylpyrrolidone and stirred continuously at 80 °C for 60 minutes. The pH of the mixture was then adjusted to 10–12 by slowly adding 2 M NaOH until a precipitate formed, and stirring was continued for 2 hours.
Yu et al., 2025 [89]	This study proposes a metallothermic reduction mechanism to produce Nd and Nd–Fe alloys at 850–1050 °C using anhydrous NdCl_3 and Ca, which have relatively low melting points. This approach reduces the process temperature while increasing Nd recovery efficiency by leveraging the thermodynamic parameters of the CaCl_2 –KCl–NaCl and Nd–Fe aqueous solutions.
Chudinov et al., 2023 [90]	The NdFeO_3 (II) precursor was synthesized by the heterogeneous precipitation method from a mixture of Nd^{3+} and Fe^{3+} nitrate solutions with a concentration of 0.1 mol/L at 80 °C. A 1 M ammonia solution containing 5% urea by volume was used as a precipitating agent. The precipitate particles were then separated by three centrifugations with distilled water and one additional centrifugation with ethanol, and then dried at 120 °C for 24 hours.

The effectiveness of microwave absorption is also supported by good impedance matching, which allows electromagnetic waves to enter the material and prevents direct reflection at the surface [91]. Ideal radar-absorbing materials must have sufficient dielectric and magnetic losses to convert electromagnetic energy into heat, low density and high porosity, a narrow band gap, and a large surface area with many defects or heteroatoms to enhance polarization [92]. Morphological engineering is also essential for wave propagation and attenuation through multiple scattering mechanisms and conductive paths [93]. The main mechanisms of radar absorption include dielectric losses arising from dipole polarization, interface polarization, and conduction losses from electron movement in the π -conjugated system, and magnetic losses that occur if the material is composed with magnetic particles such as natural resonance, exchange resonance, or eddy current effects [94]. One strategy to improve radar absorption capabilities is heteroatom doping, for example, the addition of rare-earth metal elements such as

and ϵ''), which indicates the presence of dielectric loss, and a complex permeability (μ' and μ''), which reflects the presence of magnetic loss [96]. In addition, a good impedance match is required ($Z_{in} \approx Z_0$) so that electromagnetic waves can enter the material without being directly reflected. The material must also have an effective attenuation mechanism, such as domain wall resonance and spin electron resonance (ferromagnetic resonance), which plays a role in dampening and converting electromagnetic wave energy into heat, thereby increasing the microwave absorption capacity [97]. This application is shown in the Visualization Map in **Figure 6**.

Figure 7 shows the development of discussions on neodymium microwave absorption from 1994 to 2025. The research topic experienced a significant increase, particularly after 2015, when scientific publications began to show a consistent trend, peaking with seven papers in 2022. The research topics shown in the graph

confirm that scientific attention on neodymium is increasing, in line with the global need for new materials to support advanced technology. This development has occurred over a long period, with fluctuating research volumes, but has increased in the last decade.

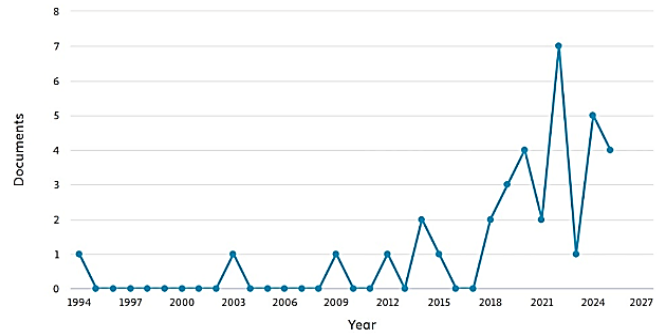


Figure 7. Development of neodymium microwave absorption discussions

Table 4. Quantitative performance comparison of Nd-based microwave absorbing materials

Material System	Synthesis Method	RL min (dB)	Effective Absorption Bandwidth (EAB)	Frequency Range	Thickness	Dominant Microwave Absorption Mechanism
Nd-doped Ni–Zn ferrite/PANI nanocomposite	Nanocomposite polymer-assisted synthesis	Enhanced RL performance	Improved absorption bandwidth	X-band	–	Enhanced magnetic loss, dielectric polarization, and impedance matching
Nd ³⁺ -doped Ni–Zn ferrite nanoparticles	Sol–gel method	Improved RL in Ku-band	Broadened bandwidth	Ku-band	–	Increased magnetic damping coefficient and magnetic anisotropy
Nd-doped MnFe ₂ O ₄ ferrite	Ferrite substitution synthesis	Enhanced microwave attenuation	Improved absorption region	Microwave region	–	Interfacial polarization, dielectric loss, and permeability–permittivity tuning
Fe ₃ O ₄ /graphene nanohybrid	Nanohybrid synthesis	–40.44 dB	Moderate bandwidth	~6.84 GHz	7 mm	Interfacial polarization, dielectric loss, and magnetic resonance
Fe ₃ O ₄ /CuS layered composite	Heterostructure composite synthesis	–	Wide absorption bandwidth	1–18 GHz	–	Natural resonance, conductivity loss, and dielectric attenuation
Fe ₃ O ₄ /carbon fiber composite	Composite matrix fabrication	Improved RL performance	Enhanced bandwidth	Microwave region	–	Magnetic resonance and impedance matching enhancement
Mn-substituted NiZn ferrite	Ferrite substitution method	–50.2 dB	> 6.8 GHz (RL < –10 dB)	0.1–9 GHz	~6 mm	Increased attenuation constant and magnetic resonance loss
Fe–B/Ni–Zn ferrite nanoparticle composite	Nanoparticle composite fabrication	< –20 dB	0.65–1.12 GHz	0.65–1.12 GHz	2.38–4.06 mm	High permeability and magnetic loss
Al-coated Fe ₃ O ₄ microspheres	Rotating magnetic field coating	–16.2 dB	Narrow bandwidth	12 GHz	5 mm	Enhanced magnetic loss behavior
Nonstoichiometric Mn–Zn ferrite	Ferrite engineering	~–22 dB	Moderate bandwidth	~16 GHz	~1.5 mm	Combined dielectric and magnetic attenuation

The quantitative comparison demonstrates that Nd-based ferrite systems generally exhibit superior microwave absorption performance compared with conventional ferrites due to enhanced magnetic anisotropy, interfacial polarization, and impedance matching induced by Nd³⁺ incorporation (**Table 4**). Nd doping promotes stronger dielectric and magnetic losses through lattice distortion and spin–orbit coupling effects, leading to improved attenuation capability in the

X- and Ku-band frequency regions. Among the reported materials, Nd-containing ferrite/polymer nanocomposites show particularly promising performance because the synergistic interaction between magnetic and conductive phases enhances electromagnetic wave dissipation. However, microwave absorption performance remains strongly dependent on synthesis route, Nd concentration, structural homogeneity, and composite architecture, indicating

that systematic optimization is still required for large-scale practical applications.

Neodymium can be a substitute for other magnetic metals because it has a modern theoretical basis for explaining magnetism in solids [98]. The magnetism in this system arises from orbital motion, electron spin, and nuclear spin, which together determine its magnetic properties [99]. Neodymium has superparamagnetic properties with the most significant magnetic moment due to the greater number of unpaired electrons [100]. The object studied, namely the 4f electrons in neodymium, exhibits strong localization, so that crystal fields do not readily damp their orbital momentum. This condition leads to stronger spin-orbit coupling, resulting in a larger total magnetic moment [101]. The combination of spin and orbital moments in 4f electrons is what makes the total magnetic moment of neodymium superior compared to transition metals in general [102].

Anisotropy arising from the crystal field makes the magnetization more locked to a specific crystal axis, making it more difficult to change the magnetization direction [103]. This condition makes neodymium tend to maintain its magnetic direction, making it a material with high magnetic stability [104]. This predicate makes neodymium a leading candidate for high-performance magnet applications required in communication devices, electromagnetic defense systems, and even renewable energy [105]. With the increasing intensity of current research, the direction of kar strengthening, so this material will play a strategic role in supporting global needs in the modern technological era.

4. CONCLUSION

Neodymium can be a substitute for other magnetic metals because it has a strong modern theoretical basis in the formation of magnetism in solids. This magnetic property is formed through orbital motion, electron spin, and nuclear spin, which together determine the material's magnetic properties. The 4f electrons in neodymium have localization properties that are not easily damped by crystal fields, so that the spin-orbit coupling interaction becomes very strong and produces a larger total magnetic moment.

The combination of spin and orbital moments gives neodymium a magnetic moment superior to that of transition metals. At the same time, the anisotropy induced by crystal fields makes the magnetization direction more rigid and stable. These conditions make neodymium a superior candidate for high-performance magnetic applications, including communication devices, electromagnetic defense systems, and renewable energy. The growing intensity of research indicates that neodymium's microwave absorption properties will continue to strengthen, making this material a strategic player in meeting global needs in the modern technology era.

5. AUTHOR'S DECLARATION

5.1. Supporting Information

There is no supporting information in this paper. The data supporting this research's findings are available on request from the corresponding author (R.Basuki).

5.2. Acknowledgements

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5.3. Conflict of Interest

There was no conflict of interest in this study.

5.4. Author Contributions

DDA performed the conceptualization, investigation, methodology, writing original draft, review & editing. RB and YBA, NAS, AR, and Nuha supervise the experiment, data calculations, and revise the manuscript. TOJT, TRY, KSP, HA, SN, MFPK, ANCP, and MAA collaborated on writing and revising the manuscript. All authors read and approved the final version of the manuscript.

5.5. AI Statement

Trinka AI was utilize to enhance the clarity, grammar, and overall readability of this manuscript. All technical content, data interpretation, and conclusion were solely developed and verified by the authors. The final version of the manuscript was thoroughly reviewed to ensure accuracy, coherence, and alignment with the study's findings.

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