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$CoFe_2O_4$ Nanopartikülleri ve Odun Talaş Katkısı İçeren Boyanın Mikrodalga Soğurma Özellikleri

Ali Onur KAYA[1*], Mert Can EMRE[2], İbrahim Halil MUTLU[3]

[1]Vocational School of Health Service, Radiotherapy Department, Akdeniz University, 07070, Antalya, Türkiye
[2]Sorgun Vocational School, Motor Vehicles Department, Yozgat Bozok University, 66700, Yozgat, Türkiye
[3]Material Science and Engineering Department, Akdeniz University, 07070, Antalya, Türkiye

[1]https://orcid.org/0000-0003-4220-1866
[2]https://orcid.org/0000-0002-1445-0358
[3]https://orcid.org/0000-0003-1643-4332
* Corresponding author: alionurkaya@akdeniz.edu.tr

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Elektromanyetik girişim (EMI)
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Mikrodalga absorpsiyonu
Yansıma kaybı

ÖZ

Elektromanyetik girişim (EMI) koruma ihtiyacı; manyetik ve dielektrik özellikleri birleştiren ileri düzey malzemelerin geliştirilmesine öncülük etmiştir. Bu çalışma; 3,2–5,0 GHz aralığında EMI korumasını artırmak için kobalt ferrit ($CoFe_2O_4$) nanopartikülleri (%5) ve odun talaşı (%10) içeren bir kompozit boya sunmaktadır. Odun talaşı; gözenekli yapısı ve dielektrik özellikleri sayesinde $CoFe_2O_4$'ün manyetik kayıp özelliklerini tamamlayarak elektromanyetik dalga soğurumunu artırmıştır. Bu boya, $CoFe_2O_4$ içeren sistemin 10 dB'lik performansını aşarak maksimum 12 dB soğurma koruma etkinliği (SE) elde etmiştir. Yansıma SE değerleri ise -1 ile +1 dB arasında azalmıştır. Bu çevre dostu ve maliyet etkin malzeme, endüstriyel ve savunma uygulamaları için önemli bir potansiyel sunmaktadır.

Microwave Absorption Properties of Paint Containing $CoFe_2O_4$ Nanoparticles and Wood Shaving Additive

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ABSTRACT

The demand for effective shielding against electromagnetic interference (EMI) has driven the development of advanced materials combining magnetic and dielectric properties. This study presents a composite paint with cobalt ferrite ($CoFe_2O_4$) nanoparticles (5 wt%) and wood shavings (10 wt%) for enhanced EMI shielding in the 3.2–5.0 GHz range. Wood shavings improved electromagnetic wave absorption through their porous structure and dielectric properties, complementing $CoFe_2O_4$'s magnetic loss characteristics. The paint achieved a peak absorption shielding effectiveness (SE) of 12 dB, surpassing the 10 dB of the $CoFe_2O_4$-only system. Reflection SE values were reduced between -1 to +1 dB. This eco-friendly and cost-effective material offers significant potential for industrial and defense applications.

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1.Introduction

Electromagnetic pollution, resulting from the swift progression of wireless communication technology and electronic devices, has become a notable environmental issue. In contrast to conventional pollutants, including water, air, and soil toxins, electromagnetic interference (EMI) poses distinct issues owing to its ubiquitous nature and its effects on human health and technology systems. Extended exposure to electromagnetic waves (EMWs), especially in high-frequency ranges, can interfere with biological processes, resulting in immune suppression and heightened susceptibility to chronic diseases (Wu et al., 2021; Ghaffarkhah et al., 2023).

The development of microwave-absorbing materials (MAMs) has received considerable attention. For MAMs to work well, they should have a wide effective absorption bandwidth (EAB), a high reflection loss (RL), a light structure, and a thin matching thickness. The properties of MAMs facilitate the efficient conversion of electromagnetic energy into heat, thereby reducing EMI while preserving structural and functional integrity (Gan et al., 2020; Shi et al., 2023). Cobalt spinel ferrite ($CoFe_2O_4$) stands out among various magnetic materials as a promising candidate, attributed to its high magnetic loss, adjustable magnetic properties, and cost-effectiveness (Gupta and Tai, 2019). $CoFe_2O_4$ has some problems, like being very dense and not conducting electricity well, which limits its use as an independent microwave absorber. Composite systems that integrate $CoFe_2O_4$ with lightweight and porous materials have been investigated to address these limitations. The composites improve impedance matching and interfacial polarization, resulting in enhanced microwave absorption performance (Cheng et al., 2022; Shi et al., 2022). Wood shavings, recognized as a renewable and environmentally sustainable material, demonstrate significant potential as an auxiliary element in MAMs. The porous structure, low density, and large surface area make it the perfect matrix for adding $CoFeO_4$ nanoparticles. The integration of wood shavings with $CoFe_2O_4$ enhances both the mechanical and electromagnetic characteristics of the composite while simultaneously addressing sustainability issues (Guan et al., 2021; Liu et al., 2021). The porous structure of wood shavings promotes multiple reflections of electromagnetic waves, thereby increasing absorption capacity. This study investigates the electromagnetic absorption performance of a novel $CoFe_2O_4$-wood shaving composite paint. The paint is engineered to optimize absorption efficiency through the synergistic effects of $CoFe_2O_4$ nanoparticles and the porous, dielectric characteristics of wood shavings. This study evaluates reflection loss, effective absorption bandwidth, and frequency-dependent absorption properties of the composite. This study seeks to enhance the development of high-performance, environmentally sustainable electromagnetic absorbers by focusing on material efficiency and sustainability.

2. Experimental Methods

2.1. Synthesis of Cobalt Ferrite Nanoparticles ($CoFe_2O_4$)

$CoFe_2O_4$ nanoparticles were synthesized through an optimized hydrothermal method. Cobalt chloride ($CoCl_2{\cdot}6H_2O$) and ferric chloride ($FeCl_2{\cdot}6H_2O$) were used as starting materials, and ammonia (NH_3) was added to make the solution pH level 10.5 which made it a stable place for the reaction to happen. Polyethylene glycol (PEG,2g) was utilized to prevent nanoparticle agglomeration and control particle size (Cheraghali, 2022). The reaction mixture was heated at 180 °C for 12 h in a hydrothermal reactor. After cooling, the nanoparticles were separated by a magnetic field, extensively washed with deionized water and ethanol, and finally dried at 80 °C for 24 h. A heat treatment at 600 °C for 6 h was conducted in order to enhance the crystallinity and magnetic properties (Fu and Liu, 2007; Hazra, 2015; Cheraghali, 2022). Figure 1 shows the schematic representation of the process of synthesis for the nanoparticles.

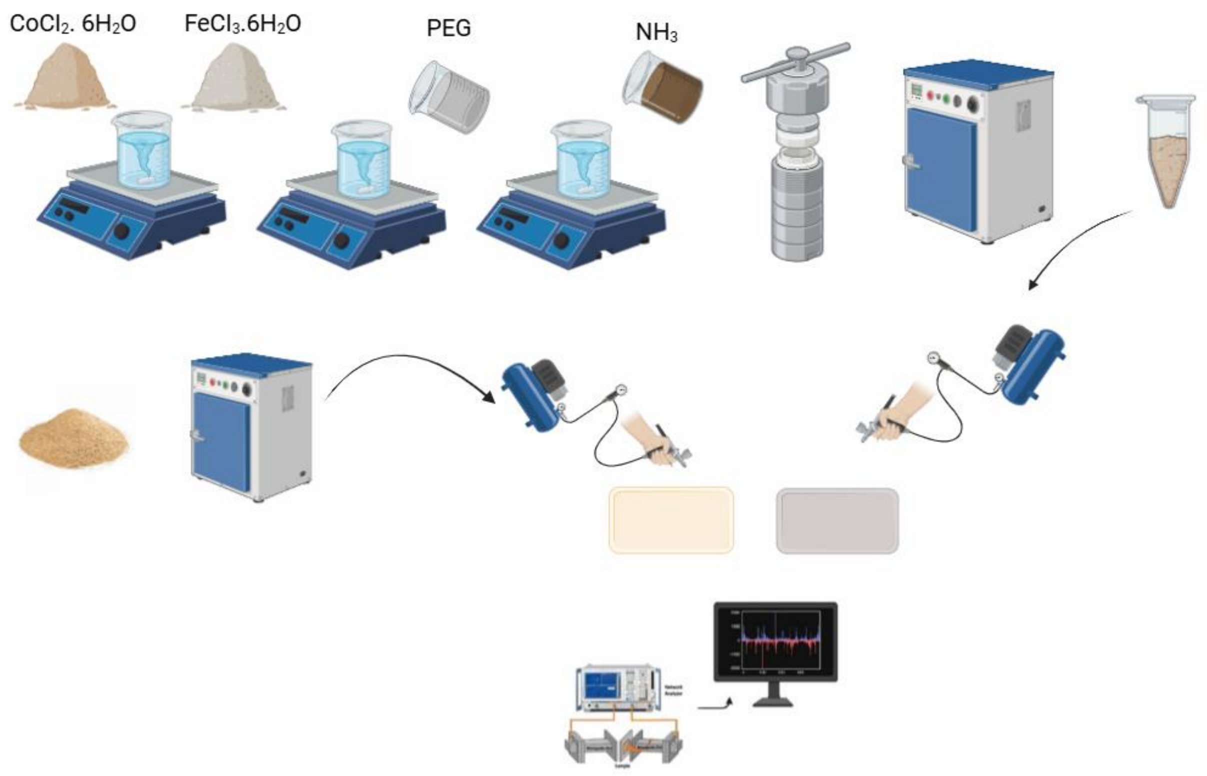

Figure 1. Schematic representation of the nanoparticle production method.

2.2. Structural Analysis of Samples

The synthesized $CoFe_2O_4$ nanoparticles have been characterized to determine the structural properties by using X-ray Diffraction (XRD) analysis. The experiment was conducted using a Bruker D8 Advanced Diffractometer using Cu Kα radiation having $\lambda = 0.15406$ nm. Diffraction patterns were obtained in the range of 2θ from 20° C to 80 ° C, and PCPDFWIN software was used for analysis. Cross-referencing of the obtained results with the JCPDS database confirmed the spinel structure. Crystallite size was estimated by using the Scherrer equation with a focus on the (311) reflection plane. Measurements were in the range from 10 to 50 nm, considering instrumental broadening and strain effects (Ren et al., 2015; Sahoo, 2015). SEM was performed to confirm both morphology and uniformity in particle size.

2.3. Magnetic Characterization

This work used a vibrating sample magnetometer (VSM) to study the magnetic properties of $CoFe_2O_4$ nanoparticles. Hysteresis loops representing magnetization (M) versus magnetic field (H) at room temperature over the range between -6,000 Oe and 6,000 Oe was registered. Important parameters, such as coercivity (H_C) and saturation magnetization (M_S), were analysed, revealing remarkable improvements after the annealing process.

2.4. Electromagnetic Shielding Effectiveness

A vector network analyser (VNA) was used to measure the shielding effectiveness (SE) of $CoFe_2O_4$ nanoparticles over a frequency range of 3.2–5.0 GHz. The scattering parameters, namely S_{11} and S_{21}, were used to determine reflection loss (SER), absorption loss (SEA), and multiple reflection loss (SEMR). $CoFe_2O_4$ nanoparticles were introduced in a composite paint system in three different weight concentrations: wt 5%, wt 10%, and wt 15%. Paint samples were applied on glass fiber composite substrates in order to investigate the shielding behaviour, which is mainly determined by absorption (Keskin et al., 2019; Ozturk and Chung, 2021; Ates et al., 2023; Paul et al., 2023). All coatings were systematically kept within a thickness of 1 μm to 6 μm to ensure optimum shielding effectiveness over the desired frequency range.

SE and its components can be estimated from scattering parameters using Equations (1) – (3) (Hong et al., 2023):

$$SE_R = -10\log(1-|S_{11}|^2) \tag{2.1}$$

$$SE_A = -10\log\left(\frac{|S_{21}|^2}{1-|S_{11}|^2}\right) \tag{2.2}$$

$$SE = SE_R + SE_A = -10\log(|S_{21}|^2) \tag{2.3}$$

2.5. Thermal Treatment and its Impact

Thermal treatment at 600 °C for 6 h was found to significantly improve the crystallinity and magnetic properties of $CoFe_2O_4$ nanoparticles. The process improved the atomic structure, reduced lattice imperfections, and increased the phase purity, as demonstrated by the sharper XRD peaks. Also, magnetic parameters, such as H_C and M_S improved drastically owing to better domain alignment and homogeneous distribution of ions (Hazra, 2015; Kakati et al., 2021). The effectiveness of $CoFe_2O_4$ in the applications of electromagnetic interference shielding and radar absorption depends on these characteristics.

2.6. Application and Integration Process of Cobalt Ferrite Nanoparticles

The present work examined the efficiency of a paint system made from Hempadur Easy 47700 primer and Hempathane Topcoat 55210 Ral 7001 as a shielding agent against electromagnetic fields. To enhance the radar absorbing characteristics, $CoFe_2O_4$ nanoparticles at three various weight concentrations (5 wt%) were incorporated into the paint. Radar-absorbing materials (RAMs) are very important in military applications, especially for stealth operation and technologies for EMI shielding (Hazra, 2015; Wang et al., 2020; Kakati et al., 2021; Tudose et al., 2022). The well-dispersed $CoFe_2O_4$ nanoparticles were firstly mixed into paint and then coated on glass fiber composite substrates. This led to the formation of three distinct sample groups, each corresponding to a specific nanoparticle concentration. The multi-layered paint formulation facilitated uniform nanoparticle distribution throughout the substrate, enhancing the absorption of electromagnetic waves. The coating thickness varied between 1 µm and 6 µm, designed to optimize electromagnetic shielding performance in the 3,2–5,0 GHz frequency range (Figure 2) (Wang et al., 2020; Tudose et al., 2022). Adding $CoFe_2O_4$ to the paint system made it easier to match the impedance and better at absorbing radar waves. This is because the nanoparticles and the composite matrix worked together to make the system work better. The properties underscore the material's suitability for advanced military and industrial electromagnetic shielding applications.

Figure 2. Paint Sample Containing $CoFe_2O_4$ Particles and Wood Shavings.

2.7. Preparation of Wood Shavings

The wood shavings utilized in this investigation were sourced directly from untreated natural wood through mechanical shaving methods. The initial step involved processing the raw wood to produce fine shavings, which were subsequently sieved to obtain a consistent particle size distribution within the range of 200–500 µm. The shavings underwent a comprehensive washing process using deionized water and ethanol to eliminate any dirt and organic contaminants, thereby ensuring their purity and compatibility with the composite system. Following the washing process, the shavings underwent drying in an oven set at 80 °C for a duration of 24 hours to ensure the removal of moisture. Finally, we rinsed the processed shavings, followed by a second drying phase, and stored them in airtight containers. This meticulous approach was taken to maintain their structural integrity and dielectric properties, thereby ensuring optimal performance within the composite paint system.

3. Results and Discussion

3.1 Crystallite Size Analysis of $CoFe_2O_4$ Nanoparticles Using XRD

X-ray Diffraction (XRD) analysis confirmed the spinel structure of the synthesized $CoFe_2O_4$ nanoparticles, as indicated by the characteristic (311) peak, which is a half mark of spinel ferrites (Figure 3). The crystallite size of $CoFe_2O_4$ was determined using the Scherrer equation:

$$D = \frac{K\lambda}{\beta cos\theta} \quad (3.1)$$

Where:

- D = Crystallite size,
- K = Shape factor (0.9),
- λ = X-ray wavelength (0.15406 nm for Cu Kα radiation),
- β = Full width at half maximum (FWHM) of the diffraction peak,
- θ = Bragg angle.

The analysis indicated that $CoFe_2O_4$ nanoparticles displayed a crystallite size ranging from 10 to 20 nm. The relatively small size is associated with broader XRD peak widths, suggesting an increased defect density and minor lattice strain. $CoFe_2O_4$'s properties make it better at coercivity and magnetic anisotropy, which means it can be used for moderate electromagnetic shielding tasks in the 3.2–5.0 GHz frequency range. The nanoscale size and spinel structure make it better at matching impedance and absorbing microwaves, even when there are lower concentrations in composite systems.

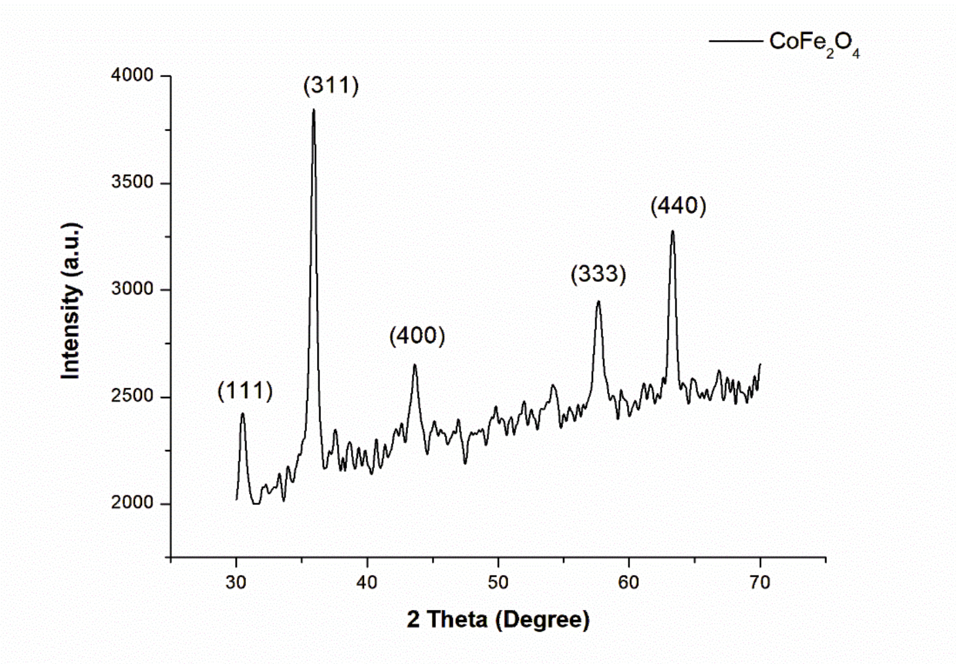

Figure 3. XRD analysis results of as-prepared $CoFe_2O_4$ samples synthesized with 2 g of PEG and at pH level 10.**5.**

The XRD pattern of $CoFe_2O_4$ nanoparticles demonstrates prominent diffraction peaks corresponding to specific crystallographic planes: (111), (311), (400), (333), and (440). The intense peak at (311) confirms the spinel structure of $CoFe_2O_4$, which is characteristic of ferrite materials. The presence of these planes indicates high crystallinity, with the (311) plane being the most dominant, suggesting a well-ordered crystal lattice. These reflections align well with the standard JCPDS data, affirming the successful synthesis of $CoFe_2O_4$ nanoparticles. The observed peaks also reflect the material's potential for applications requiring high magnetic and dielectric properties.

3.2. Morphological Analysis of $CoFe_2O_4$ Nanoparticles

Scanning Electron Microscopy (SEM) analysis provided detailed insights into the morphological characteristics of $CoFe_2O_4$ nanoparticles, complementing the XRD-derived crystallographic data. The SEM images (Figure 4) revealed that $CoFe_2O_4$ particles exhibited irregular shapes with significant porosity. These features are consistent with the calculated crystallite size range of 10–20 nm, as determined from XRD analysis.

The observed morphology is indicative of smaller, less aggregated nanoparticles, a result of controlled nucleation during the hydrothermal synthesis process and subsequent thermal treatment. The porous structure enhances the surface area, which can improve electromagnetic wave interaction and absorption efficiency. The irregular particle shapes and higher defect density further align with the broader diffraction peaks observed in the XRD patterns.

The SEM findings reinforce the suitability of $CoFe_2O_4$ nanoparticles for moderate EMI shielding applications, as their nanoscale dimensions and porosity contribute to better impedance matching and effective radar wave absorption within the 3.2–5.0 GHz frequency range.

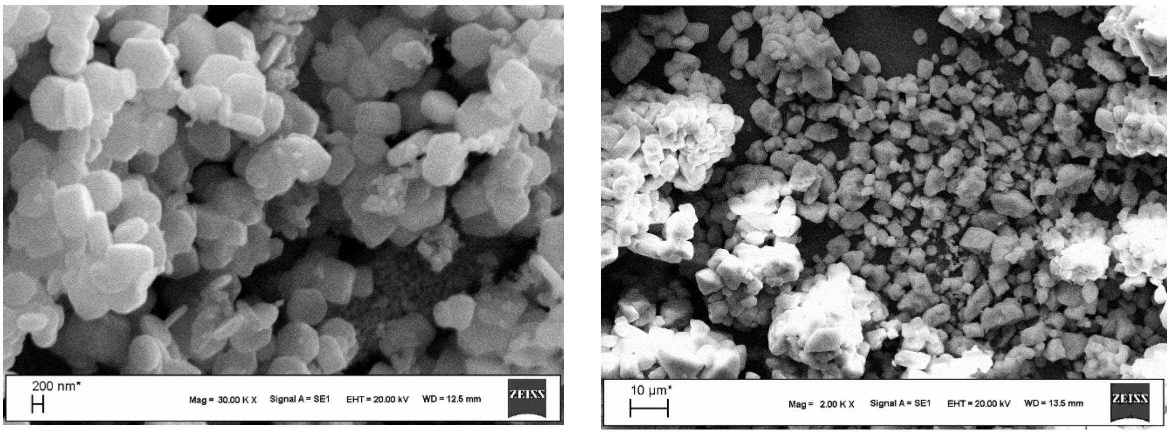

Figure 4. Analysis of SEM images of $CoFe_2O_4$ samples synthesized with 2 g of PEG and at pH level 10.5.

3.2.1 Absorption Shielding Effectiveness

The effectiveness of absorption shielding (SE) for the composite paint systems was assessed across the frequency range of 3.2–5.0 GHz (Figure 5). The hybrid paint system, comprising 5 wt% $CoFe_2O_4$ and 10 wt % wood shavings, reached maximum SE values of around 12 dB, surpassing the $CoFe_2O_4$-only system, which peaked at 10 dB. The wood shavings' porous structure and dielectric characteristics, which facilitate numerous internal reflections and wave scattering, are responsible for the improvement. The identified characteristics enhanced impedance matching and energy dissipation, leading to more effective electromagnetic wave absorption. The results validate the significant impact of wood shavings in facilitating increased absorption SE values via mechanisms like interfacial polarization and improved dielectric loss.

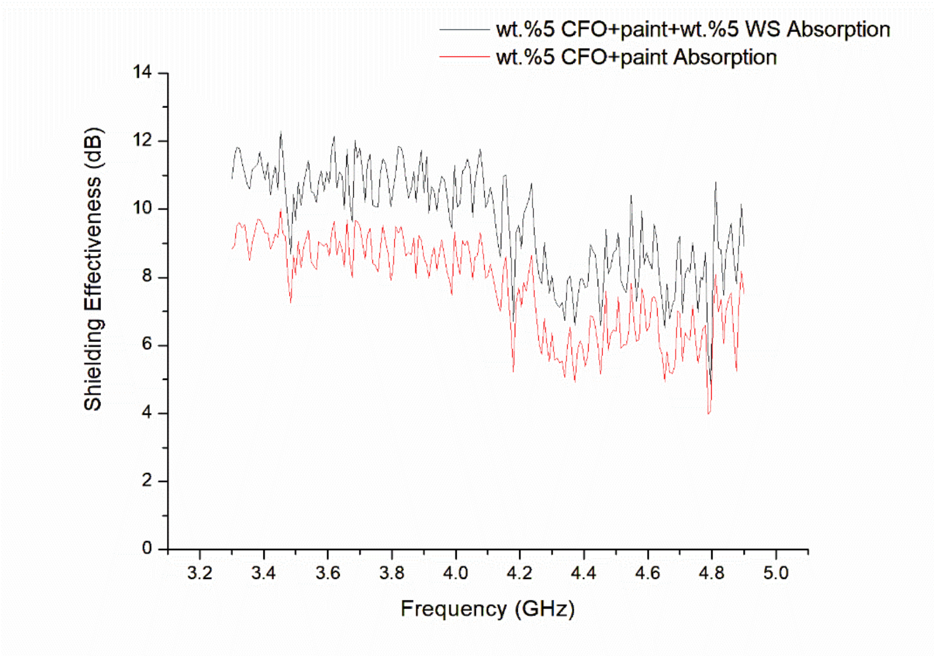

Figure 5. Absorption shielding effectiveness (SE) of composite paints within the 3.2–5.0 GHz frequency range, comparing systems with and without wood shavings.

3.2.2. Reflection Shielding Effectiveness

The analysis of reflection SE was conducted within the frequency range of 3.2–5.0 GHz, as illustrated in Figure 6. The addition of 10 wt% wood shavings to the paint system led to a notable decrease in reflective losses when compared to the system containing only $CoFe_2O_4$. The hybrid system demonstrated consistent reflection SE values, fluctuating between -1 dB and +1 dB, which suggests efficient wave penetration and reduced back-reflection. The $CoFe_2O_4$-only system had higher and more variable reflection SE values, with peaks reaching 2–3 dB. This suggests that it was less good at matching impedance and releasing energy. The porous and dielectric characteristics of wood shavings played a significant role in diminishing surface reflections, thereby improving the overall electromagnetic shielding effectiveness of the hybrid paint system.

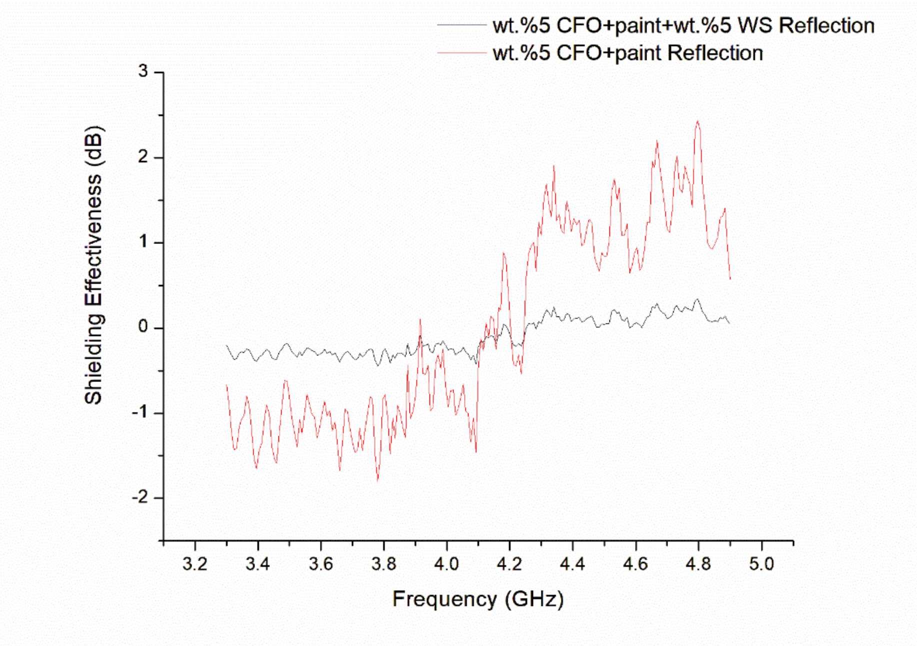

Figure 6. Reflection shielding effectiveness (SE) of composite paints within the 3.2–5.0 GHz frequency range, comparing systems with and without wood shavings.

3.2.3. Combined Absorption and Reflection Analysis

The combined study of absorption and reflection shielding effectiveness (Figures 5 and 6) shows clearly how adding 10 wt percent of wood shavings and 5 wt percent of $CoFe_2O_4$ to the composite paint system works effectively. In the frequency range of 3.2–5.0 GHz, the hybrid system exhibited enhanced performance, attaining higher absorption SE values (up to 12 dB) and notably lower reflection SE values (stabilizing between -1 dB and +1 dB). The findings also highlight how wood shavings can improve electromagnetic wave attenuation by utilizing mechanisms like wave scattering, internal reflections, and enhanced impedance matching. The $CoFe_2O_4$-system demonstrated effectiveness but showed limited absorption, peaking at 10 dB, along with increased reflection. This underscores the essential contribution of wood shavings in attaining a well-rounded shielding performance.

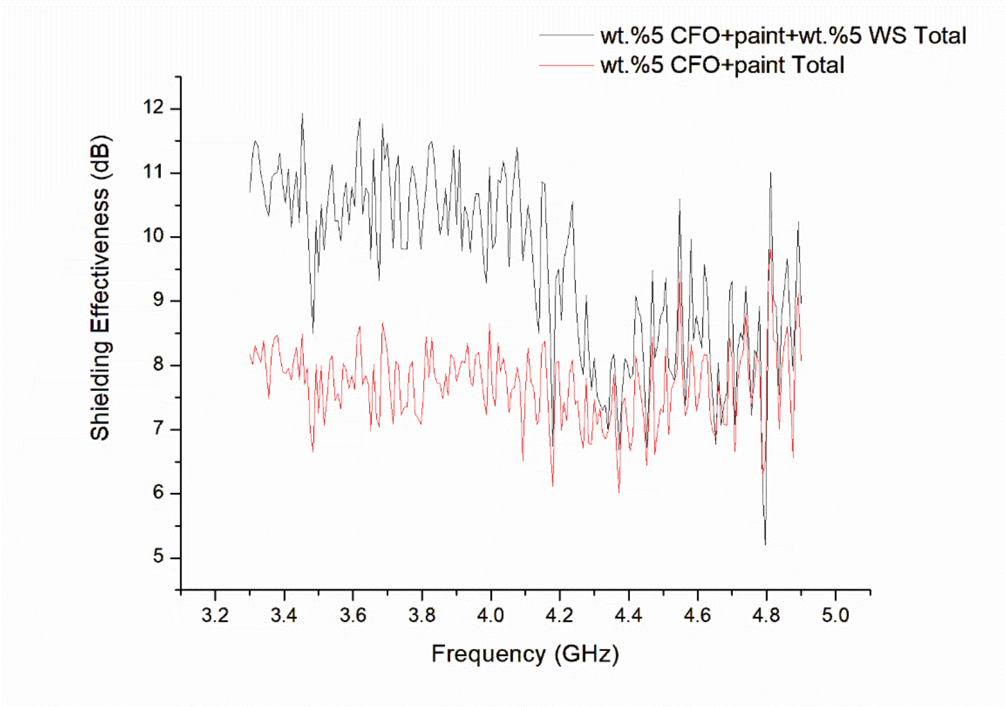

Figure 7. Combined analysis of absorption and reflection shielding effectiveness (SE) within the 3.2–5.0 GHz frequency range for hybrid and $CoFe_2O_4$- systems.

3.3. Magnetic Characteristics Enhance Structural and Morphological Examination

The VSM measurements (Figure 8) revealed significant differences in the magnetic properties of the ferrites. $CoFe_2O_4$ exhibited the highest H_C, attributed to its small crystallite size (10–20 nm) and irregular morphology, which increase magnetic anisotropy and domain wall pinning. These factors highlight the critical role of synthesis parameters in determining the magnetic, structural, and morphological properties of the materials. Such properties directly influence their effectiveness in EMI shielding and radar absorption applications, underlining the importance of precise control over synthesis conditions (Rajender et al., 2024).

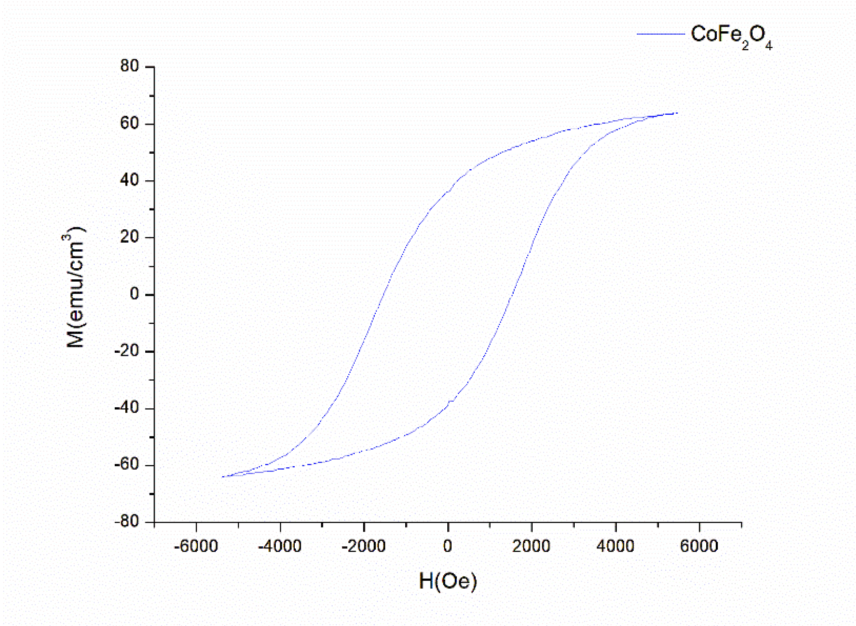

Figure 8. M-H hysteresis curves of ferrite samples: $CoFe_2O_4$

4. Conclusion

This investigation showcases the innovative incorporation of wood shavings into a $CoFe_2O_4$-based composite paint system aimed at improving electromagnetic interference shielding. The addition of 10 wt% wood shavings in combination with 5 wt% $CoFe_2O_4$ nanoparticles enhanced absorption shielding effectiveness (12 dB compared to 10 dB) and markedly decreased reflection losses. The improvements observed can be directly linked to the porous structure, dielectric characteristics, and scattering phenomena of the wood shavings, which work together with the magnetic properties of $CoFe_2O_4$ in a synergistic manner. The results highlight the sustainability and cost-effectiveness of wood shavings when used as a supplementary filler in advanced shielding materials. This combined method improves overall shielding effectiveness while also meeting the increasing need for sustainable and lightweight materials. Future investigations could examine the effectiveness of analogous systems across wider frequency ranges or in different environmental contexts, setting the stage for additional advancements in EMI shielding technologies.

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Conflict of Interest Declaration

The authors declare that there is no conflict of interest between them.

Summary of Researchers' Contribution Rate Declaration

The authors declare that they have contributed equally to the article.

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