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Review Article

Comparative Review of Metal Ferrites for Heavy Metals Adsorption in Water

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Abstract— Heavy metal contamination in water is one of the most critical environmental issues, posing direct threats to human health and ecosystems. Various methods have been developed to address this problem; however, adsorption remains the most effective technique due to its simplicity, low cost, and regenerability. In this context, ferrite based materials (MFe_2O_4) offer great potential as heavy metal adsorbents owing to their combined advantages of magnetic properties, chemical stability, large surface area, and easy separation under an external magnetic field. This review paper provides a systematic comparison of various types of metal ferrites (Ni, Mn, Co, Zn, Mg, Cu, and Nd) applied for the removal of heavy metal ions from water. The comparison covers their crystal structures, morphology, surface area, magnetic properties, adsorption capacity, as well as the isotherm models and kinetics underlying the adsorption process. The findings show that each type of ferrite possesses specific advantages and limitations. $NiFe_2O_4$ exhibits high structural stability, $MgFe_2O_4$ demonstrates high adsorption capacity but is susceptible to dissolution under acidic conditions, $CuFe_2O_4$ exhibits strong chemical affinity, and $NdFe_2O_4$ shows potential selectivity toward specific ions. Meanwhile, $MnFe_2O_4$ and $CoFe_2O_4$, particularly in composite forms such as $MnFe_2O_4$/biochar and $CoFe_2O_4$/FAU, stand out with adsorption capacities exceeding 400 mg/g, sufficient magnetic properties, and easy magnetic separation, making them the most promising candidates for water treatment applications. This paper provides a comprehensive understanding of the structure property function relationship of metal ferrites as selective, stable, and efficient adsorbent materials for heavy metal remediation in aquatic environments.

Keywords— *Adsorption; Heavy metal; Metal ferrites; Water treatment; Magnetic.*

1. INTRODUCTION

Water is universally recognized as an essential element that supports life for all organisms on earth and is the foundation of living things [1]. However, with advances in science and industrialization, the positive impacts achieved are often accompanied by negative consequences for the environment and human health. Issues related to water quality are a major concern, especially since water is a vital resource for survival. One of the most pressing issues is the presence of heavy metal ions as harmful contaminants when accumulated in water bodies [2]. Rapid industrialization and increasing human needs have driven a surge in global production of various products containing heavy metals. As a result, emissions of industrial wastewater laden with toxic metal ions, such as Pb(II), Cu(II), Cd(II), Cr(VI), and As(V), have increased, posing serious risks to aquatic ecosystems and human health [3].

Various methods have been developed to address heavy metal pollution, including chemical precipitation, ion exchange, fractional crystallization, solvent extraction, and adsorption. However, among these methods, adsorption is considered one of the most effective approaches because it is simple, relatively low cost, environmentally friendly, and allows for regenerating the adsorbent. Nevertheless, the use of conventional adsorbents such as activated carbon,

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zeolite, and clay still has limitations, particularly in terms of adsorption capacity, selectivity, and stability under complex operating conditions.

In this case, ferrite-based materials (MFe_2O_4) are of interest due to their unique properties. Ferrite is a metal oxide with a spinel structure that exhibits an attractive combination of magnetic properties, chemical stability, and specific surface area that supports the adsorption process [4]. An additional advantage is that its magnetic properties facilitate the separation of materials from liquid media with the help of an external magnetic field, making it highly potential for applications in the treatment of contaminants in water. Various synthesis methods have been used to produce ferrite, such as sol-gel, hydrothermal, and co-precipitation, but the co-precipitation method stands out due to its simplicity, low cost, and ability to produce particles with nano size and homogeneous distribution. Synthesis conditions such as pH, temperature, and aging time can affect the chemical and physical properties of the resulting ferrite material, thereby impacting its adsorption performance [5].

Transition metals (such as Mg, Zn, Mn, Co, and Ni) and rare earth metals (such as Nd) are two groups of metals that are widely used in ferrite synthesis. Transition metal-based ferrites generally have high magnetization and considerable adsorption capacity, while rare earth metal-based ferrites are known to have structural stability and potential selectivity towards certain ions [6]. However, despite the growing body of research on ferrite-based adsorbents, existing review asrticles generally focus on specific ferrite compositions, individual metal ions, or isolated performance indicators. Systematic comparative reviews that simultaneously evaluate transition metal ferrites and rare-earth fferrites synthesized using the same preparation route particularly the co-precipitation method and assessed for heavy metal adsorption under comparable conditions remain limited. Consequently, this study aims to provide a structured comparative overview of the chemical, structural, and magnetic properties of metal-based ferrites, with particular emphasis on their adsorption performance toward heavy metal ions. By correlating morphology, surface characteristics, and functional behavior, this review seeks to clarify key structure property function relationships and to offer insight that may support the rational design of ferrite-based adsorbents for water treatment applications.

This study employed a systematic literature review approach. Literature searches were conducted across four major databases, including SINTA, Scopus, ScienceDirect, and SpringerLink, using keywords related to spinel ferrites, co-precipitation synthesis, magnetic properties, and heavy metal adsorption. Eligible studies were limited to peer-reviewed journal articles published between 2015 and 2025 that explicitly reported the synthesis of spinel ferrites via the co-precipitation method and their application in the adsorption of heavy metal ions from aqueous media. Only studies involving ferrites based on Ni, Mn, Co, Zn, Mg, Cu, and Nd and providing quantitative adsorption and/or magnetic performance data were included. Review articles, conference papers, studies employing other synthesis routes, and reports lacking adsorption data were excluded. Article selection was carried out through a two-stage screening process consisting of tittle abstract evaluation followed by full-text assessment based on predefined criteria. Relevant data, including ferrite composition, structural and surface characteristics, magnetic parameters, adsorption capacity, and esperimental conditions, were systematically extracted and comparatively analyzed to elucidate strusture property performance relationships. In addition, bibliometric analysis using VOSviewer version 1.6.20 was performed to map research trends and thematic linkages related to ferrite-based adsorbent.

2. BIBLIOMETRIC INSIGHTS ON METAL FERRITE RESEARCH FOR HEAVY METAL ADSORPTION

Bibliometric analysis serves as an essential approach in review based research, as ot enables a comprehensive mapping of the scientific landscape, including thematic trends, research focuses, and the evolutionary direction of a specific field. In the context of ferrite materials for heavy metal adsorption in water, this analysis plays a crucial role in identifying dominant research topics, interconnections among key concepts, and existing scientific gaps that warrant further investigation. The VOSviewer based visualization employed in this study provides an extensive overview of how concepts such as spinel structure, adsorption mechanisms, composite modification, and environmental applications are interrelated with the effectiveness of ferrite materials in heavy metal remediation. The resulting visualization map reveals sveral major research clusters, distinguished by node colors, sizes, and connection intensities. The node size represents the frequency of keyword occurrences in the literature, whereas the linkages illustrate the conceptual relationship among research topics.

Based on **Figure 1**, which is the result of bibliometric analysis using VOSviewer 1.6.20 which illustrates the thematic relationshop between keywords in publications related to the use of metal ferrite in heavy metal adsorption processes. In Figure 1a, the formed cluster network shows a close conceptual relationshop between terms such as “spinel ferrite”, “composite”, “oxide”, “adsorption mechanism”, and “heavy metal removal”. The blue cluster focuses on fundamental concepts such as “spinel ferrite”, “oxide”, and “magnetite” which reflect the research focus on the crystal structure and basic composition of ferrite materials. This cluster is the foundation in understanding how the distribution of cations and spinel structure affect surface properties, stability, and adsorption behavior. The green cluster highlights the topics of “adsorption mechanism”, “isotherm”, and “affinity” which are directly related to understanding the interaction mechanism between heavy metals and ferrite surfaces, including complex formation, ion exchange, and surface area squeezing. Meanwhile, the red cluster refers to the applicative aspects such as

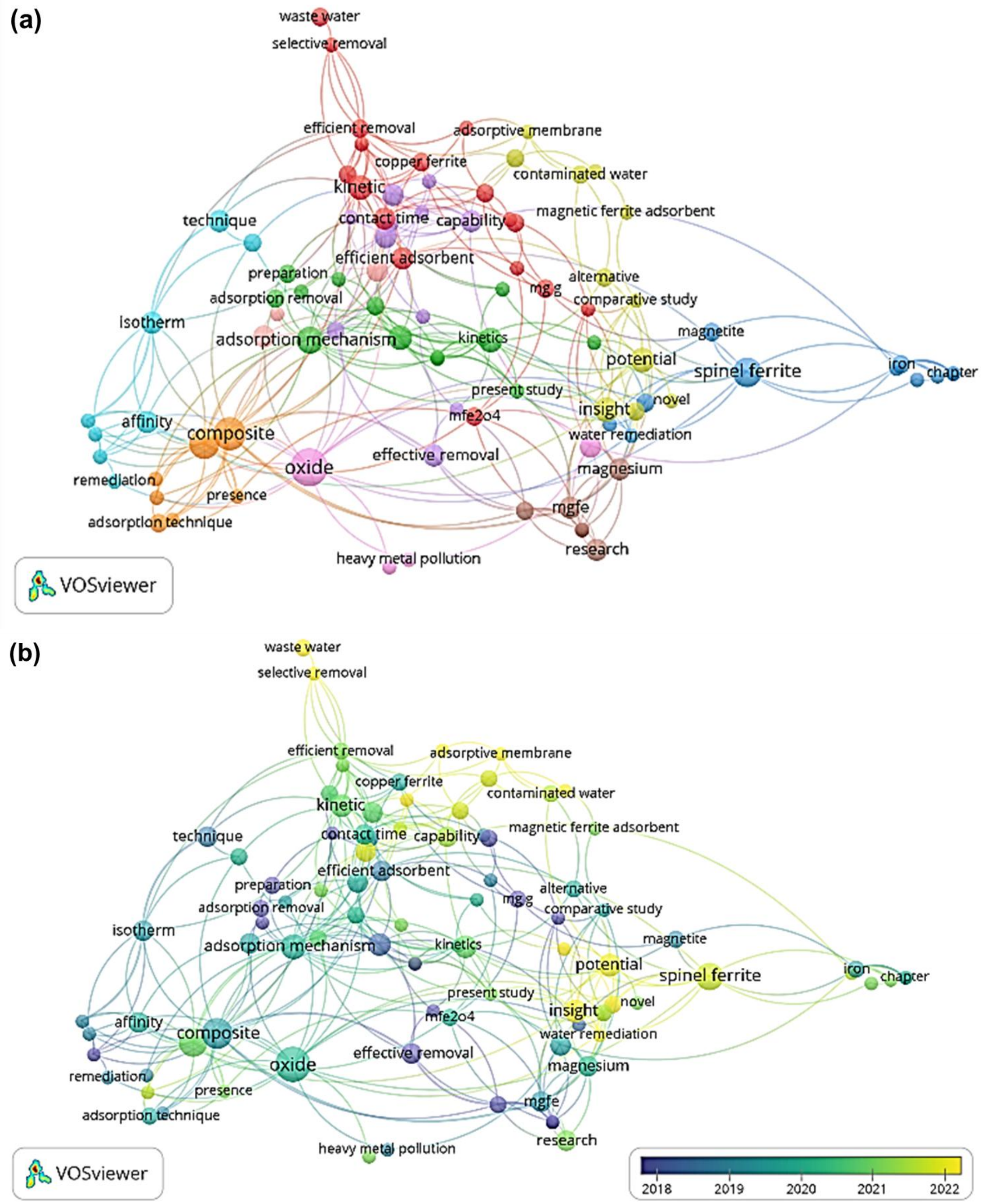

Figure 1. Visualization map of the use of metal ferrite for heavy metal adsorption

"kinetics", "efficient adsorbent", and "contact time" which indicates that the study has progressed from mere material synthesis to practical optimization of adsorption performance.

One of the dominant themes emerging in the visualization map is the keywords "composite," "oxide," and "magnesium," indicating increasing attention to the development of ferrite based composites. This trend reflects the need to improve adsorption performance through material modification, either by adding carbon (e.g., biochar or graphene oxide) or by doping with other metals such as Mg^{2+}, Zn^{2+}, and Cu^{2+}. Ferrite composites have been shown to increase specific surface area, reduce agglomeration, and provide more active sites for interaction with heavy metal ions [7]. Furthermore, the association of keywords such as "adsorptive membrane" and "efficient removal" indicates that material development is not limited to nanoparticle powders but is also directed towards integration into membrane systems or filtration media for large-scale applications. Keywords such as "isotherm," "Langmuir," "Freundlich," "PSO," and "PFO" indicate that research has extensively explored adsorption mechanisms using modeling approaches to understand ion interaction behavior. Isotherm models help predict the maximum capacity and surface type of adsorbents, while kinetic models provide insight into the binding rate and mechanism. The association of terms such as "contact time" and "kinetic" suggests that optimizing contact time is a crucial parameter for achieving high heavy metal removal efficiency. Furthermore, the presence of keywords such as "efficient adsorbent" and "capability" underscores the importance of in depth characterization to quantitatively link material structure to adsorption performance.

Furthermore, based on **Figure 1b**, it shows a visualization overlay based on the year of publication that shows the development of research topics from 2018 to 2022. Before 2019, which is shown in bluish color, represents research topics in the early period that focused mostly on “magnetite”, “iron oxide”, and “adsorption removal” which focused on basic materials and understanding the principles of adsorption. Meanwhile, after 2020, which is shown in greenish to yellowish color, depicts newer and developing topics such as “composite ferrite”, “efficient adsorbent”, “magnesium ferrite”, “water remediation”, and “selective removal”. This indicates a shift in research direction from merely exploring basic materials to developing functionalized ferrite composites that are more efficient, selective, and environmentally friendly. Recent trends also show an increasing interest in magnetic ferrite adsorbents and novel composite systems that aim to increase selectivity to specific ions and regeneration efficiency. In addition, the emergence of terms such as “comparative study” and “potential” indicates that research is now not only focused on one type of ferrite but also comparing various metal variations to determine the material with optimal performance.

Overall, the mapping results indicate that research on ferrites for heavy metal adsorption has evolved in a multidisciplinary direction, involving a combination of structural aspects, surface chemistry, and magnetic properties. Recent trends also show a great interest in rare earth ferrites and bimetallic ferrite systems, which are associated with increased selectivity toward specific metal ions and ease of adsorbent regeneration. As a follow up to the thematic analysis, the following discussion will focus on the structural characteristics and surface properties of various types of metal ferrites reported in the literature.

3. STRUCTURAL AND SURFACE PROPERTIES

Metal ferrite-based adsorbent materials have attracted widespread attention in the last decade due to their unique combination of magnetic properties, chemical stability, and spinel structure flexibility. The basic structure of ferrite consists of metal cations distributed in octahedral and tetrahedral sites in the oxide lattice, providing high thermal and chemical stability [8]. The main advantage of ferrite over conventional adsorbent materials such as activated carbon or zeolite is its ability to be easily separated from liquid media using an external magnetic field, making it highly efficient in separation and regeneration processes [9]. This makes ferrite highly promising for environmental remediation applications, particularly in the treatment of water systems containing heavy metals. In heavy metal ion adsorption, ferrite has two main mechanisms, namely physical interaction through high porosity and surface area, and chemical interaction through active metal oxide groups on the surface [10]. These two mechanisms can be combined well due to the spinel ferrite properties that allow cationic engineering.

Variations in transition metals such as Ni, Mn, Co, Zn, Mg, and Cu, as well as rare earth metal doping such as Nd, provide great opportunities to regulate surface properties, particle size distribution, and active site density. This allows the adsorption performance of ferrite to be specifically tailored to target metal ions, such as Cr(VI), Pb(II), Cd(II), or economically valuable rare earth metal ions. Recent developments in ferrite adsorbent material design also emphasize modification and hybrid composites. For example, combining ferrite with biochar, rGO, zeolite, or chitosan polymer has been shown to increase surface area, add diversity to adsorption sites, and improve particle dispersion to prevent agglomeration [7]. Additionally, cationic substitution (e.g., Mg, Ca, Zn, or Co replacing some Ni or Mn ions in ferrite) has been shown to increase structural heterogeneity and enrich active surface properties. These modifications not only enhance adsorption capacity but also contribute to strengthening mechanical stability and material regeneration [11].

Based on the data in **Table 1**, each type of ferrite shows significant differences in terms of crystal structure, particle morphology, and specific surface area. The crystal structure of ferrite is basically dominated by the cubic spinel phase, both in the normal spinel and inverse spinel forms. Variations in the composition of transition metals (Ni, Mn, Co, Zn, Mg, Cu) and rare earth metals (Nd) affect the distribution of cations in octahedral and tetrahedral sites, which ultimately determine the morphological properties, surface area, and functional properties [29]. For example, Ni and Nd based ferrite metals tend to have an inverse spinel structure that contributes to crystal stability and homogeneous particle distribution, while Mn, Co, Zn, Mg, and Cu-based ferrite metals are generally in the normal cubic spinel phase with a more varied particle size distribution. These variations not only have implications for structural stability, but also for surface chemical properties that are directly related to adsorption applications. From a morphological perspective, ferrite particles are influenced by several synthesis parameters such as temperature, pH, precursor type, and the presence of templating agents, which have a major influence on the development of the resulting ferrite morphology [37].

Nickel based ferrite ($NiFe_2O_4$) is consistently reported to have an inverse cubic spinel structure that provides lattice stability and distribution of Ni^{2+}/Fe^{3+} cations between tetrahedral and octahedral sites. The morphology of $NiFe_2O_4$ is described as irregular spherical particles that tend to form porous aggregates

Table 1. Comparison of structural and surface properties of metal ferrites

Metal Ferrite	XRD Structure	Surface Area (m^2/g)	General Morphology	Refs
$NiFe_2O_4$	Invers Spinel Cubic	-	Irregular spherical particles form a porous aggregate with a homogeneous distribution	[12]
NiFe $Mg_{0.10}NiFe$ $Ca_{0.10}NiFe$	Cubic Spinel	16.452 to 2.525	Round in shape, dense with uniform distribution and undergoing aggregation. Decrease in crystal size due to the addition of divalent metal ions (Mg, Ca) to NiFe	[13]
rGONF	Invers Spinel	167.26	The surface is homogeneous	[14]
$MnFe_2O_4$	Cubic Spinel	84.5	Relatively larger particles and less aggrlomeration	[15]
CMFO	Spinel	-	Particles agglomerate on the surface of chitosan and heterogen	[16]
$MnFe_2O_4$/biochar	Single Phase Cubic Spinel	180.2	Morphology is non homogeneous and irregular with clumped and densely packed particles	[17]
$MnFe_2O_4$@alunite	Spinel	-	The particle size distribution is heterogeneous and there are several pores in its structure	[18]
PVP@$MnFe_2O_4$		-	In the form of round granules that clump together and have irregular shapes	[19]
$Mn_{0.6}Zn_{0.4}Fe_2O_4$	Cubic Spinel	-	-	[20]
$ZnFe_2O_4$ NPs	Cubic Spinel	-	An irregular and highly agglomerated microstructure with open porosity at low temperatures, while at high temperatures it exhibits a homogeneous microstructure with a regular cubic crystal form	[21]
$ZnFe_2O_4$/Zeolite	Cubic Spinel	31	Flat prismatic crystal particles with easily distinguishable facets and low agglomeration	[22]
$CoFe_2O_4$	Cubic Spinel	50.4	Relatively smaller particles tend to form denser and more porous aggregates	[15]
$CoFe_2O_4$@SiO_2-NH_2	Cubic Spinel	44.7	Crystalline in shape with concentric diffraction rings included in the spinel crystal structure	[23]
$CoFe_2O_4$ are distributed on FAU surface	Cubic Spinel	434.4	Having a homogeneous size and morphology	[24]
$Co(Cr_{0.25}Fe_{0.75})_2O_4$	Cubic Spinel	23.258	Polyhedral particles and small agglomeration size	[25]
$Co_{0.4}Zn_{0.6}Fe_2O_4$	Cubic Spinel	-	Good particle crystallinity, non-uniform particle distribution	[26]
$(Co_{0.7}Zn_{0.3})_{0.9}Ni_{0.1}Fe_2O_4$	Cubic Spinel	-	Formed in a single phase and has dislocation density	[27]
$CoFe_2O_4$@OA MNPs	Cubic Spinel	-	There is uncontrolled aggregation, wrinkled and porous surfaces	[28]
CMF@MF-CB	Cubic Spinel	17.653	Shaped like round grains, the structure consists of several stacked layers	[29]
RGCF	Cubic Spinel	-	Small aggregation	[7]
$MgFe_2O_4$ ($MF_{0.33}$)	Cubic Spinel	200.36	Formed of small particles that aggregate together	[30]
$MgFe_2O_4$-NH_2	Spinel	-	Crystalline granules with slight agglomeration and bimodal distribution	[31]
$Mg_{0.2}Zn_{0.8}Fe_2O_4$	Spinel	-	Agglomerated, porous particles with a homogeneous surface	[32]
B-MgFe-BC	Spinel	151.319	Aggregation is complexly bound to the biochar surface, smaller in size than MgFe-AC	[33]
MgFe-AC		91.375	Agglomeration occured, particle size is larger	
FAU:$MgFe_2O_4$ (3:1)	Spinel	400	Has smaller particles than $MgFe_2O_4$	[34]
$Cu_{0.5}Mg_{0.5}Fe_2O_4$	Cubic Spinel	41.3	Has a cube shape	[35]
$NdFe_2O_4$	Invers Cubic Spinel	-	Tend to aggregate into clusters with regular crystal structure	[36]

with homogeneous distribution; this supports the existence of sufficient physical sites for the adsorption process but is often accompanied by a relatively low intrinsic surface area [13]. The surface area of pure $NiFe_2O_4$ particles is generally reported by Kumari et al. (2023) to have a low value (< 20 m^2/g), but composite modification provides a significant increase. For example, $NiFe_2O_4$ doped with reduced graphene oxide (rGO) is a highly effective strategy, as it increases the surface area to 167.26 m^2/g [14]. The addition of carbon coated conductive phase (rGO) not only increases the surface area and number of active adsorption sites, but also provides oxygen functional groups on the surface of ferrite materials that strengthen complexation interactions with target ions [14]. Nickel based ferrite has structural stability and easy magnetic recovery, but the adsorption capacity of pure nickel ferrite without modification is limited, and its magnetic properties may decrease when the non-magnetic phase is increased. Therefore, optimization of the composite fraction is necessary to maintain a balance between adsorption capacity and magnetic separation.

Conversely, manganse based ferrite ($MnFe_2O_4$) stands out due to its tendency to produce relatively larger particles with lower agglomeration under certain synthesis conditions and a reported higher surface area compared to some pure $NiFe_2O_4$ [15]. Research by Jung et al. (2018) reported that $MnFe_2O_4$ has a morphology that varies from quasi-spherical particles to dense aggregates. Modification with biochar ($MnFe_2O_4$/biochar) increased the surface area to 180.2 m²/g from the pure $MnFe_2O_4$, which had a surface area of 84.5 m²/g. This indicates that porous substrates are highly effective in preventing agglomeration, stabilizing nanoparticle dispersion, and increasing the number of active sites on the surface. The presence of Mn^{2+} in the lattice affects Fe-O bonds and surface charge distribution, thereby lowering the neutral charge point on the surface or changing the surface acidity value. This is relevant because it determines the species of metal adsorbate that interacts. Modification of $MnFe_2O_4$ with biochar, alunite, and PVP can increase both macro and micro porosity, which accelerates mass diffusion and provides oxygen or carboxylate groups that can act as additional electron donors for metal complexation [18]. The advantage of $MnFe_2O_4$ lies in its good surface area and compatibility with the carbon matrix, giving it superior adsorption capacity. However, its magnetic properties will decrease when the fraction or doping material that does not have magnetic properties is increased.

Zinc based ferrite ($ZnFe_2O_4$) generally has a normal cubic spinel structure. Zinc-based ferrite exhibits behavior that is highly influenced by thermal conditions during the synthesis process. At low temperatures, a random, irregular microstructure with effective open porosity for physical adsorption is formed, while at high temperatures, recrystallization occurs toward homogeneous cubic crystals, which reduces porosity but increases structural stability [4]. Based on data by Tomina et al., (2023) shows that $ZnFe_2O_4$ composites with zeolite produce a surface area of 31 m²/g with a flat prismatic crystal morphology and low agglomeration levels. This is advantageous for applications that require stability and selectivity towards large ions such as Pb^{2+}. In $ZnFe_2O_4$, Zn^{2+} ions tend to occupy tetrahedral sites, which affects the number of oxygen vacancies and surface acidity. These surface conditions can influence the tendency for inner sphere complex formation versus electrostatic retention. The advantages of $ZnFe_2O_4$ are its high structural stability and the ease of obtaining controlled morphology through temperature variation, while its disadvantage lies in its generally more moderate adsorption capacity unless it is applied to porous material doping or equipped with additional surface functions.

Cobalt-based ferrite ($CoFe_2O_4$) exhibits different characteristics, with smaller particles that tend to aggregate tightly to form a dense porous structure. The surface area of pure $CoFe_2O_4$ is around 50.4 m²/g [15], but this value can increase dramatically when pure $CoFe_2O_4$ particles are placed on a porous substrate such as FAU zeolite, reaching up to 434.4 m²/g [24]. Modification of cobalt ferrite, such as functionalization with amines ($-NH_2$) on the SiO_2 layer, can add effective nitrogen sites that form strong coordination with target metal ions, thereby increasing selectivity in a specific pH range [23]. Cobalt-based metal ferrites have magnetic strength that facilitates post adsorption separation and have the potential for high adsorption capacity when modified on porous materials. However, they have a tendency to agglomerate and risk reducing the accessibility of active sites and decreasing adsorption capacity if coated with organic materials that cause the surface to become hydrophobic. Therefore, modifications to $CoFe_2O_4$ must consider the balance between increasing surface area and maintaining the accessibility of hydrophilic active sites, as well as magnetic stability for separation.

Furthermore, manganese based ferrite ($MgFe_2O_4$) tends to exhibit a very high surface area. In $MgFe_2O_4$ ($MF_{0.33}$), it is reported to be 200.36 m²/g, and in the FAU: $MgFe_2O_4$ composite, it reaches 400 m²/g [30],[34]. This indicates the important role of Mg^{2+} in modulating porosity when synthesized in combination with doping or a substrate. This material has different characteristics because Mg^{2+} ions are small ionic in size, causing lattice distortion and implying an increase in micro/nano pores and heterogeneous distribution of active sites. The basic structure of manganese ferrite remains cubic spinel with a partial inverse tendency where some Mg^{2+} enters the octahedral site [30]. In its application as an adsorbent material, the combination of high porosity and abundant active site distribution supports high adsorption capacity and good kinetic access for heavy metal ions. However, the disadvantage of $MgFe_2O_4$ is that, under strong acidic conditions, Mg^{2+} ions have the potential to dissolve from the ferrite structure, thereby reducing the stability of the material and causing additional contamination in the water. In addition, the performance of $MgFe_2O_4$ needs to be tested over the long term, especially in repeated adsorption desorption cycles, to ensure that the material does not degrade quickly [38].

Copper based ferrite ($CuFe_2O_4$) exhibits unique characteristics derived from the presence of Cu^{2+} ions in its spinel strusture. Cu^{2+} ions in octahedral positions often undergo Jahn Teller distortion, which causes a change in the basic shape from ideal cubic to tetragonal deviation. This distortion has direct implications for particle morphology and surface properties, as it can result in heterogeneity in the adsorption energy distribution [35]. Based on the data, it shows that sopper ferrite doped with other metals such as $Cu_{0.5}Mg_{0.5}Fe_2O_4$, reports a cubic particle morphology with a surface area of approximately 41.3 m²/g [35]. Although this surface area value is not particularly high, the presence of Cu^{2+} provides the advantage of increasing the density of active sites that tend to interact strongly with heavy metal ions. The dominant mechanism can be partial ion exchange or complex formation. The main advantage of $CuFe_2O_4$ lies in its ability to form strong complex bonds with target metal ions, making it effective for use in low concentration conditions often found in actual wastewater. However, its weaknesses cannot be ignored. Lattice distortion due to Jahn Teller effects has the potential to increase the tendency of particles to agglomerate, thereby reducing the number of exposed active sites. In addition, this structural deformation can reduce the cyclic stability of the material during repeated adsorption-desorption processes, which ultimately limits the service life of the adsorbent.

Finally, neodymium-based ferrite ($NdFe_2O_4$), which belongs to the rare-earth ferrite group, has different structural and surface characteristics compared to transition metal-based ferrite. This difference is mainly due to the presence of +3 charged Nd^{3+} ions with highly localized 4f orbitals, which can affect lattice stress and crystal structure stability. Morphologically, this material is generally composed of spherical nanoparticles that tend to aggregate into clusters with a certain degree of crystalline order [36]. However, quantitative data on the specific surface area of $NdFe_2O_4$ is still very limited, making it difficult to comprehensively compare it numerically with other ferrites. The presence of Nd^{3+} has the potential to cause local distortion in the lattice and modify the point of zero charge (pH_{pzc}) value. This will affect the interaction of the material with highly charged ions. The main potential advantage of $NdFe_2O_4$ lies in its specific affinity for certain heavy metal ions, which is thought to be influenced by the contribution of 4f orbitals in the coordination process. However, a notable disadvantage is the possibility of Nd^{3+} ion leaching into the medium and a reduction in magnetic site density due to Nd^{3+} substitution, which in turn can reduce adsorption performance and regeneration cycle stability.

Based on a comparison of the structural and surface properties of various ferrite materials (Ni, Mn, Co, Zn, Mg, Cu, and Nd), it can be seen that each type of ferrite has specific advantages rooted in the distribution of cations in the spinel structure and the influence of its morphology and specific surface area. $NiFe_2O_4$ has high crystal stability with homogeneous morphology, but its adsorption capacity is limited unless modified with conductive carbon materials such as rGO, which can increase its surface area. $MnFe_2O_4$ naturally excels in surface area, which is around 84.5 m^2/g, and shows a significant increase when composited with biochar to around 180.2 m^2/g, making it a very potential candidate for heavy metal adsorption applications due to its combination of high porosity and compatibility with carbonaceous materials. $CoFe_2O_4$ exhibits outstanding performance in terms of surface area enhancement through integration with porous materials, reaching approximately 434.4 m^2/g in $CoFe_2O_4$@FAU material, which theoretically provides the most abundant active sites and the best metal ion diffusion access. Meanwhile, $ZnFe_2O_4$ and $MgFe_2O_4$ demonstrate the important role of synthesis and doping parameters. $ZnFe_2O_4$ exhibits high structural stability despite its relatively low surface area, while $MgFe_2O_4$ stands out with a very large surface area in the range of 200-400 m^2/g, making it one of the most promising candidates in terms of adsorption capacity. $CuFe_2O_4$, despite its relatively low surface area, is a ferrite material with the unique feature of Jahn Teller distortion, which enhances interactions with certain metal cations. On the other hand, $NdFe_2O_4$ is still relatively unexplored quantitatively, but its potential lies in the rare earth dopant effect, which can modify lattice tension, surface acidity, and magnetic strength for adsorption selectivity. Overall, when considering the balance between specific surface area, accessibility of active sites, structural stability, and magnetic properties, the $CoFe_2O_4$@FAU and $MnFe_2O_4$/biochar-based systems can be considered the most promising materials. Both not only offer high adsorption capacity through abundant porosity but also retain magnetic properties that enable rapid separation after the adsorption process, making them relevant and applicable for water treatment systems.

4. MAGNETIC AND ADSORPTION PROPERTIES

Understanding the magnetic properties and adsorption performance of ferrite-based materials is crucial in determining their potential applications in water treatment, especially heavy metal pollution. The role of ferrite-based materials in their application as heavy metal adsorbents is not only determined by their structural and morphological properties, but also greatly influenced by their magnetic characteristics. The unique magnetic properties of ferrite allow this material to not only act as an adsorbent with an active surface area, but also facilitate a rapid and efficient separation process after adsorption through an external magnetic field, which is a major advantage of ferrite over conventional adsorbents [20]. In addition, this magnetic property is determined by the distribution of cations at tetrahedral and octahedral sites in the spinel structure. The presence of transition metal ions such as Ni^{2+}, Mn^{2+}, Co^{2+}, Zn^{2+}, Mg^{2+}, Cu^{2+}, and rare earth metal ions Nd^{3+} produces different superexchange interactions between sites, resulting in variations in magnetic moment, coercivity, and saturation magnetization (Ms) [39]. On the other hand, adsorption performance is influenced by surface area, crystal size, crystal properties, and the distribution of active sites that enable interaction with metal ions through electrostatic mechanisms, ion exchange, or complex formation. Therefore, an integrated analysis of magnetic aspects and adsorption capacity is the basis for assessing the effectiveness of ferrite materials in their practical and sustainable application for water treatment.

Ferrites with different transition metal compositions exhibit significant variations in magnetic properties. $NiFe_2O_4$, for example, has a relatively high saturation magnetization value, allowing for efficient separation, but its adsorption capacity is relatively limited without surface modification [40]. $MnFe_2O_4$ and $CoFe_2O_4$, on the other hand, stand out in terms of the combination of magnetic properties and adsorption capacity, especially after being composited with porous materials such as biochar or zeolite, which increase the number of active sites while maintaining their magnetic properties. Meanwhile, Zn, Mg, Cu, and Nd based ferrites exhibit unique characteristics stemming from their specific cation distributions, resulting in distinct advantages and disadvantages in both magnetic and adsorption capacity. Furthermore, adsorption isotherms and kinetics are crucial in explaining the interaction mechanism of ferrite with heavy metal ions. Most studies demonstrate good agreement with Langmuir isotherms and pseudo second order kinetics, indicating the presence of chemical adsorption processes through specific bonds between metal ions and active sites on the ferrite surface. This is reinforced by the varying maximum adsorption capacity values of each material, depending on the ferrite composition, particle size and operational conditions such as pH, contact time and temperature.

The influence of modification and composite formation is also a determining factor in adsorption performance. Modification of $NiFe_2O_4$ with reduced graphene oxide (rGO), $MnFe_2O_4$ with biochar, or $CoFe_2O_4$ with FAU-zeolite shows a drastic increase in adsorption capacity while maintaining magnetic properties that support separation efficiency. This indicates that modifying ferrite metals not only increases the number of active sites through an increase in specific surface area, but also provides the additional structural stability required for repeated use.

Table 2 and **Table 3** present a comparison of the magnetic properties and adsorption performance of metal ferrites based on the same parameters, including adsorbent type, adsorption isotherm and kinetic models, particle size, maximum adsorption capacity, magnetic properties (Ms and Hc), as well as operational conditions such as pH, temperature, and contact time. The data in both tables are compiled from different studies, allowing for a more systematic comparative analysis of the consistency and variation in the magnetic properties and adsorption performance of metal ferrites reported in the literature.

Analysis of the magnetic properties and adsorption performance of various ferrite metals (Ni, Mn, Co, Zn, Mg, Cu, and Nd) shows a consistent relationship between surface structure, particle size, and magnetic parameters with adsorption capacity as described in the isotherm model and adsorption kinetics. Based on the data in Table 2 and Table 3, from several studies that have been conducted, the majority report data compatibility with the Langmuir isotherm and Pseudo Second Order (PSO) kinetics. In addition, several composite materials show other isotherm models such as Sips and Freundlich, which indicate the heterogeneity of active sites due to modification, so that combinations of mechanisms such as a combination of monolayer and multilayer or a combination of physical and chemical mechanisms also often occur.

Nickel ferrite ($NiFe_2O_4$) material, according to research by Hassan et al., (2025), stands out as a ferrite with good crystal stability and a fairly high saturation magnetization (Ms) value, namely around 50-55 emu/g, thus greatly supporting efficiency in the separation process by an external magnetic field. Based on the data in **Table 2**, this material was synthesized using the reflux coprecipitation method and produced nanoparticles (approximately 18-29 nm) that showed effective adsorption capacity for hazardous metal ions such as Cr(VI) and As(V). Adsorption follows the Langmuir isotherm model, while the kinetics show a mixed model, namely Cr(VI) according to the Pseudo First Order (PFO) model and As(V) according to the Pseudo Second Order (PSO) model. This indicates the simultaneous involvement of physical and chemical adsorption mechanisms. Optimal conditions at pH 5 and a contact time of 120 minutes show that ion speciation and surface charge greatly determine the affinity of the adsorbent. However, the maximum adsorption capacity of pure $NiFe_2O_4$ tends to be moderate, generally only ranging from 18 to 20 mg/g [41]. Other studies testing nickel ferrite against heavy metal ions such as Pb(II) and Cd(II) reported significant variations in performance depending on particle size and composition modification [42]. Kumari et al., (2023) reported q_{max} for Pb(II) and Cd(II) of 39.28 and 17.16 mg/g in larger particles of around 50-56 nm, but their saturation magnetization was lower at 8.84 emu/g, indicating a relationship between surface area and adsorption capacity and magnetic response. Partial cation substitution efforts such as $Mg_{0.10}NiFe$ and $Ca_{0.10}NiFe$ show that doping can substantially modulate magnetic parameters. In other words, doping has an important influence on regulating the combination of adsorption capacity, pH_{pzc}, and magnetic properties. To improve its performance, structural modifications were made by forming a $NiFe_2O_4$-rGO (rGONF) composite, which showed the most notable improvement in performance. Data from Lingamdinne et al. (2017) show composite particles measuring approximately 32 nm with Ms around 31.6 emu/g and very high q_{max} for Pb(II) and Cr(III), namely 121.96 and 126.58 mg/g, as well as a short equilibrium time of 30 minutes. The increase in adsorption capacity in rGONF may occur due to an increase in surface area and porosity caused by rGO, which increases the number of active sites, and the presence of oxygen functional groups in rGO, which strengthen the interaction with target metal ions. A consequence that needs to be considered is the decrease in saturation magnetization (Ms) compared to pure $NiFe_2O_4$, from around 55 to 31.6 emu/g. Therefore, the amount of carbon fraction in the composite needs to be adjusted appropriately so that the increase in adsorption capacity does not reduce the material's ability to be separated magnetically.

Pure manganese ferrite ($MnFe_2O_4$) has been reported to have very attractive characteristics for adsorption applications. The size of the nanoparticles is in the range of 20-80 nm and the saturation magnetization is relatively high at around 61.4 emu/g, enabling a combination of large adsorption capacity and efficient magnetic separation capabilities. Data by Asadi et al. (2020) reported an extraordinary maximum

Table 2. Comparison of magnetic and adsorption properties of metal ferrites

Adsorbent	Adsorbate	Isotherm	Kinetics model	Particle Size (nm)	Adsorption Capacity (mg/g)	Ms (emu/g)	Hc (Oe)	pH	Tempe-rature (°C)	Time (min)	Refs
NiFe$_2$O$_4$	Cr(VI) & As(V)	Langmuir	PFO & PSO	18-29	18 & 23.5	55	-	5	25	120	[12]
NiFe	Pb(II) & Cd(II)	Langmuir	PSO	64.83-50.88	39.28 & 17.16	8.8411	31.0	9 & 6	25	60	[13]
Mg$_{0.10}$NiFe	-	-	-	-	-	3.8766	65.89	-	-	-	
Ca$_{0.10}$NiFe	-	-	-	-	-	12.3514	18.07	-	-	-	
rGONF	Pb(II) & Cr(III)	Langmuir		32.0	121.95 & 126.58	31.6	100	5 & 4	25	30	[14]
MnFe$_2$O$_4$	Zn(II)	Langmuir	PSO	20-80	454.5	61.4		6	25	120	[15]
CMFO	Cu(II) & Pb(II)	Langmuir	PSO	203	14.86 & 15.36			4.5	45	14440	[16]
MnFe$_2$O$_4$/ biochar	Pb(II), Cu(II), & Cd(II)	Sips	PSO	8.0	248.5, 179.1 & 146.3	61.9	5.5	5	25	1440	[17]
MnFe$_2$O$_4$ @alunite	Cu(II) & Pb(II)	Langmuir	PSO	45	129.87 % 158.73	36.0	-	6-7	25	10	[18]
PVP@MnFe$_2$O$_4$	Pb(II), Cd(II), & Ni(II)	Freundlich	-	-	Pb(II)> Cd(II)> Ni(II)	-	-	5	-	180	[19]
Mn$_{0.6}$Zn$_{0.4}$ Fe$_2$O$_4$	Cd(II), As(III), & Pb(II)	Langmuir	PSO	42.6	22.9, 8.7, & 33.9	68.9	53.6	5, 5, & 3	25	30	[20]
ZnFe$_2$O$_4$ NPs	Se(IV)	Freundlich	-	-	43.67	-	-	2.5	35		[21]
ZnFe$_2$O$_4$/ Zeolite	Cu(II)	Freundlich	PSO	60	161.3	0.5		Low	25	5-40	[22]
CoFe$_2$O$_4$	Zn(II)	Langmuir	PSO	20-80	384.6	37.54	-	6	25	120	[15]
CoFe$_2$O$_4$ @SiO$_2$-NH$_2$	Dy(III), Tb(III), & Hg(II)	-	-	17.7	4.7, 6.2, 1.2	33.24	122	4-4.5	25	120	[23]

capacity for Zn(II) of approximately 454.5 mg/g following the Langmuir isotherm model and Pseudo Second Order (PSO) kinetics. Under operating conditions of pH 6, the speciation of Zn(II) and the surface charge state of the ferrite are conducive to the formation of inner sphere complexes or direct coordination to Fe-O or Mn-O sites. The combination of nano particle size and active site distribution facilitates mass diffusion and site accessibility, resulting in high adsorption capacity and relatively fast kinetics. Modifying and creating MnFe$_2$O$_4$ composites with porous or polymer matrices shows substantial but varied functional improvements depending on the strategy used. For example, MnFe$_2$O$_4$/biochar in the study by Jung et al. (2018), which has very small particles of about 8 nm and saturation magnetization (Ms) of about 61.9 emu/g, produces a high maximum adsorption capacity for heavy metals Pb(II), Cu(II), and Cd(II), namely 248.5; 179.1; and 146.3 mg/g, respectively, as well as compatibility with the Sips isotherm and PSO kinetics, indicating surface heterogeneity resulting from the addition of biochar and the combined contribution of physical and chemical adsorption. In contrast, research by Shirkhoidaie et al. (2016) reported that alunite-modified manganese ferrite (MnFe$_2$O$_4$@alunite) showed Cu(II) adsorption capacity of 129.9 mg/g and Pb(II) adsorption capacity of 158.7 mg/g with very short contact time (~10 minutes) and Ms decreased to about 36 emu/g. This shows that mineral supports such as alunite can increase kinetic access and particle dispersion but also reduce magnetic properties. Furthermore, the polymer coating (PVP@MnFe$_2$O$_4$) followed the Freundlich isotherm model and the selectivity order in adsorbing heavy metal ions, namely Pb(II)>Cd(II)>Ni(II), with equilibrium achieved in hundreds of minutes. This phenomenon indicates that the addition of functional groups can increase the heterogeneity of active sites but can slow down mass diffusion. Manganese based ferrite materials have structural and magnetic advantages that have high

Table 3. Comparison of magnetic and adsorption properties of metal ferrites

Adsorbent	Adsorbate	Isotherm	Kinetics	Particle Size (nm)	Ads. Capacity (mg/g)	Ms (emu/g)	Hc (Oe)	pH	Temperature (°C)	Time (min)	Refs
$CoFe_2O_4$ are distributed on FAU surface	Pb(II)	Langmuir	PSO	25	602.4	18.93	-	7	25	1440	[24]
$Co(Cr_{0.25}Fe_{0.75})_2O_4$	Pb(II)	Langmuir	PSO	30-50	2.12	41.3	181.6	-	30	1440	[25]
$Co_{0.4}Zn_{0.6}Fe_2O_4$	Pb(II)	Langmuir	-	14	271.21	-	-	7	25	1440	[26]
$(Co_{0.7}Zn_{0.3})_{0.9}Ni_{0.1}Fe_2O_4$	Pb(II)	Langmuir	PSO	-	-	67.1	-	7	-	40	[27]
$CoFe_2O_4$@OA MNPs	Pb(II)	Langmuir	PSO	59-170	16.7	16.6	2500	5	25	140	[28]
CMF@MF-CB	Cu(II) Cd(II)	Langmuir	PSO	-	212.8, 175.4	9.64	-	6	30	240	[29]
RGCF	As(V)	Langmuir	PSO	10	222.2	23.6	1575	10	25	60	[7]
$MgFe_2O_4$ ($MF_{0.33}$)	As(III, As(V)	Freundlich	-	-	103.9 45.5	-	-	7	-	-	[30]
$MgFe_2O_4$-NH_2	Pb(II) Cu(II) Zn(II)	Langmuir	PSO	428.1	0.715 0.657 1.768	-	-	7	-	90	[31]
$Mg_{0.2}Zn_{0.8}Fe_2O_4$	Cr(VI) Ni(II)	Langmuir	-	-	30.49 8.20	5.1	2.5	7	25	-	[32]
B-MgFe-BC	Cr(III) Ni(II)	Temkin	PSO	355	50.0 54.1	-	-	1 6	60	110	[33]
FAU:$MgFe_2O_4$ (3:1)	Co(II) Mn(II)	Langmuir	PSO	50	3.85 3.54	0.47	-	7	25	1440	[34]
$Cu_{0.5}Mg_{0.5}Fe_2O_4$	Pb(II)	Langmuir	PSO	29.5	57.7	23.1	83	7	25	180	[35]
$NdFe_2O_4$	Pb(II)	Langmuir	PSO	90-230	-	4.9-17.6	71.1-188	-	-	-	[36]

adsorption capacity when dispersed and with optimal pore modification, resulting in an increase in surface area and an increase in the number of active sites without significantly losing magnetic separation capabilities.

Partial substitution of Zn in spinel structures, such as in /$Mn_{0.6}Zn_{0.4}Fe_2O_4$, has a multifaceted impact on magnetic properties and adsorption capacity for heavy metal ion treatment. Data from Wang et al. (2025) reported that $Mn_{0.6}Zn_{0.4}Fe_2O_4$ particles have a particle size of approximately 42.6 nm and follow the Langmuir isotherm model and PSO kinetics for Cd(II), As(III), and Pb(II), with maximum capacities of 22.9, 8.7, and 33.9 mg/g, respectively. The agreement with the Langmuir and PSO models indicates the dominance of monolayer chemisorption over physisorption. This material has an Ms value of approximately 68.9 emu/g and an Hc of approximately 53.6 Oe, indicating that the addition of Zn^{2+} does not significantly reduce the magnetic moment contributed by Mn or Fe ions, as these ions tend to occupy tetrahedral sites and regulate the superexchange interaction between Fe^{3+} and Mn^{2+} ions. The difference in optimum adsorption pH (pH 5 for Cd(II) and Pb(II), and pH 3 for As(III)) is related to the form of ion species in solution and the binding mechanism, such as electrostatic interactions and complex formation on the surface. Pure $ZnFe_2O_4$ material and its composites also have good adsorption performance and vary depending on the structure and surface conditions. $ZnFe_2O_4$ nanoparticles, for example, follow the Freundlich isotherm model with an adsorption capacity of approximately 43.7 mg/g for Se(IV), reflecting the presence of heterogeneous adsorption sites and the possibility of multilayer formation. The combination of $ZnFe_2O_4$ with zeolite ($ZnFe_2O_4$/zeolite) results in a significant increase in adsorption capacity for Cu(II) of approximately 161.3 mg/g [22], as zeolite expands the surface area and provides additional cation exchange sites that enhance ferrite particle dispersion and active site accessibility. However, this increase is accompanied by a decrease in magnetic properties (Ms around 0.5 emu/g), resulting in lower separation efficiency with an external magnet.

Pure cobalt ferrite ($CoFe_2O_4$) material exhibits strong magnetic properties and high adsorption capacity for several heavy metal ions. Research by Asdi et al. (2020) reported $CoFe_2O_4$ particle sizes ranging from 20-80 nm, Ms values of around 37.54 emu/g, and a maximum adsorption capacity for Zn(II) of 384.6 mg/g with consistent Langmuir isotherm and PSO kinetics. The pH value of approximately 6 indicates the importance of ion speciation and surface zero charge point in determining affinity. In addition, the size of nanoparticles supports rapid mass diffusion, resulting in relatively fast kinetics of 120 minutes [15]. Modification and compositing of $CoFe_2O_4$ show effects that support adsorption performance and magnetic properties. The distribution of $CoFe_2O_4$ on the surface of FAU zeolite increases the maximum adsorption capacity of Pb(II) metal to approximately 602.4 mg/g [24], but Ms decreases to approximately 18.93 emu/g and the equilibrium time is longer at approximately 1440 minutes. This indicates that larger pore sizes can increase the number of adsorption sites but reduce the magnetic fraction, resulting in less efficient separation. Conversely, surface functionalization such as $CoFe_2O_4@SiO_2\text{-}NH_2$ by Allwin et al. (2023) shows nitrogen donor sites that increase affinity for certain ions (Dy^{3+}, Tb^{3+}, Hg^{2+}) at acidic pH (4-4.5), although the absolute capacity is relatively small. Other modifications such as $Co_{0.4}Zn_{0.6}Fe_2O_4$ and carbon composites (CMF@MF-CB, RGCF) also show high maximum adsorption capacities for Cu(II), Cd(II), and As(V), but often with a decrease in Ms or a change in Hc. Therefore, the design and composition of the material must be balanced and appropriate in order to obtain more optimal results while maintaining stability and magnetic separation capabilities, as well as achieving high adsorption capacity.

Magnesium-based ferrite also shows great potential as a multifunctional material in heavy metal adsorption and magnetic separation applications due to its easily modifiable chemical and magnetic properties. Pure $MgFe_2O_4$, for example, exhibits high adsorption capacity for arsenic in its two oxidation forms, namely As(III) at 103.94 mg/g and As(V) at 45.52 mg/g [30]. This difference in capacity reflects differences in speciation and complex formation tendencies on the ferrite surface, where the more neutral As(III) exhibits stronger interactions with active surface sites than the anionic As(V). Surface functionalization with -NH2 groups further enhances the affinity of $MgFe_2O_4$ for metal cations such as Pb(II), Cu(II), and Zn(II), which are bound through chemisorption mechanisms with PSO kinetics. This indicates that the presence of amino groups plays an important role in providing electron donor sites for coordination interactions, while also expanding the application of $MgFe_2O_4$ under neutral pH conditions. Modification of the structure of pure $MgFe_2O_4$ with other metals or porous materials has a significant impact on its adsorption performance and magnetic properties. Partial substitution Mg^{2+} with Zn^{2+} in $Mg_{0.2}Zn_{0.8}Fe_2O_4$, resulted in adsorption capacities of 30.49 mg/g for Cr(VI) and 8.20 mg/g for Ni(II), indicating that changes in cation distribution affect the number and strength of available active sites. The B-MgFe-BC composite also showed an increase in surface area and good adsorption capacities for Cr(III) and Ni(II) of 50.00 and 54.05 mg/g, respectively. Furthermore, the integration of $MgFe_2O_4$ into the zeolite framework (FAU:$MgFe_2O_4$) increased the stability and selectivity towards Co(II) and Mn(II) ions, although the capacity was relatively low at around 3.85 and 3.54 mg/g, indicating a relationship between surface area, number of active sites, and magnetic fraction.

Next is copper based ferrite ($CuFe_2O_4$), which has the unique characteristic of Jah Teller Cu^{2+} distortion, capable of enhancing purification interactions with heavy metal ions through the formation of strong coordination complexes. Research by Tran et al. (2020) with a composition of $Cu_{0.5}Mg_{0.5}Fe_2O_4$ showed a Pb(II) adsorption capacity of 57.7 mg/g with a PSO kinetic model. The balanced distribution of Cu^{2+} and Mg^{2+} cations not only expands the number of active sites but also increases surface acidity, thereby strengthening the affinity for high-valent cations. The saturation magnetization (Ms) value of 23.1 emu/g and coercivity (Hc) of 83 Oe indicate that despite its lower magnetic capacity, this material still allows for efficient magnetic separation. With an equilibrium time of approximately 180 minutes at neutral pH, copper ferrite provides a balance between adsorption efficiency and ease of material recovery, making it a potential material for applications in the treatment of water contaminated with heavy metals.

Meanwhile, neodymium-based ferrites are still relatively understudied but show great promise thanks to the role of rare earth metal dopants in modulating the structural and electronic properties of the material. $NdFe_2O_4$ reported by Song et al. (2023) has a particle size ranging from 90 to 230 nm with moderate saturation magnetization of around 4.89 to 17.61 emu/g and high coercivity values of around 71.05 to 188 Oe. This indicates significant magnetic anisotropy due to the presence of Nd^{3+}. Although adsorption capacity data has not been fully quantified, this property suggests the potential of $NdFe_2O_4$ as a highly selective adsorbent, particularly for heavy metal ions with large ionic radii. The influence of Nd^{3+} ions in inducing lattice strain and increasing surface acidity will play an important role in increasing the number of active sites and electrostatic interactions. Therefore, further research evaluating the relationship between cation distribution, microstructure, and adsorption mechanisms is crucial for optimizing the performance of $NdFe_2O_4$, while also providing opportunities for the development of rare earth-based ferrite materials with high selectivity in the separation of heavy metal ions in water [43].

Overall, based on the comparison data, each ferrite material has advantages and limitations that are influenced by its cationic composition, morphology, magnetic properties, and specific surface area, which directly determine the performance of heavy metal adsorption in water. $NiFe_2O_4$ and $ZnFe_2O_4$ excel in stability and ease of magnetic separation, but their adsorption capacity is relatively moderate. $MgFe_2O_4$ offers high surface area and significant capacity, but is susceptible to dissolution under acidic conditions. $CuFe_2O_4$ exhibits strong affinity for metal ions through surface complex formation, although lattice distortion can reduce regeneration cycle stability. $NdFe_2O_4$ has high selectivity potential due to the rare earth metal effect, but further characterization and research are needed to understand its adsorption mechanism. Of the various types of ferrite materials, $MnFe_2O_4$ and $CoFe_2O_4$, especially in composite forms such as $MnFe_2O_4$/biochar and $CoFe_2O_4$/FAU, are the most promising materials because they combine high adsorption capacity of up to >400mg/g, magnetic properties that are sufficient for effective separation, and abundant accessibility to active sites. This combination of characteristics makes both highly relevant for large scale water treatment applications, where heavy metal absorption efficiency, ease of material separation, and long-term stability are key factors in the performance and sustainability of adsorption technology [44].

5. CONCLUSION

This study shows that each type of ferrite metal material has its own advantages and limitations as an adsorbent material in adsorbing heavy metal ions in water, depending on the metal composition, crystal structure, and magnetic properties. $MnFe_2O_4$ and $CoFe_2O_4$, especially in composite form, excel with high adsorption capacity, adequate magnetic properties, and ease of separation, making them the most potential candidates for water treatment applications. Meanwhile, $MgFe_2O_4$ excels in arsenic metal adsorption capacity, $ZnFe_2O_4$ and $NiFe_2O_4$ are structurally stable, $CuFe_2O_4$ has high chemical affinity, and $NdFe_2O_4$ offers specific selectivity. These results confirm that modifying materials through metal substitution and composite formation is an important strategy for optimizing the performance of ferrite as an efficient and applicable heavy metal adsorbent in water treatment systems.

SUPPROTING INFORMATION

There is no supporting information in this paper. The data that support the findings of this study are available on request from the corresponding author (R. Basuki).

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CONFLICT OF INTEREST

There was no conflict of interest in this study.

AUTHOR CONTRIBUTIONS

MFPK, SN, WS performed the methodology, writing original draft, review & editing. RB supervises the methodology, data analysis, and revise the manuscript. NAS, NN, AR, YEP, ZAH collaborated on writing and revising the manuscript. All authors approved the final version of the manuscript.

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