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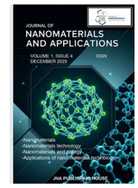

Advanced Spinel Ferrite Nanoparticles for Sustainable Wastewater Treatment: A Comprehensive Review on Synthesis, Cation Distribution, and Mechanism-Driven Performance

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Abstract: Spinel ferrites have emerged as one of the most versatile multifunctional magnetic oxides owing to their tunable electronic structure, excellent chemical stability, and magnetic separability. Ferrites have attracted increasing attention for environmental remediation owing to their excellent magnetic recoverability, tunable electronic structures, and remarkable catalytic activity because of their high resistance and saturation magnetization. Enhancing ferrite characteristics by different synthesis methods and doping has been the focus of recent research, increasing its uses in environmental remediation and sustainable energy. The synthesis, characterisation, and uses of nanosized ferrites are covered in this work. This review systematically compares the major synthesis routes including sol–gel, hydrothermal, co-precipitation, combustion, biosynthesis, and microwave-assisted methods with emphasis on their effects on structural and catalytic properties. The diverse applications of ferrites in microwave devices, communications, dielectric applications, water detoxification, biomedical areas, sensors, catalysis, photoluminescence, data storage, and environmental remediation are also described. The performance of ferrite nanoparticles is strongly governed by band gap tuning and Reactive Oxygen Species (ROS) generation. Additionally, adsorption capacity and photocatalytic efficiency are influenced by particle size and surface functionalization.

Keywords: Cobalt Ferrite, Magnetic Nanoparticles, Synthesis, Wastewater Treatment, Photo Catalysis

1. Introduction

Magnetic ferrite nanoparticles have attracted considerable attention for wastewater treatment because of their multifunctional physicochemical properties [1-3]. However, there is currently a lack of a more comprehensive explanation of how the efficiency of wastewater treatment is affected by modifiable ferrite properties. Ferrite nanoparticles have traditionally been employed as adsorbents for pollutant removal; however, recent studies have demonstrated their outstanding photocatalytic activity under UV and visible-light irradiation. Water pollution caused by industrial effluents, agricultural runoff, pharmaceuticals, heavy metals, and emerging contaminants has become one of the most pressing global environmental challenges [4]. Numerous sources, such as untreated wastewater, agricultural runoff, and industrial discharges, contribute to these pollution levels. Water pollution is a critical issue that must be managed since it rises with population growth and industrial activity. To handle this growing problem, more efficient wastewater treatment methods are needed [5]. These unique magnetic, catalytic, and structural characteristics contribute to the exceptional pollutant removal efficiency of ferrite nanoparticles [6]. Besides ferrites, carbon nanotubes, activated carbon, MOFs, MXenes, and TiO_2-based photocatalysts have also been extensively investigated for wastewater treatment [7, 8]. One of the main advantages of ferrites is their chemical stability, particularly in harsh environments. This is important for wastewater treatment applications where pH, temperature, and other variables might change significantly. Cobalt ferrite ($CoFe_2O_4$) and magnetite (Fe_3O_4) are two examples of ferrites with strong magnetic properties that allow for efficient separation from treated water using external magnetic fields [9]. Ferrites frequently have higher saturation magnetization than other kinds of magnetic nanoparticles when doped with metals like nickel or cobalt, which improves their separation efficiency [10]. They may recover more quickly due to their magnetic strength, which reduces the time and energy required for the operation and makes their employment in continuous flow systems more practical overall. Ferrites' adsorption capacity and selectivity can be greatly increased by including organic ligands, polymers, or inorganic substances [11]. The adsorption of lead and cadmium ions from industrial wastewater, for example, has demonstrated to be enhanced by silane-coated ferrites. The low toxicity and environmental impact of ferrites is another benefit. Additionally, because iron-based materials are readily available and reasonably priced, ferrites are more cost-effective. Co-precipitation, sol-gel processes, and hydrothermal technologies are examples of ferrite synthesis techniques that are economically viable for widespread application in wastewater treatment facilities due to their relative simplicity and scalability [12, 13]. These Reactive Oxygen Species (ROS) degrade organic pollutants found in wastewater, such as pesticides, medications, and colours. Catalytic efficiency is higher in cobalt ferrite due to the redox cycling of cobalt ions (Co^{2+}/Co^{3+}). However, despite extensive studies, a systematic comparison between adsorption and photocatalytic mechanisms in ferrite-based systems remains limited. In particular, the relationship between structural properties, band gap energy, and treatment efficiency has not been comprehensively analyzed. This review aims to critically evaluate synthesis methods, structural properties, and performance of ferrite nanoparticles in wastewater treatment, with emphasis on mechanism-driven analysis [14-16].

2. Magnetic Ferrite nanoparticles

AB_2O_4 is the general formula for magnetic ferrite nanoparticles, where A and B stand for metal atoms at two distinct lattice positions. They can be employed in a wide range of high-tech applications, such as wastewater treatment, drug delivery, photocatalysis, biosensing, and sensing applications, due to these special properties. Given the significance of magnetic ferrite nanoparticles for a range of applications, researchers are driven to develop customized ferrites nanoparticles with specific structure and magnetic characteristics. The spinel crystal structure consists of tetrahedral and octahedral crystallographic sites occupied by different metal cations. The magnetic moments of atoms' unpaired electrons frequently give rise to ferromagnetic behaviour, which determines several sub-lattices [17].

Different ferrite nanoparticle preparation techniques are depicted in Figure 1.

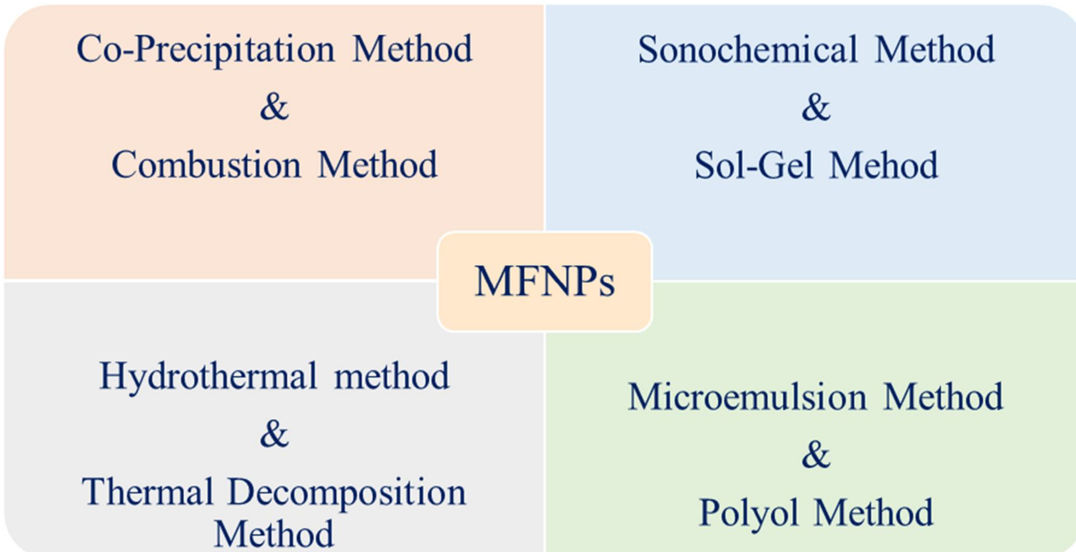

Figure 1. Synthesis of Magnetic Ferrite Nanoparticles (MFNPs)

The physical characteristics of ferrite materials are evidently determined by the distribution of cations. As a result, the variable coordination numbers and sizes of different types of cations, which show diverse forms of magnetizations in the structure, have an impact on the sub lattice structure. These cation distributions in magnetic ferrites have been the subject of numerous studies. A variety of metal cations, including Mn^{2+}, Co^{2+}, Cu^{2+}, Ni^{2+}, and Zn^{2+}, have been doped into magnetic ferrite nanoparticles to modify their activity. Recent research has previously examined the co-doping of distinct atoms that typically share the same valence state. Nevertheless, changes in ionic radii lead to structural changes in the micro-lattice, which substantially modifies the magnetic exchange interaction, electrical conductivity, optical band gap, and catalytic activity [18-20]. They transferred Cu ions to the octahedral location because Cu^{2+} has a greater ionic radius (0.73 Å) than Ni^{2+} (0.69 Å), which increased the lattice constant [21]. Numerous authors looked into the doping of Ti4+ and Zn^{2+} ions in nickel ferrites as well as alterations in certain properties of magnetic ferrite nanoparticles. They observed lattice distortions brought on by Ti^{4+} ions, whose larger ionic radius and different oxidation state from Fe^{3+} change grain boundaries and raise electrical resistance. The capacity of Zn^{2+} ions to enhance magnetic and dielectric properties is well recognized. The cation distribution in the spinel structure is influenced by the co-doping of these two ions, which enhances electrical conductivity and magnetic behaviour. These variations in cation distribution directly influence magnetic behavior, electron transfer processes, and ultimately the adsorption and photocatalytic performance of ferrite nanoparticles. For instance, when doping Zn^{2+} into the tetrahedral (A) site, Fe^{3+} ions are pushed to the octahedral (B) site, enhancing the total saturation magnetization M_s according to Néel's theory M = M(B) - M(A). Conversely, high-valence ions like Ti^{4+} induce lattice distortion and suppress the superexchange interaction, lowering M_s but significantly increasing electrical resistivity [22].

3. Wastewater Treatment

Ferrite nanoparticles' distinct structural, optical, electrical, and magnetic capabilities make them useful for treating a variety of pollutants owing to their high surface area, magnetic separability and tunable surface chemistry [10]. Adsorption of heavy metal contaminants from wastewater and photo-catalytic treatment are the main uses of spinel ferrite. In addition to heavy metals, bacteriologic contamination and other organic compounds are significant risks in water that must be considered.

3.1. Heavy metals

Heavy metals found in nature include chromium (Cr), lead (Pb), arsenic (As), cadmium (Cd), and mercury (Hg). Yet, their concentrations in aquatic habitats have grown as result of human activities like mining, industrial discharges, agricultural runoff, and poor waste management. In contrast with organic contaminants, heavy metals are persistent in the environment and cause aquatic organisms to bio-accumulate as well as bio-magnify throughout the food chain. Thus, exposure to heavy metals can cause both acute and long-term damage in both humans and wildlife. Because heavy metals can bind to sediments, they become more persistent in water, making conventional water treatment methods less effective. Furthermore, other pollutants' chemical shapes and toxicity can be altered by heavy metals. Heavy metals often occur in complex combinations, making it difficult to assess their individual and combined impacts [23]. Furthermore, factors like pH and temperature affect these metals' mobility and bioavailability, making it more challenging to predict and manage their effects on the environment [24]. For adsorption, a common technique for eliminating heavy metals, high surface area magnetic nanoparticles are an excellent choice. The removal of heavy metals by ferrites is mainly governed by electrostatic interactions, ion exchange, and surface complexation mechanisms.

3.2. Organic Compounds

Organic pollutants include a wide range of materials, such as colours, medications, and insecticides. Because they are resistant to biodegradation and chemically stable, these colors accumulate in water. Among the breakdown products of azo dyes, which account for 60–70% of all colors used, are highly toxic and carcinogenic aromatic amines [23]. When released into water, azo dyes can diminish under anaerobic conditions, producing dangerous by-products that pose a major risk to aquatic life and humans. Pesticides and medications are another significant group of organic pollutants. In aquatic environments, pesticides that are designed to be toxic to specific creatures can still cause harm to non-target species. For instance, popular insecticides such as carbamates and organophosphates can disrupt the neurological systems of fish, amphibians, and aquatic invertebrates. Hormones, analgesics, and antibiotics are examples of emerging pollutants that are persistent in groundwater because conventional water treatment facilities are unable to sufficiently remove them. It has been shown that drugs in water, even at low concentrations, can disrupt the endocrine systems of aquatic animals, altering their development, reproduction, and behaviour. Male fish exposed to synthetic hormones from contraceptives, for example, may feminize, which could impair their ability to procreate. When pharmaceuticals and pesticides are mixed in wastewater, their cytotoxic and genotoxic effects are often amplified by additive or synergistic actions [25]. The degradation of organic pollutants using ferrite nanoparticles occurs mainly through photocatalytic reactions involving reactive oxygen species such as hydroxyl radicals (-OH) and superoxide radicals (O^{2-}).

4. Synthesis of Magnetic Ferrite Nanoparticles:

4.1. Chemical Methods

The size distribution, stability, shape, and surface alterations of nanoparticles are all accurately controlled by chemical techniques. The structure and morphology of magnetic ferrite nanoparticles can be altered according to their intended use [26-28]. These nanoparticles, which take the form of nano-rods and nano-cubes, have special catalytic and adsorption capabilities due to their higher surface area, as seen in Figure 2 below. Nanostructure morphology promotes the adsorption of pollutants, whereas form predominantly influences catalytic reactions, which help break down harmful compounds. In certain catalytic processes, nano-rods may be more efficient due to their greater surface area for reactions.

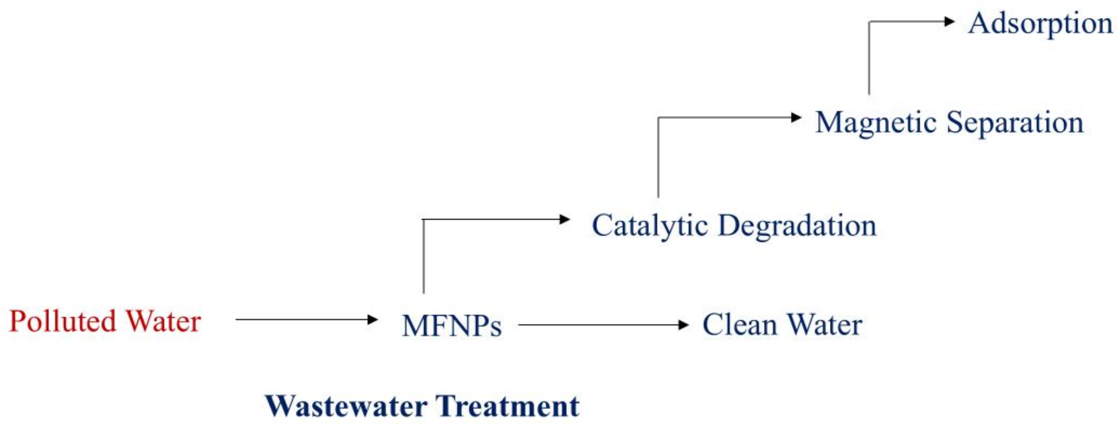

Figure 2. Magnetic Ferrite Nanoparticles Application in Wastewater Treatment

Table 1 Comparison of synthesis methods for ferrite nanoparticles

Method	Size control	Cost	Efficiency	References
Hydrothermal	High	Medium	High	[4, 15, 30]
Co-precipitation	Medium	Low	Medium	[20]
Sol-gel	High	High	High	[29]

MFe_2O_3 nanoparticles' magnetic properties can exploited to extract them from the water after treatment. This paper discussed how these sorbents' enormous surface area and magnetic properties improve the adsorption of heavy metals and facilitate their separation from water using a magnetic field. Numerous researchers offered a thorough analysis of wastewater and environmental treatment techniques that employ magnetic cobalt ferrite nanoparticles to remove heavy metals including arsenic (As), cadmium (Cd), and lead (Pb) from contaminated water. In applications where uniformity and ease of dispersion are important, spherical nanoparticles might be used. The efficiency of these nanoparticles in water treatment applications is significantly influenced by their size.

4.2 Hydrothermal synthesis

Magnetic ferrite nanoparticles are produced by hydrothermal synthesis and are increasingly being employed in water treatment [30]. As seen in Figure 3, the process starts with the production of precursor materials. Throughout the process, the temperature is maintained between 150 and 250 degrees Celsius. Because larger nanoparticles frequently result from higher water concentrations, the reaction mixture's water content is essential. Along with other transition metal salts, iron salts are typically present in the reaction mixture. The solvent is typically either water or a mixture of water and alcohol. The required size, shape, and crystallinity of the nanoparticles are achieved by carefully regulating these properties. After the reaction, the system is cooled, and washing solutions are used to rid the nanoparticles of impurities and excess reagents. The cleaned nanoparticles are then collected using filtration or centrifugation. CuO and WO^{3-}modified Fe_2O_3 nanoparticles were thus produced by Asmaa et al. for use in biological applications [31].

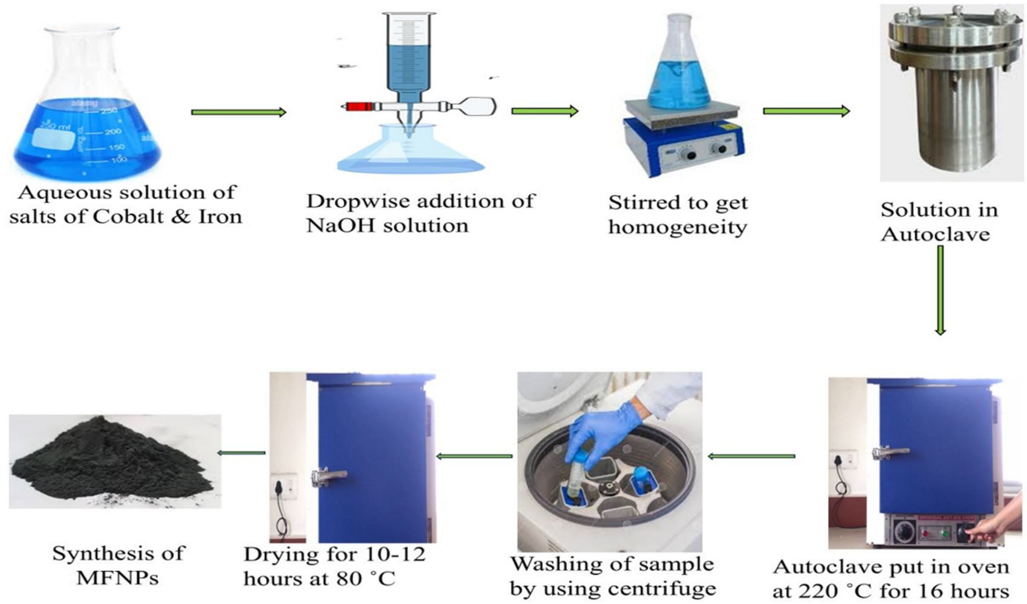

Figure 3. Synthesis of magnetic ferrite nanoparticles by hydrothermal method

5. Innovative Wastewater Treatment Applications

5.1. Photo catalytic Degradation Using Magnetic Ferrite Nanoparticles

The fundamental concept of photo catalysis is the creation of electron-hole pairs when photons of visible light interact with photoactive material. The resultant charge carriers will eventually produce reactive species, which further break down the target pollutant into innocuous molecules through redox processes. An excellent photo catalyst should have the three qualities depicted in Figure 4 below.

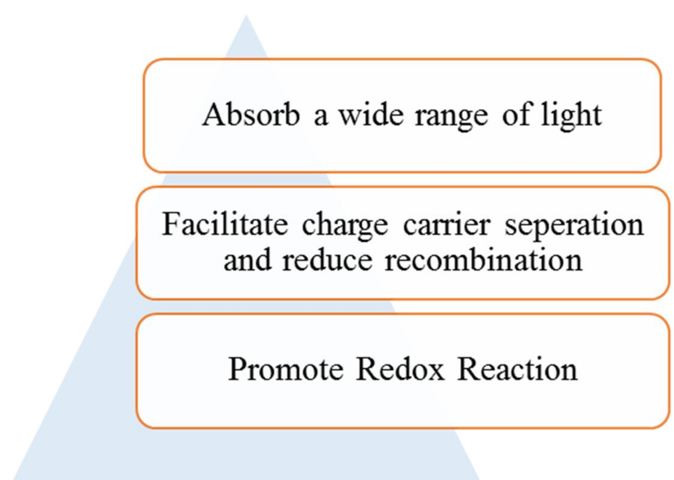

Figure 4. Ideal Characteristics of Photo catalyst

By absorbing photons in proportion to its band gap, the core photoactive material will excite ground state valence band (VB) electrons to stimulated conduction band (CB) electrons. This electron transfer eventually results in the creation of a positive hole in the VB. These generated e-h pairs can transform pollutant compounds both directly and indirectly. Photogenerated holes in the valence band oxidize surface hydroxyl groups or adsorbed water molecules to generate hydroxyl radicals (-OH). Additionally, Photogenerated electrons in the conduction band (CB) reduce dissolved oxygen to generate superoxide radicals (O_2^{-}). These reactive oxygen species (OH^-, O^{2-}) eventually convert pollutants into harmless products like CO_2 and H_2O [32-34]. Ferrites have received a lot of attention lately from the scientific community for their ability to photo-catalytically destroy a variety of water-soluble organic and inorganic pollutants. This enhanced performance is mainly attributed to efficient charge carrier separation and reduced recombination rates. A broad spectrum of light spectra will be able to be absorbed due to the reduced band gap. In contrast to other ferrite nanoparticles, such as nickel and cobalt ferrite nanoparticles, which have band gaps of 2.2 eV and 2.7 eV, respectively, copper ferrite nanoparticles have a lower band gap (1.7-1.9 eV) [35]. A lower band gap enables better visible light absorption, thereby significantly improving photocatalytic efficiency under solar irradiation [36]. Cu-based magnetic ferrite nanoparticles are also inexpensive, highly photo-stable, and catalytically hazardous. Under visible sunlight, copper ferrite's narrow band gap enables the degradation of impurities. When using UV energy as the source of irradiation, H_2O_2 increased the degradation capabilities. A Fenton-type photo catalyst system that employs oxidizing agents in the form of peroxides enhances the breakdown of $CuFe_2O_4$ nanoparticles. These peroxides react with Fe^{2+} to form extremely reactive hydroxyl radicals, whereas Fe^{3+} interacts with H_2O_2 to form HOO^- radicals. This causes the concentration of reactive species to increase, which eventually speeds up the dyes' breakdown. High-energy photons in UV light also increase the production of electron-hole pairs and, ultimately, the efficiency of degradation. Using a solvothermal method, a $ZnO/ZnFe_2O_4$ heterojunction photocatalyst was fabricated with enhanced crystalline and optical properties. In this context, how efficiently the surfaces of nanoparticles and adsorbents function determines the maximum pollutant uptake. Furthermore, they demonstrated that a $ZnO/ZnFe_2O_4$ composite exhibits higher photo-catalytic activity than separate ZnO and $ZnFe_2O_4$ nanoparticles for the degradation of methylene blue, achieving 91.2% and 82.7% degradation efficiency followed by 140 minutes of visible light ($\lambda \geq 420$ nm) and 120 minutes of UV-vis (350 ≤ 780 nm), respectively. Similar to this, X. Hu, et al. produced $ZnCuFe_2O_4$ nanoparticles by co-precipitation and examined how various operational factors, including pH levels, pollutant concentration, nanoparticle dosage, and photo-catalytic activity, affected the performance of Zn Cu-based magnetic ferrite nanoparticles [37]. Yao et al. investigated pre-annealed samples for the photo-degradation of Congo red dye, a major waste product of the textile industry, and produced $CoNiFe_2O_4$ magnetic ferrite nanostructures using the co-precipitation method. By exposing Congo red dye-containing water to continuous sunlight for 90 minutes, they showed that $CoNiFe_2O_4$ magnetic ferrite nanoparticles pre-annealed at 750 °C had a maximum efficiency of 94.8% and could be recycled [38]. Alzahrani et al. prepared Nd-doped $NiFe_2O_4$/CNT nanocomposites using the co-precipitation method followed by thermal treatment. The incorporation of carbon nanotubes improved charge-carrier separation and electron transport, resulting in superior photocatalytic degradation performance compared with pure $NiFe_2O_4$ nanoparticles. In their investigation of the photo degradation performance of three important textile wastes for ninety minutes under visible light irradiation, Nd-doped NiFe2O4 has the best efficiency of 83.87%, 90.80%, and 66.96% for Rhodamine B, methylene blue, and benzoic acid, respectively. It has shown that the presence of carbon nanotubes and rare earth Nd ions is what causes the enhanced activity of Nd-doped $NiFe_2O_4$ [39]. The removal of complex organic chemicals, like pesticides, medicines, and pigments, calls for more advanced wastewater treatment processes than conventional water treatment methods. This process of removing complicated chemical compounds has thoroughly examined by scientists. Organic chemicals are present in industrial, agricultural, and household wastewater processes. Conventional wastewater treatment technologies present a number of difficulties for dyes, including increased resilience to degradation because of aromatic rings. Usually, these vivid hues are studied as model reactions for the breakdown of large molecules. Kinetic models such as Langmuir-Hinshelwood can be used to forecast their deteriorating process, and UV-vis spectroscopy can readily trace it [40, 41]. Due to the extended half-lives of pesticides and pharmaceuticals in the ecosystem, sustainable water treatment that includes these complex organic chemicals is necessary. Producing sludge is one of the major drawbacks of traditional methods. Photo-degradation and chemical oxidation are essential methods for wastewater treatment. Pharmaceuticals are used to treat and prevent illnesses in people, animals, and the environment. The most widely used medications are antibiotics because of their strong ability to combat dangerous bacteria and diseases. Phenol and phenolic compounds are basic chemicals used in the production of medications and pesticides [42]. Asma et al. decorated graphene oxide (GO) with ferrite nanoparticles. Under regulated settings, a GO-$CoFe_2O_4$ composite was used to photodegrade the pesticide acetamiprid, achieving a 97% breakdown efficiency. Because of their better light absorption, charge carrier separation, and larger surface area, Cu-doped ferrite nanoparticles exhibit higher photocatalytic activity to photodegrade the pesticide triazophos.

5.2. Adsorption of Toxic Materials

Selective adsorption is a cost-effective method for recovering toxic chemicals from wastewater [16, 43]. The adsorption behavior of ferrite nanoparticles is often described using Langmuir and Freundlich isotherm models [44, 45], while kinetics typically follow pseudo-second-order models [18, 46]. The various ways that pollutant anions, cations, and organic molecules are adsorbed depend mostly on how efficiently the surfaces of nanoparticles and adsorbent's function [47-50]. Adsorption of ions from wastewater is usually caused by ion exchange, electrostatic interaction, and complex formations, whereas adsorption of organic molecules is caused by weak forces such hydrogen, van der Waals contacts, π-π bonding, and dipole–dipole bonding. These metals can directly contaminate water reservoirs and have an indirect impact on human life through agriculture and aquatic life. In addition to causing lung cancer, skin dermatitis, renal failure, dyspnea, and other conditions, they can harm the brain, liver, and reproductive systems [30]. Alkaline metal-doped Ni ferrites were investigated by Kumari et al. utilizing the co-precipitation technique. They used a range of parameters, including pH, concentration, contact time, etc., to study absorption. Ni (II) heavy metal removal experiments were conducted at room temperature with a pH of 6 and a contact period of 60 minutes. 99.13% of Ni (II) ions were removed from wastewater at 44.42 mg/g, and after eight cycles, the adsorption effectiveness did not considerably decrease. Co-based ferrites' dynamic behaviour was confirmed by modelling. To remove Pb (II) ions from wastewater, Hu et al. created $(Co_{0.7}Zn_{0.3})_{0.9}Ni_{0.1}Fe_2O_4$ ferrite and studied a medium pH and contact time. At pH 7, it was discovered that the current system operated adequately after 40 minutes of contact. 99.9% of the Cr (III) ions from the trash were effectively adsorbed after 30 minutes of contact. Magnesium-based ferrites are remarkably stable in terms of both chemical and thermal properties, with a wide surface area and many active sites [51-53]. Furthermore, layered spinel ferrites can also be effectively synthesized from environmental waste products such as fly ash [54. In order to use magnetic ferrite nanoparticles for wastewater treatment, the existing obstacles must be removed. Catalyst recovery, cost-effectiveness, and the development of dependable reactor designs are some of the most important issues.

5.3. Advanced Matrix of Cation Inversion and Mechanism-Driven Engineering

The fundamental performance of spinel ferrites MFe_2O_4 in both adsorption and photocatalytic wastewater treatment is governed strictly by the degree of cation inversion x, expressed via the formula $(M_{1-x}Fe_x)_A(M_xFe_{2-x})_BO_4$. Recent breakthroughs from 2020 to 2026 demonstrate that the positioning of divalent metal ions M^{2+} and trivalent iron Fe^{3+} between the tetrahedral (A) and octahedral (B) sublattices directly modulates the optical band gap (E_g), surface hydroxyl (-OH) density, and magnetic separation efficiency. In a perfectly normal spinel (x = 0), such as bulk $ZnFe_2O_4$, Zn^{2+} occupies the A-sites while Fe^{3+} populates the B-sites. However, when synthesized at the nanoscale or modified via non-thermal plasma or sudden thermal quenching, a mixed spinel structure emerges ($0 < x < 1$). This structural inversion triggers a dramatic migration of Fe^{3+} into the A-site, creating active Fe^{3+}_A - Fe^{3+}_B electron hopping pathways. This migration narrows the optical band gap to the visible-light region (1.7 - 2.2eV) and retards the recombination of photogenerated electron-hole (e^-/h^+) pairs. Furthermore, surface-sensitive X-ray Absorption Spectroscopy (XAS) and Density Functional Theory (DFT) simulations indicate that surface terminations induce a much higher degree of inversion at the near-surface layer compared to the bulk core. This phenomenon maximizes the density of surface active sites Fe^{3+} centers), which act as coordination spots for hazardous organic molecules (like tetracycline or dyes) during adsorption, and simultaneously function as radical generators -OH and O^{2-} via advanced oxidation processes (AOPs) and Fenton-like activations. To provide a comprehensive roadmap for tailoring spinel ferrites for high-efficiency environmental remediation, Table 1 maps the intricate relationships between specific synthesis routes, engineered cation distributions, and targeted pollutant degradation metrics reported in the most recent landmark studies.

Table 2. Comprehensive matrix mapping synthesis methods, cation distribution tuning, and mechanism-driven wastewater treatment performance.

Spinel Ferrite System	**Synthesis Route & Modifiers**	**Cation Distribution & Structural Modification**	**Optical Band Gap (Eg, eV)**	**Pollutant Target & Degradation Mechanism**	**Removal / Degradation Efficiency**	**Ref.**
$ZnFe_2O_4$	Sol-gel / Metal acetylacetonates	High surface inversion $x_{surface}$ = 0.52 vs. x_{bulk} = 0.26 via thermal engineering	1.92	Radical trapping - OH dominant); active in Oxygen Evolution Reaction (OER)	98.4% (Tetracycline)	[34]
Ni-$ZnFe_2O_4$	Sol-gel combined with Non-thermal Microwave Plasma	Plasma-driven rearrangement of Ni^{2+} and Zn^{2+}; reduced peak intensity ratios	1.85	Advanced Oxidation Processes (AOPs); enhanced microwave-induced carrier separation	95.2% (Rhodamine B)	**[55, 57]**
$MnFe_2O_4$/NaA	Hydrothermal fly ash utilization	Uniform integration of mixed spinel within NaA Zeolite frame	2.10	Synergistic Adsorption + Photocatalysis; electrostatic binding of NH^{4+}	89% (TC) & 66% (NH^{4+})	**[52]**
$CoFe_2O_4$	Thermal	Tailored magnetic	1.78	Rapid magnetic	97.5%	[56]

	decomposition Zn^{2+}/Ni^{2+} dual-doping)	anisotropy; 40% increase in saturation magnetization (sim 143 $Am^2.kg^{-1}$		separation <15s; persistent Fenton-like dye degradation	Methyl Orange	
$CoFe_2O_4$	co-precipitation / Bio-char hybrid	Fully inverse spinel (x ~0.91); high concentration of octahedral Cu^{2+} active sites	1.72			[53]

6. Conclusions and Future Perspectives

The features of nano-sized magnetic ferrite nanoparticles and their useful applications in several industries, including wastewater treatment, have attracted substantial scientific interest in the past ten years [58-60]. When it comes to visible light photocatalysis, cobalt ferrite nanoparticles have demonstrated superior photocatalytic performance. However, before this type of particle is widely used in everyday life for commercial purposes, some concerns still need to be resolved. Creating ferrite nanoparticles with a large surface area and a uniform size is one of the main challenges. Even though these elements are essential for optimizing adsorption efficiency, controlling them during large-scale production is still challenging. When ferrite nanoparticles clump together in water, it becomes difficult to maintain high adsorption rates since this reduces their surface area. The industrial-scale treatment systems already in use are unable to handle nanomaterials, leading to significant modifications or the development of new systems. Despite the challenges, advancements in materials science and nanotechnology are expected to address many of these problems. More environmentally friendly and scalable ferrite nanoparticle production procedures could be the outcome of improved synthesis techniques. The effectiveness of treatment may be increased by giving nanoparticles functional groups on their surface, which may increase their selectivity for specific pollutants. Ferrite nanoparticles demonstrate dual functionality in wastewater treatment through adsorption and photocatalysis. Their performance is strongly dependent on structural properties, including particle size, surface area, and band gap energy. However, challenges such as nanoparticle agglomeration, recovery efficiency, and large-scale applicability remain critical issues. Future research should focus on surface functionalization, hybrid nanocomposites, and reactor-scale implementation to enhance practical applicability [18, 41]. Future investigations should integrate operando characterization, density functional theory, machine learning-assisted catalyst design, and pilot-scale reactor validation to accelerate industrial implementation.

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