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Review on Nickel doped Cobalt ferrite nanoparticles and their antimicrobial applications

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Abstract

This review focused on the fundamental properties and characteristics of cobalt ferrites and nickel-doped cobalt ferrites' nanoparticle composition, particle size, and calcination temperature. The structural, texture, composition, particle size, cation, and anion distribution of the dopants, calcination temperature impacts, and effects on the doped compound of different studies are compiled. Moreover, the sol-gel, hydrothermal, and co-precipitation synthesis are reviewed among the prominent synthesis techniques. Anisotropy, coercivity, saturation magnetization, biological compatibility, chemical stabilities, optical and electrical applications, and the substituted element's impact are presented. The antibacterial application of cobalt ferrites and nickel-substituted cobalt ferrite nanoparticles are reviewed with their compatibility and others.

Keywords:

Nanoparticle, Ferrite, Nickel-doped cobalt ferrite, synthesis, antibacterial

Introduction

Nanotechnology is transforming radically and dynamically the lifestyle of the globe, and societies live worldwide. Nearly everyone uses nanotechnology-based goods daily thanks to groundbreaking scientific and technological developments (Purohit et al., 2017).

It is a paramount research area in physics, biological and materials science, chemistry, pharmacy, medicine, agriculture, biotechnological, etc., as Tamboli et al. (2023) indicated. Furthermore, this global collaboration is improving the quality of machinery, transportation, energy storage and distributer, entertainment, construction materials, IT, aviation, automobiles, electronics, common appliances, consumer products, agricultural, scientific equipment, health and diagnostic analyses, and medicinal (Di Sia, 2017); (Singer et al., 2018).

Novel physicochemical and morphological characteristics make tremendous applications in the ranges of 1 to 100 nm particle's average size. Due to the particle's tiny size, its behavior differs significantly from that of bulk materials (Morais et al., 2021).

As a type of nanomaterial, magnetic nanoparticles are getting a lot of attention because they can be used to produce magnetic drug delivery equipment, permanent and temporary magnets, magnetic fluids, microwave devices, high-density recording media (Safi et al., 2015), sensors, biomedical drug delivery spintronics, solar cells, and ferrofluids (Vadivel et al., 2014).

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The spinel ferrite structure of MFe_2O_4, where M stands for metals like Ni, Mn, and Zn, which affect the material's electric, magnetic, chemical, and mechanical properties (Safi et al., 2015). Tamboli et al. (2023) also noted that nanoscale particles had higher Curie temperatures, strong coercive fields, and low saturation magnetization than their bulk counterparts.

Nickel ($NiFe_2O_4$) and cobalt ($CoFe_2O_4$) Ferrites are applicable because they are chemically stable, have a low melting point, are catalytic, and have a high specific heat capacity, coercivity, saturation magnetization, and conductivity. Their particle size and composition can suit various uses (Dippong et al., 2019).

Because of the nature of their magnetic dipole moments, cobalt ferrites are hard ferrite materials with high magnetocrystalline anisotropy, exceptional chemical stability, mechanical hardness, and saturation magnetization. They have recently found applications in photocatalysis, MRI, biomedical diagnostics, hyperthermia, drug delivery, high-density digital recording, and biomedicine (Torkian et al., 2017). However, it cannot attain high initial susceptibility due to its substantial magnetocrystalline anisotropy (Torkian et al., 2017). A typical soft magnetic material, $NiFe_2O_4$, has low magnetocrystalline anisotropy because Ni^{2+} substitutes Co^{2+}, significantly decreasing the anisotropy of $CoFe_2O_4$ (Dippong et al., 2019).

As (Khan et al. (2021), the composition and microstructure of magnetic ferrite nanoparticles and the synthesis method and conditions significantly impact their structural, magnetic, and surface properties.

1 Nickel-doped cobalt ferrite nanoparticles (NCFNPs)

1.1 Basics

The flexibility to substitute components makes ferrite nanoparticles one of the most prominent benefits for producing a material appropriate for a particular purpose. Doping with various elements is an ideal method for modifying the behavior of ferrites because it alters the structure, crystallinity, and element distribution between the tetrahedral (A) and octahedral (B) sites of the dopant and doped ions (Dou et al., 2020). Kavitha and Kurian (2019) state that dopants determine doped cobalt ferrites' magnetic, structural, and electrical properties by quantity, valency, size, and site preferences.

Dipping divalent metal ions with cobalt ferrite alters its inverse spinel structure. The ratio of cobalt to the dopant ion affects how quickly regular spinel changes to inverse spinel. Modifying the hard-magnetic substance cobalt ferrite by doping it with soft and non-magnetic ions is possible (Cadar et al., 2020), (Andhare et al., 2020).

Compared to nickel in its elemental form, nickel nanoparticles display remarkable electrochemical capabilities, extraordinary superparamagnetic properties, and stability, making them highly desirable in nanotechnology. In addition, nanoparticle nickel has been used in medicine as a catalyst for producing hydrogen nanoparticles (Ahamed and Alhadlaq, 2014). Some investigations have shown that nickel nanoparticles generate cytotoxic effects in vitro and platelet shape changes (Di Bucchianico et al., 2018). Nonetheless, despite their widespread use in industry, they can potentially be hazardous (Hante et al., 2019).

The uses of nanoparticle magnetic materials in high and low-frequency equipment, drug delivery, magnetic resonance imaging, recording medium, ferrofluid, sensors, catalysts, and magneto-optical equipment have long attracted considerable interest. These nanoparticles have a significant impact because of their unique electronic, optical, radiation shielding, magnetic, and low or high magnetic coercivity, typically altered bulk structure (Desoky et al., 2022). In addition, magnetic nanoparticles have recently attracted much interest in biomedicine due to their beneficial magnetic, optical, and antibacterial capabilities at the nanoscale (Nigam and Pawar, 2020).

According to research, the widespread use of magnetic properties depends significantly on the crystal orientation composition (elemental), particle size, cations, and anions ionic distribution between tetrahedral and octahedral as stated by (Dippong et al., 2021). Furthermore, as Melo et al. (2018), conferring, chemical composition, crystalline size, morphology, and cation distribution over A and B sites can all be altered to alter the magnetic and electrical properties. Additionally, high surface-to-volume ratios and finite size effects cause numerous atoms to congregate at the surface of magnetic nanoparticles, which results in several intriguing and superior properties compared to bulk materials (Margabandhu et al., 2016).

According to Nikumbh et al. (2014), Spinel ferrites have attracted much attention due to their prospective applications in magnetic bulk cores, low-temperature high-density ferrites, suspension materials in ferromagnetic fluids, and catalysis. Ferrites are widely employed in the electronics sector (Nikumbh et al., 2014), magnetic freezers, microwave devices, color imaging, and high-density recording devices (Ding et al., 2016), among other applications.

As a result, according to Hieda et al. (2018), the general formula of the spinel ferrites is $(A)[B]_2O_4$, with eight formula units contained in each spinel unit cell. The larger oxygen anions pack densely into a face-centered cubic structure, while the smaller metal cations fill the tetrahedral (A) and octahedral (B) interstitial spaces.

Several variables, including the preparation process, chemical makeup, and sintering temperature, affect how cations are distributed in the crystal lattice. The characteristics of ferrites are altered by changing the placement of cations and anions at tetrahedral and octahedral sites, respectively. The difference between the magnetization of these two (A) and (B) sublattices is what makes up hard ($CoFe_2O_4$'s) and soft ($NiFe_2O_4$'s) ferrites net magnetization (Ortiz-Quiñonez et al., 2018).

According to several studies, both nickel and cobalt ferrite nanoparticles crystallize in the inverse spinel structure, represented by (Ni^{2+}) $[Fe_2^{3+}]O_4^{2-}$ and (Co^{2+}) $[Fe_2^{3+}]O_4^{2-}$ are Fe^{3+}, $Ni^{2+,}$ and Co^{2+} ions shared the sites of octahedral (A-site). In contrast, $Fe3^{+}$ ions occupied the tetrahedral (B-site) respectively (Stein et al., 2018).

As a result of the Ni2+ ions present in the nickel substitution cobalt ferrites, they exhibit low crystallographic anisotropy, increased resistivity, and higher saturation magnetization, which is supported by (Melo et al., 2018).

Recent studies show that nickel nanoferrites are widely used in different devices such as magnetic data storage, biological sectors, electronic systems radar, and microwave; because nickel nanoferrites have unique properties, such as high electrical resistance and high permeability at high frequencies (Kiani et al., 2023). Nickel ferrite, a cubic ferromagnetic oxide, can have this remarkable feature because it can display surface disorderliness.

Numerous investigations have been sieved on integrating soft and hard magnetic materials to generate unique and affordable multifunctional nanoparticle materials. However, reasonable control is needed on both the percentage between the soft (for example, nickel) and hard magnetic compounds (for example, cobalt ferrite nanoparticles) magnetic nanoparticle size in the produced material to customize its variety of ferrite nanoparticle properties for various applications (Maaz et al., 2009).

1.2 Synthesis techniques

Synthesis plays a significant role in determining materials' fundamental properties and characterization. Extreme changes in the physical and chemical characteristics were seen whenever the bulk ferrite particles changed into nanoparticles.

The synthesis process significantly influences numerous characteristics, including particle size, anion and cation distribution, texture, and electrical, magnetic, and optical properties. To tune ferrite's various features for particular purposes, scientists have recently developed a method for creating ferrite by regulating its size, shape, and chemical composition (Vinod et al., 2021). Spinel ferrites have been made using many different methods, such as high-temperature self-propagating and combustion, hydrothermal, micro-emulsion, solvothermal, solid-state reactions, sol-gel, and co-precipitation (Agrawal et al., 2016; Abdullah et al., 2022; Khan et al., 2021).

1.2.1 Sol-gel

Sol-gel is a simple, accessible, low-temperature preparation method that enables precise chemical and microstructural control, according to Shanmugavel et al. (2014). This expert claims that a lot of homogenous mono and multicomponent oxides, high-purity oxide powders, and films, including substances like spinel, have been made using this technique. This method has several advantages, such as a low-temperature synthesis procedure, the ability to synthesize various materials, a vacuum-free environment, monodisperse particles, and predetermined stoichiometric compounds (Joshi et al., 2018).

The sol-gel approach is more effective for the mass production of ferrite NPs in the necessary sizes and shapes. According to Sutka and Mezinskis (2012) and Islam et al. (2022), this process is relatively easy, quick, and economical and provides good chemical uniformity with little external energy use. Changing the annealing temperature and synthesis conditions makes it possible to modify the produced ferrites' size, surface area, and morphology (Sharma et al., 2019).

1.2.2 Hydrothermal

This technique is also called solvothermal synthesis. Hydrothermal procedures are efficient and effective for creating magnetic nanoparticles, according to research by K. et al. (2020). Ch et al., 2019). The crystallite size and morphology depend on the sintering temperature, so they can be easily controlled using hydrothermal and all other techniques.

Hydrothermal is a well-known solution reaction-based method for producing MNPs at high pressure and temperature. MNPs are created via the hydrothermal process of oxidation and hydrolysis. By employing the stated procedure, uniform-sized particles of various magnetic nanomaterials can be produced. This approach makes them with high crystallinity, a stable composition, and nanoparticles of desirable shape and size (Ali et al., 2021).

1.2.3 Co-precipitation

According to Vashist (2013), co-precipitation is the technique most frequently employed to create MNPs with regulated size and magnetic characteristics. It is commonly employed in biomedical applications and involves using less harmful materials and methods. This method typically produces NPs with desirable magnetic characteristics and tunable sizes. MNPs are created by dissolving various metal ions in a solvent (Ali et al., 2021).

Co-precipitation is a straightforward and low-cost technique for adjusting the nucleation and growth rates during synthesis to regulate size and ion distribution. The particles are commonly coated with a surfactant, such as oleic acid, and then dispersed in a liquid, like ethanol, methanol, or ammonia, to prevent oxidation and agglomeration. In some experiments, the precipitating agent is promptly added to the salt solution, and the reaction is aggressively agitated throughout (Maaz et al., 2007).

Co-precipitation is easy to accomplish and requires no special equipment. This technique is used to create core-shell nanoparticles, and the only way it differs from co-precipitation is in how long it takes to add the shell before dialyzing the particles (Houshiar, 2014).

2 NCFNPs characteristic and Electro-magnetic applications

Based on their sensitivity to the magnetic field, ferromagnetic materials are classified as either "soft" or "hard" magnetic. Soft magnetic materials have low coercivity (Hc) and demagnetize in weak magnetic fields. As a result of their ease of magnetization, soft magnetic materials, on the other hand, have a higher permeability than hard magnetic materials. As a result, a ferromagnetic material needs to have low magneto-crystalline isotropy for the magnetic domains to move around quickly (Gubin, n.d.; Houshiar et al., 2014).

Investigation and sieving of nanoparticles, particularly the combination of hard and soft magnetic materials, is one of the most prominent research areas at the moment due to their numerous applications in data recording, drug delivery, electric, biological, and magnetic materials (Maaz et al., 2009), (Sabbar et al., 2023).

Researchers have put much effort into creating various nickel-substituted cobalt ferrite nanoparticles. For instance, Chitra et al. (2014) attempted to build a $Ni_{0.4}Co_{0.6}Fe_2O_4$ nanocomposite using in situ chemical polymerization while ultrasonically processing ferrite nanoparticles produced through a urea-assisted solution combustion process.

In addition, Maaz et al. (2012) also attempted to produce $Co_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticles via co-precipitation; instead of a single homogenous phase, they obtained a combination of Ni- and Co-ferrite. Individual ferrite phases are unquestionably present in the sample based on magnetic hysteresis loops exhibiting beehive-like behavior.

By adjusting the nickel doping percentage, nickel-doped cobalt ferrite nanoparticles can customize their magnetic properties. Dippong et al. (2019) found that as the nickel concentration in the mixed Ni-Co ferrites went up, the activation energy of each ferrite ($NiFe_2O_4$ $Ni_{0.3}Co_{0.7}Fe_2O_4$, $Ni_{0.7}Co_{0.3}Fe_2O_4$ and $CoFe_2O_4$) embedded in silica went down from 13.530 to 1.944 kJ mol^{-1}. This study used FT-IR spectroscopy to determine how succinate precursors were made and broken down and how silica matrix formed. The XRD shows that $CoFe_2O_4$ and $NiFe_2O_4$ can be made in a single phase. It also shows that the size of the nanocrystallites decreases from 31.7 nm for cobalt ferrite to 18.5 nm for nickel ferrite. Moreover, mixed Co-Ni ferrites had optical band gaps substantially more extensive than the corresponding $CoFe_2O_4$.

Nickel-doped cobalt ferrite nanoparticles having the general formula $Ni_xCo_{1-x}Fe_2O_4$ (x = 0.0, 0.3, 0.5, 0.7, and 1.0) synthesized by Desoky et al. (2022) using the co-precipitation method. When Ni2+ ions were used instead of Co2+ ions, the lattice parameter, porosity, and hopping lengths in tetrahedral and octahedral sites shrank. Additionally, this study found that the ions Co2+ and Ni2+ significantly occupy the octahedral B-site. However, they occupy tetrahedral and octahedral positions at greater Ni^{2+} ion concentrations. According to this finding, high-resolution transmission electron microscopy reveals that sintered powders are nearly spherical, polyhedron-shaped, and have a diameter of approximately 39–45 nm, and saturation magnetization, magnetic anisotropy, coercivity, and remanence decrease with an increase in Ni^{2+}.

The findings indicate that the material is ideal for photodegradation and dye removal catalysis, which could be recommended for future uses for these intriguing samples (Desoky et al., 2022). As a result, Ni-doped cobalt ferrites may be promising candidates for a wide range of magnetic applications.

According to the findings of (Kumar et al., 2019), the $Co_{1-x}Ni_xFe_2O_4$ (x = 0.02, 0.04, and 0.06) is synthesized by the sol-gel auto-combustion process, and its structural, functional, magnetic, and morphological properties are analyzed. When the nickel concentration increases from 0.02 to 0.06, the average crystallite size drops from 31 to 27 nm, indicating the inclusion of Ni^{2+} ions in the cobalt ferrite lattice. Raman spectroscopy reveals spinel ferrites' distinctive stretching vibrations at 486.87 cm^{-1} and 696.96 cm^{-1}, which are the characteristic vibrations of spinel ferrites.

Aside from structural studies, magnetic property studies show that the saturation magnetization (MS = 20.25, 9.41, and 18.5 emu/g) and coercivity (H_C = 746.06, 953.03, and 885.59 Oe) change as the concentration of Ni^{2+} ions goes from 0.02 to 0.04 to 0.06 respectively Kumar et al. (2019). The magnetic nature of the compound indicates that the ferromagnetism of the nanoparticles is due to the formation of an antiparallel spin and the magnetic moment created by the cation at tetrahedral and octahedral sites.

The optical bandgap (Eg) values decreased with the Ni^{2+} ion concentration (x), from 2.94 eV for x = 0 to 2.51 eV for x = 1, as demonstrated by the hydrothermal synthesis of nickel-doped cobalt ferrite Co_{1-x} $Ni_xFe_2O_4$ (0:1) nanoparticles (Melo et al., 2018).

The magnetic characteristics are influenced by the presence of nickel in the cobalt ferrite structure. For example (Melo et al., 2018), as expressed by substituting nickel on cobalt ferrite nanoparticles between x = 0:1, the saturation magnetization and remanent magnetization fell from 369 to 256 emu cm^{-3} and 131 to 45 emu cm^{-3}, respectively. However, the coercivity (Hc) increased from 890 Oe to 1590 Oe for x = 0 and x = 0.6 and decreased dramatically to 50 Oe for x = 1. The study highlighted the higher coercivity regarding particle size, flaws, and residual strain, which may operate as pinning centers.

Ridha and Khader (2021) used a sol-gel auto-combustion procedure to create nickel-doped cobalt ferrites nanoparticles of $Co_{1-x}Ni_xFe_2O_4$ (x = 0, 0.5, and 1) at a low temperature (200oC). For balancing the oxidizing agent to reducer ratio, citric acid was used as a chelating agent with a solution of nickel nitrate and ferric nitrate in a 3:1 ratio. The computed crystallite size from the full width at half maximum of the brightest peak (311) is in the 27- 44 nm range. While the crystallite size of $Co_{0.5}Ni_{0.5}Fe_2O_4$ NPs is more significant than that of $NiFe_2O_4$, it is smaller than that of $CoFe_2O_4$ NPs.

Also, this work shows that SEM pictures of NPs show that they are spherical and have a uniform shape, with particle sizes ranging from 25 to 47 nm. The distribution of the grains for cobalt ferrite is better than that of nickel and Co-Ni ferrites, and the samples' average grain size is greater than the crystallite size estimated using XRD measurements (Ridha and Khader, 2021).

Hieda et al. (2018) looked at $Ni_{0.9}Co_{0.1}Fe_2O_4$ nickel replacement cobalt ferrites because they are good candidates for magneto-mechanical sensors and electro-magnetic wave absorbers. Before forming, it was discovered that sifting the calcined powder enhanced the ceramic's flexural strength. Additionally, the discovery reveals that the actual magnetic permeability of the complex fluctuated between 2.2 and 2.3 at frequencies between 100 MHz and 1 GHz.

Nickel ferrites with cobalt doping were also investigated as a potential advancement and replacement for the recording medium. As a result, Ati et al. (2014) researched $Ni_{1-x}Co_xFe_2O_4$ produced using the co-precipitation method (0.0, 0.2, and 1.0). The XRD spectra of this investigation revealed the single-phase spinel structure, and it is assumed that the average size of the nanoparticles is 16–19 nm. These small enough sizes enable a high signal-to-noise ratio in the high-density recording medium. The lattice parameter and coercivity expand monotonically when Co concentrations increase because of the cobalt ion's larger ionic radius, as in the studies of Ati and his colleagues.

Co_xNi_{1-x} Fe_2O_4 (x = 0.2, 0.4, 0.6, 0.8) nanoparticles with cobalt added were made using a low-temperature hydrothermal process. Their structure and physical properties were studied. Consequently, X-ray diffraction estimates that the size of the structural crystallites is 18.9 to 24.09 nm (Khan et al., 2021).

Studies of the samples using XRD and other methods show that the lattice parameters of $Co_{0.5}Ni_{0.5}Fe_2O_4$ NPs are more significant than those of $NiFe_2O_4$ but smaller than those of $CoFe_2O_4$ NPs.The NPs' high coercivity (Hc, 875 Oe) shows that they behave in a harsh ferromagnetic way. Thus, the VSM confirmed that the saturation magnetization (Ms) of $Co_{0.5}Ni_{0.5}Fe_2O_4$ NPs is between the saturation magnetization values of $CoFe_2O_4$ NPs and $NiFe_2O_4$ NPs. According to Ortiz-Quiñonez et al. (2018), the catalytic behavior of the synthetic spinel nanoparticles showed that samples containing metallic Ni are effective catalysts for the aqueous medium-based degradation of 4-nitrophenol.

3 NCFNPs Application for Antibacterial

Due to the fast growth of nanoscience and technology, much work has been done in recent years to make adaptable nanomaterials that can be used as new antibacterial agents against a wide range of bacterial pathogens (Miller et al., 2015). Li et al. (2019) found that bacteria are less likely to become resistant to nanomaterials than traditional antibiotics. Because nanomaterials have a high membrane permeability and are biocompatible, and have the potential to do many different antibacterial activities.

According to Sharma et al. (2019), even in the post-antibiotic era, the fact that many harmful bacteria are resistant to common antibiotics is cause for concern. Gram-positive and Gram-negative bacterial strains harm human and animal life, prompting the development of a new alternative technique. The field of nanotechnology is ideal for tackling a variety of environmental issues.

Spinel ferrite NPs, a type of magnetic nanoparticle, have recently attracted much attention from the academic community for their potential to restore antibacterial activity. Spinel ferrite NPs, a type of magnetic nanoparticle, have recently attracted much attention from the academic community for their potential to restore antibacterial activity. According to Bose and Banerjee (2015), the transition-metal-substituted cobalt ferrite NPs exhibit the best contact biocidal properties out of all the NPs. Cobalt ferrite NPs exhibit the highest biocompatibility of these metal ferrite NPs, and their antibacterial activity makes them a suitable option for antibacterial uses in industrial, food, and medical areas. Nickel ferrite nanoparticles are an excellent way to clean up polluted water because they have potent properties that stop microbes from growing. They exhibit outstanding antibacterial capabilities against S. aureus and Pseudomonas aeruginosa (Iqbal et al., 2019).

Alternative antimicrobials are gaining popularity due to rapidly rising bacterial resistance to conventional medications. In this regard, there is a lot of interest in creating innovative, multifunctional materials with antimicrobial properties that can be used to develop drug-delivery systems that minimize the concentration of antibiotics. Dangerous microorganisms react more strongly to ferrite nanoparticles because of their nanoscale particle size and high surface-to-volume ratio. Because of their high surface area, small crystallite size, and porosity, NPs have a much higher efficiency even at low (20 ppm) concentrations (Ashour et al., 2018). The main drawbacks of employing these materials are that changes in their size, shape, and crystallinity are easily capable of causing variations in their antibacterial properties (Webster and Seil, 2012).

Metals and metal oxides are used in medicine in the age of nanoparticles when antibiotic-resistant microbes constitute a significant health risk. Sharma et al. (2019) demonstrated that cobalt ferrite nanoparticles showed promise in vitro antibacterial activity against gram-positive and gram-negative bacteria (15 mm).

Sabbar et al. (2023) used the co-precipitation method to make $Co_{x-1}Ni_xFe_2O_4$ nanoparticles (NPs). XRD found the cubic spinel phase, and the size of the crystals ranged from 19.5 to 24.2 nm. It has been found that $Co_{x-1}Ni_xFe_2O_4$ nanoparticles release ions into the environment. These ions bond with the protein group (-SH) on bacterial cells, which causes the cell membrane to break and the cell to die.

Naik et al. (2019) made nickel-doped cobalt ferrite nanoparticles from the plant extract of Andrographis paniculate with the help of microwaves. In the FTIR spectrum, ferrites' two prominent absorption peaks are 584 and 393 cm^{-1}, respectively. The cubic lattice structure of ferrites is visible in XRD, and when nickel dopant concentration increases, the lattice parameter drops.

According to some findings, the potential use of these NPs in wastewater treatment and food-packing industries is pretty promising. As (Naik et al., 2019) findings show, Ni-doped CoFe2O4 nanoparticles have enhanced antibacterial activity against food-borne infections in the food packaging sector. Hence, compared to pure CoFe2O4 nanoparticles, the antibacterial activity increased by Ni doping.

This time is urgently needed for the development of novel materials for biomedical purposes. In the current study, Gram-negative and Gram-positive bacteria, which are prevalent pathogens, are used to evaluate the antibacterial characteristics of $Co_{0.5}Ni_{0.25}Mg_{0.25}$ Fe_2O_4 NPs, were very effective against both P. aeruginosa and S. aureus, with 6 mm and 6.5 mm inhibition zones, respectively. The results suggest that nanoparticle bacteriostatic properties could be used in many ways, such as in hyperthermia, antibacterial treatments, and the delivery of drugs to specific areas (Kiani et al., 2023).

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