Chapter 1

“Ferrites”: Synthesis, Structure, Properties and Applications

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Abstract

Ferrites synthesis method and characterization techniques are attracting huge attentions of researchers because of their wide scope of uses in numerous areas. The ferrites include high resistivity, saturation magnetization, permeability, coercivity and low power losses. The above-mentioned useful ferrites characteristics make them appropriate for use in different applications. These ferrites are used in biomedical field for cancer cure and MRI. Electronic applications are transformers, transducers, and inductors which are also made using ferrites and also used in making magnetic fluids, sensors, and biosensors. Ferrite is a profoundly helpful material for many electrical and electronic applications. It has applications in pretty much every domestic device like LED bulb, mobile charger, TV, microwave, fridge, PC, printer, etc. This review mainly focus on the synthesis method, characterization techniques, and implementation of FNPs. This Chapter presents various methods used for ferrites preparation with distinctive examples, their advantages as well as limitations in detail. Ferrites properties like structural, optical, electrical and magnetic with their characterization techniques and various applications in the areas of biomedical, electronics, and environment are also discussed.

Keyword

Ferrites, Magnetic-Nanoparticles, Synthesis, Characterization, Biomedical Applications

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1. Introduction

The name ferrite comes from the Latin word ‘Ferrum’ meaning iron [1]. Magnetite (Fe_3O_4) also called Lodestone, a natural mineral is a genuine ferrite. Ferrites are derived from magnetite and hematite (Fe_2O_3) along with other metal oxides. A ferrite is a ceramic-like magnetic material with ferromagnetic ordering (in macroscopic phase) mainly composed of a small proportion of one or two metallic elements with a large iron oxide ($\alpha\text{-Fe}_2\text{O}_3$) proportion. In modern days, ferrites have gained immense attention as magnetic nanoparticles because of their distinctive structural properties, surface reactivity, electrical properties and magnetic properties and the nanostructured phase greatly influenced all these properties [2-10] which are not the same as the bulk material. Nanoparticles are ranged between 1 and 100 nm in size.

At the nanoscale nanoparticles display exceptional physical, chemical, and biological properties contrasted with their individual particles at high scales. This occurrence is because of a relatively larger surface area to the volume, increased reactivity or stability in a chemical process, enhanced mechanical strength, etc. Macro-structured have the same properties as the bulk material. **On the surface, the number of particles increases as the particle size decreases.** Surface atoms can move easily because they have less coordination number as compared to inner atoms. quantum size effects appears when the size of nanoparticles approaches the de Broglie wavelength limit and diameter reaches smaller than the quasiparticle interaction [11]. Controlling size of nanoparticles during synthesis by utilizing various methods, controlling of nanomaterials properties is feasible. The electronic property depends upon electronic band structure of a metal. The band structure depends upon the size of the particle. The delocalized bands are seen in the molecular states. The band structure of nanocrystal is in between the discrete states of atoms (and molecules) and continuous bands of crystals. The adjacent lines energy separation depends on the particle size. As the size decreases, the separation of energy levels increases. The metallic nature decreases and gradually changes to the semiconductor nature. There are various kinds of magnetic materials (dia, para, ferro, antiferro, ferromagnetic materials) [12]. Magnetic material are distinguished as the soft and hard materials on the bases of their coercivity. Low coercivity belongs to soft magnetic material with a small hysteresis area and these are magnetized by a low magnetic field and vice-versa. The coercivity will change with the particle size. Generally, on decreasing grain size and increasing the surface area the coercivity and also the saturation magnetization increases. So, the nanoparticles have an additional surface

area with less grain size with high magnetic strength. If further, size of the particle decreased then the ferromagnetic particles changed to paramagnetic due to instability. The behaviour of these paramagnetic materials is different than the bulk magnetic material due to which they called superparamagnetic. The material interaction with light is called optical property. This property arises because of surface plasmon and electrons quantum confinement. The surface plasmon resonance energy will evaluated by dielectric medium and free electron density of the nanomaterial. This property also depends upon the size, shape, doping, surface characteristics, and also on the surrounding environment interaction. All properties generally rely upon the size and state of nanomaterials. So the controlling and control of nanomaterials properties is conceivable by controlling their size during their preparation by utilizing various techniques [13, 14]. **Figure 1** depicts the immense research attention in the research community from various researchers for ferrites.

Figure1: As per Scopus data, the number of publications for the keyword “ferrites” from 2012 to 2020.

2. Magnetic material and types of magnetism

Classification of materials can be done by how they respond in an applied external magnetic field [4, 12]. When the magnetic field is applied externally, the atomic current loops, which arise due to the electrons orbital motion counter to oppose it. Depictions of the magnetic moments orientations help to classify different type of magnetism. Diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism and ferrimagnetism are the five fundamental kinds of magnetism. This classification is associated to the material net magnetization and magnetic dipole, the behaviour of which is schematically represented in **Figure 2**.

a) Diamagnetism: The materials show a kind of weak repulsion in an externally applied magnetic field well-known for diamagnetism. Nonetheless, diamagnetism is feeble, and accordingly some other type of magnetic behaviour that material may have usually overcome the effects of the atomic current loops. In terms of materials electronic configuration, materials which have filled electronic sub-shells and so have paired magnetic moments and on the whole cancel each other. Diamagnetic materials possess a negative susceptibility $\chi < 0$ so examples of diamagnetic materials are quartz SiO_2 and calcite CaCO_3 . The effects of atomic current loops can be overpowered if the material exhibits magnetic moments with long-range order or a net magnetic moment.

b) Paramagnetism: All other kinds of magnetic behaviour shown by materials have unpaired electrons, frequently in the 3d and 4f atomic shells of each atom. Materials whose atomic magnetic moments are unpaired show paramagnetism. Thus, paramagnetic materials moments have a little positive magnetic susceptibility $\chi \approx 0$ and have no long-range ordering e.g., montmorillonite and pyrite.

c) Ferromagnetism: Materials that own ferromagnetism have aligned equal atomic magnetic moments and there is direct pairing interactions among the moments in their crystalline structure, which can strongly boost the flux density. Some examples are Fe, Ni, and Co. Furthermore, even in the absence of externally applied magnetic field, in ferromagnetic materials the aligned atomic moments can give a spontaneous magnetization. The Materials that preserve permanent magnetization even if the applied field is absent are hard magnets.

d) Antiferromagnetism: Materials in which equal atomic magnetic moments in magnitude arranged antiparallely show antiferromagnetism for instance troilite FeS , ilmenite FeTiO_2 etc. Due to antiparallel exchange interaction coupling of moments net magnetization is zero. Above the Neel temperature (T_N), the material exhibits paramagnetic behaviour because there is enough thermal energy which randomly

fluctuate the antiparallely aligned atomic moments which leads to the vanishing of long-range order of materials.

e) **Ferrimagnetism:** Ferrimagnetism is shown by materials in which atoms or ions have non-parallel ordered arrangement in absence of applied magnetic field below the Neel temperature. In the typical case, a significant net magnetization is due to the antiparallel arrangement of ions within a magnetic domain. These have higher saturation magnetization as compared to ferromagnetic materials. Ferrites (e.g., Fe_3O_4) are ferrimagnetic materials where cations (metal) and anions (oxygen) arranged with this fashion in the crystal lattice.

f) **Superparamagnetism:** Superparamagnetism arises when size is reduced in magnetic materials leading the creation of single-domain of particles. Briefly, superparamagnetism arises when an applied field or thermal fluctuations can easily displace the magnetic moments to the chosen crystallographic axes where the magnetic moment have to point along.

Figure 2: Schematic illustration of the arrangement of the magnetic dipoles of various types of magnetic materials (diamagnetic, paramagnetic, ferromagnetic, and ferrimagnetic) and representative hysteresis loops that illustrate the magnetic behavior of materials when an external field is applied.

2.1 Classification of ferrites based on response in a magnetic field

Based on the ability of magnetization and demagnetization, there are two types of ferrites; soft and hard [9, 15]. Coercive force (H_c) which is the main property of these magnetic substances.

Soft ferrites: Materials with low H_c are termed as magnetically soft, easy to magnetize, and demagnetize. With a narrow hysteresis loop these materials exhibit soft magnetic properties for example high permeability, low coercivity, and high value of saturation magnetization and are free of magnetic field amplitude. They utilized the field of electronics to make effective magnetic cores for transformers, high-frequency inductors, antennas and in different microwave parts. Ferrites used in electromagnetic cores containing Ni, Zn, or Mn are soft ferrites. They are widely used to make the cores of RF transformers, Switched-Mode Power Supply (SMPW) and inductors due to their relatively low losses at high frequencies.

Hard ferrites: Ferrites with higher H_c are termed magnetically hard materials. Once magnetized hard ferrites retain their magnetization. With a wide hysteresis loop hard ferrites have high coercive strength [7]. These ferrites are used as permanent magnets for applications such as refrigerator magnets, loudspeakers, and small electric motors. In contrast to soft ferrites, hard ferrites (permanent ferrite magnets) have a high value of remanence after magnetization and are prepared using iron oxide with barium/strontium oxides. These ferrites conduct magnetic flux pretty well in a state of magnetic saturation, and have a high value of magnetic permeability. This makes these ceramic magnets ideal for the storage of strong magnetic fields as compared to pure iron [15].

2.2 Classification of ferrites based on crystal structures:

Ferrites generally have classification on the bases of spatial arrangement of oxygen atom around the metal ion i.e cubic close-packed and hexagonal arrangement of oxygen atoms. In the structure the cation must satisfy both size and charge neutrality consideration. Cubic ferrites have two kinds as spinel ferrites and garnet ferrites. **Figure 3** shows different crystal structures of ferrites. A brief explanation of ferrites crystal structures is given below:

Spinel ferrite:

Various anions including sulphur (thiospinels), chlorine (halospinels), and oxygen can form spinel structures. Spinel ferrites with the general formula $MeFe_2O_4$ or $A[B_2O_4]$ where Me refers to the metal, can be depicted as a cubic close-packed arrangement of oxygen atoms at two different crystallographic sites with Me^{2+} and Fe^{3+} . These sites have tetrahedral (A-sites) and octahedral (B-sites), oxygen coordination and hence, both sites

have different resultant local symmetries. In the spinel structure metal cation occupies cation sites. One is 8 A-sites where the metal cations with oxygen are coordinated tetrahedrally and the second is 16 B-sites that have octahedral coordination. Depending upon the arrangement of metal cation Me^{2+} , ferrosinels further classified as:

Normal spinel structure $A[B_2O_4]$: In this all Me^{2+} cations occupy A(tetrahedral) sites and Fe^{3+} cations in B (octahedral) sites; the structural formula for these ferrites is $Me^{2+}[Fe_2^{3+}]O_4^{2-}$. This kind of arrangement occurs in $CdFe_2O_4$ and $ZnFe_2O_4$.

Inverse spinels, $B[ABO_4]$: Here the Me^{2+} ions occupy the B (octahedral) sites and Fe^{3+} ions are arranged over both B octahedral and A tetrahedral sites. Fe^{3+} cations occupy the A-sites completely and Me^{2+} and Fe^{3+} cations occupy the B-sites randomly; the structural formula of inverse ferrites is $Fe^{3+}[Me^{2+}Fe^{3+}]O_4^{2-}$. Magnetite Fe_3O_4 , ferrites $MgFe_2O_4$, $NiFe_2O_4$ and $CoFe_2O_4$ have inversed spinel structure.

Mixed spinels, $A_{1-x}B_x[A_xB_{2-x}O_4]$ or $(Me_{1-x}Fe_x)[Fe_{2-x}Me_x]O_4$ with Me^{2+} and Fe^{3+} ions distributed over both octahedral and tetrahedral sites e.g. $MnFe_2O_4$. Where the degree of inversion is x. In the majority of spinels, the cation arrangement have an intermediate value of degree of inversion and where both sites have a fraction of both the cations (Me^{2+} and Fe^{3+})

Garnet Ferrites:

Garnet ferrites own the silicate mineral garnet structure, $X_3Y_2(SiO_4)_3$, where divalent cations [Ca^{2+} , Mg^{2+} , Fe^{2+}] generally occupy the X site and trivalent cations [Al^{3+} , Fe^{3+} , Cr^{3+}] occupy the Y site in the octahedral/tetrahedral framework where $[SiO_4]^{4-}$ provides the tetrahedra. The general formula $(A_3B_5O_{12})$, or $M_3Fe_5O_{12}$ is for garnet ferrites where M is a rare-earth (yttrium) cation. Crystal structure of garnet ferrites possess three crystallographic lattices sites (a, b, and c). With the octahedral and tetrahedral sites, which are seen in spinels, garnets possess dodecahedral (12- coordinated) sites. $24Fe^{3+}$ ions take place in tetrahedral sites among three lattice sites, $16Fe^{3+}$ ions take place octahedral sites and $24R^{3+}$ ions go on the dodecahedral sites, while oxygen ions are arranged in the interstitial sites [16]. The net ferrimagnetism is therefore a complex result of spin alignment among these three types of sites. Garnets are magnetically hard. While spinels have superior magnetization properties, garnets have superior dielectric properties, as these are more stress-sensitive than spinels.

Hexagonal ferrites:

The magnetic mineral magneto plumbite $PbFe_{12}O_{19}$ was first described in 1925 have a hexagonal structure, so they are called as hexagonal ferrites and possess the general composition, $MeFe_{12}O_{19}$ where (Me= Ba, Pb, Sr). These ferrimagnetic oxides contain a

principal component, Fe_2O_3 in combination with divalent oxides (BaO , PbO , or SrO). Hexagonal ferrites have high uniaxial anisotropy, high magnetization values, and good chemical stability, consequently fitting very well in the necessities of recording technology. Films of hexaferrites of $\text{BaFe}_{12}\text{O}_{19}$ are capable candidates for microwave wave devices and high-density recording media [17, 18].

Figure 3: Schematic representation of (a) perovskite ferrite (b) garnet ferrite (c) spinel ferrite and (d) hexagonal ferrite structure.

Perovskites ferrites:

Cubic perovskite or ortho ferrites structure has the general formula ABX_3 , where cations A and B have different oxidation numbers and with anion X. The cation A resides at the center, while the arrangement of cation B and the anions X are in the corners and at the edges of the unit cell, respectively [19]. Rare earth ferrites RFeO_3 compounds such as orthoferrites of lanthanum and samarium are two most considered materials [20, 21]. BiFeO_3 [22]. Perovskite ferrites nanoparticles had shown strong absorption at nearly 590

nm arising from the bandgap absorption, which has applications of environmental purification and/or water splitting.

The commonly known soft ferrites Mn–Zn ferrite, Ni– Zn ferrite, etc. whereas BaFe₁₂O₁₉ and SrFe₁₂O₁₉ are examples of hard ferrites. It is well established that the ferrites magnetic properties depend upon chemical compositions, microstructure, crystal structure, particle size, and also the surface area of the material. The methods of material preparation greatly influence these parameters.

3. Formation of ferrites nanoparticles

Ferrites nanoparticles (FNPs) formation can be done by two kind of approaches top-down and bottom up as shown in **Figure 4**. To get nanoparticles the bulk material is broken down in the **top-down**. Top down has many limitations for example the constraint of high temperature, inhomogeneity, presence of impurities, crystal defects, broad size distribution, surface imperfection. On the other side, the **bottom-up** puts together small atomic building blocks to form nanoparticles and is the mainly approving approach as the nanoparticles formed in these methods are homogeneous, highly pure and narrow size distribution. **Table 5** shows the electrical, magnetic, and optical properties of ferrites with different methods.

Fabrication of NPs further includes a range of methods such as **physical-chemical, biological and hybrid** methods to fabricate the various kinds of ferrites, the NPs formed by each method exhibit particular properties. Usually, there are four basic steps in ferrite preparation. First step is to prepare the materials to generate an close blend of the metal ions in a ratio which we will require in the final yield. The second step is calculations of the blend to yield a ferrite. In the third step, there is yielding a materials powder and shape it into the requisite form and the fourth one involves the sintering of the processed material to get the final produce. These four steps cannot be isolated; however, only the first step has a different operation. The property and application aspects of the synthesized ferrite depend strongly upon the particle size, composition, and morphology, which are very sensitive to preparation methodology used in their synthesis as given in **Table 1**. Hence ferrite preparation of desired size, composition and morphology has attracted more attention by researchers in the past few decades. Every method possess some advantages and limitations as described in **Table 2** and some important methods which are used for ferrite preparation are discussed below.

Figure 4: Bottom-up and the top-down approaches in ferrites nanomaterials.

3.1 Mechanical milling

Among the various top-down methods, mechanical milling is extensively used to yield various nanoparticles. Mechanical milling utilized for milling and post-annealing of NPs through synthesis by milling different elements in an inert atmosphere. The influencing factors in mechanical milling are plastic deformation that leads to particle shape, crack leads to reduction in particle size, and cold-welding is used to enhance the particle size [23]. Zhigang Zhang et al. [24] have prepared pure NiFe_2O_4 nanoparticles using a planetary ball milling assisted solid-state reaction process. By planetary ball milling one can be lower the temperature to 750 °C to obtain impurity-free NPs of NiFe_2O_4 having wide range of size (35–85 nm) distribution and double morphology (sphere for smaller grains and polygon for larger ones). The v saturation magnetization is improved from 33.4 emu/g at 750 °C to 42.7 emu/g at 800 °C, and coercivity is reduced from 143.2 Oe to 116.6 Oe. But [25] saturation magnetization and coercivity NPs of the NiFe_2O_4 , got from calcining the precursor ground by hands at 800 °C for 1 h, are 46.5 emu/g and 107.6 Oe

respectively. E. Manova et al. [26] synthesized CuFe_2O_4 by two-step procedure, including first co-precipitation and second mechanical milling which together is called mechanochemical synthesis of the co-precipitation precursors. Co-precipitated hydroxide carbonates, used as precursors were prepared from an aqueous solution of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ by dropwise addition of 1 M sodium carbonate up to pH 9 at continuous stirring. The obtained precursor powders were milled by using a Fritsch Planetary miller in a hardened steel vial together with grinding balls with the different diameters (from 3 to 10 mm). Precursors were mechanically milled for 1, 2, 3, and 5h. The phase composition of the as obtained materials depends upon the milling duration. The ferrites catalytic properties are strongly affected by their phase transformations under the reaction medium.

3.2 Thermal decomposition

To control the synthesis of ferrite, solid-state thermal decomposition method is a simple, general and effective method. Thermal decomposition of organometallic precursors for example metallic acetylacetonates and carbonyls in organic solvents and surfactants (oleic acid and hexadecyl amine) for the production of ferrites nanoparticles shown in **Figure 8(b)**. On the bases of the kind of precursor materials, the temperature used can be high or low. Generally, the method can be used for larger production (at the 40 g level per each synthesis) of high-quality crystalline FNPs with size- and shape-controlled output. The method can be used to prepare the FNPs required for industrial as well as medical applications. The strontium ferrite [27] NPs was prepared by a solid-state thermal decomposition without using any catalyst, surfactant, and solvent at 800 °C for 2 h in a horizontal tube furnace having an inner diameter of 10 cm and length of 120 cm. In the typical procedure, a mixture including 1 mmol of the obtained SrC_2O_4 and 2 mmol of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, was put into a small quartz boat. The quartz boat entered into tube furnace in a gas blend of 85% Ar and 15% H_2 . The quartz boat kept in the heating zone at 800 °C for 2 h and afterthat was slowly dragged out of the furnace. The sample was cooled down naturally in ambient conditions. Obtained ferrites particles have nano size of about 40 nanometer and the strontium FNPs showed a ferromagnetic behavior. MnFe_2O_4 [28] nano-ferrites prepared using thermal decomposition method. The stoichiometric amounts of iron (III) acetylacetonate $\text{Fe}(\text{acac})_3$ (6 mmol) and manganese (II) acetylacetonate $\text{Mn}(\text{acac})_2$ (3 mmol) were dissolved in solvent benzyl ether (40 ml) under mechanical stirring. Equimolar amounts of oleylamine(surfactant), oleic acid, and 1, 2-hexadecandiol were mixed with the metal salt solution. The molar ratio of oleic acid, oleyl amine to 1, 2-hexadecandiol was 3:3:5. Solution was transferred to an autoclave reactor bomb and was placed into a preheated oven at 270 °C for 90 min. After cooling, the nanoparticles were obtained. Produced particles are spherical and the mean particle

size ranged ~ 18.9 nm. The influence of aging of the oleate precursor is studied to obtain cobalt ferrite [29] nanoparticles with narrow size distribution and which respond to changes in the magnetic field exclusively by the Brownian relaxation mechanism. It was observed that aging for up to 30 days resulted in changes in the coordination mode between the oleate molecules and the iron/cobalt ions, which in turn influenced the thermal behavior of the iron-cobalt oleate precursor and resulted in the formation of the correct crystal ferrite structure and cobalt ferrite nanoparticles synthesized using the iron-cobalt oleate aged for only 2 days showed poor agreement with the expected ferrite structure, possibly due to the presence of a contaminant phase which may be a cobalt oxide.

3.3 Co-precipitation method

Because of its many advantages, such as being less time-consuming, cost-effective, easy to accomplish, and dependable, the co-precipitation approach is widely utilised for the synthesis of ferrite nanoparticles. It generates a homogenous powder with the highest yield while requiring no organic fuels such as citric acid. Aqueous solutions containing a mixture of divalent and trivalent transition metals (Soluble salts containing Fe(III) are usually utilised as a source of trivalent metal ions) are combined together at a mole ratio of 1:2 in this procedure. On most cases, the experiment is carried out in an alkaline media. To protect these nanoparticles from oxidation and agglomeration in the ambient atmosphere oxygen, they are usually coated with a surfactant such as sodium dodecyl sulphate (NaDS) or oleic acid and then dispersed in a carrier liquid such as ethanol, methanol, ammonia, or other liquids based on the nature of the materials (nanoparticles) to be dispersed. To make high-quality FNPs, the synthesis technique necessitates precise pH adjustment and control. The solution pH is usually adjusted using ammonium solution or sodium hydroxide solution. The solution will then be vigorously stirred in the absence or presence of heat under inert conditions.

The advantage of this technique over the others is that the production rate of ferrite nanoparticles and the disadvantage is the low crystallinity of FNPs [32, 33]. This method is used by many researchers to prepare FNPs such as BiFeO_3 [34], CoFe_2O_4 [35], ZnFe_2O_4 [36]. **Figure 7(b)** describes the fabrication of AFe_2O_4 NPs via the co-precipitation method.

Figure 5: Synthesis of nanoparticles via (a) microwave-assisted [30] (Copyright with permission from Copyright Clearance Centre, License Number, 5024660680757) (b) sonochemical and thermal treatment method adopted by Ashassi-Sorkhabiet al. for the synthesis of ferrites [31]

3.4 Combustion method

The solution combustion technique is of great importance because of its potential advantages like simple, fast production rate, low temperature/cost and produces pure and homogeneous nanoparticles. The combustion process is an exothermic redox reaction between an oxidizer and a fuel. Oxidizer (O) and fuel (F) are used to carry out combustion. The fuel chosen has a very important effect on ferrite prepared. The fuel in this process is either urea or glycine [37, 38] or their mixture [39]. By balancing the oxidising (O) and reducing valency (F) of the reactants, the Stoichiometry $\phi = (O/F)$ is maintained at unity. The purity, crystallite size, shape, porosity, and carbon content of as-prepared samples are all influenced by the F/O ratio [40]. Both raw materials are

dissolved in deionized water with constant stirring and heating at some moderate temperature. Heating will lead to complete oxidation in the open air which results in fine particles having homogenous particles symmetry (**Figure 6(b)**). Some examples of ferrites prepared using this method are α -LiFe₅O₈ and β -LiFe₅O₈ [41], Co²⁺ doped Mg–Mn ferrites [42] etc.

3.5 Hydrothermal method

The hydrothermal synthesis method [43, 44], established at the end of the nineteenth century, is one of the most promising approaches because of its many benefits over others, including its simplicity and the ability to create high crystallinity products at low temperatures. The structure and performance of the hydrothermal products during the process are affected by the parameters, such as the ratio of raw materials, pH value of the solution, hydrothermal temperature, and time [45]. Improvements to hydrothermal treatment, with an emphasis on improving reaction kinetics or optimising experimental conditions, are still a popular area of research. More recently, the inclusion of external energy to hydrothermal treatment, such as microwave energy, sonar, mechanochemical, magnetic, electrical and so on, has created a whole new zone in materials processing known as multienergy processing of naomaterials. Microwave hydrothermal method [46], organic solvent hydrothermal method, ball milling assisted hydrothermal technique, and magnetic field-assisted hydrothermal technique are examples of multi-energy systems. Examples of ferrites prepared by this method are Hexagonal M type SrFe₁₂O₁₉ (SrM) ferrites [47] and NiFe₂O₄ nanoparticle [48]. **Figure 6(a)** shows the preparation of ferrites via hydrothermal method for the preparation of ferrites.

3.6 Sol-gel method

The sol-gel method has many advantages, including better starting material, excellent chemical homogeneity, great stoichiometric control, and the ability to produce ultrafine particles with a narrow size distribution in a comparatively short reaction time at lower temperatures [49, 50]. Sol-gel is one of the wet chemical methods to produce soft magnetic ferrites (**Figure 6(a)**). The reaction starts with a chemical solution that acts as a precursor for either network polymers or discrete particles to form a gel. Metal chlorides and metal alkoxides are commonly utilised as precursors in various forms of polycondensation and hydrolysis. Metal oxides are made by connecting metal centers together with hydroxo (M–OH–M) or oxo (M–O–M) bridges in solution, resulting in metal-hydroxo or metal-oxo polymers. As a result, the sol evolves into a gel-like granulating system that includes both solid and liquid phases with morphologies ranging from discrete particles to continuous polymer networks.

Figure 6: Fabrication of nanomaterial's via (a) Hydrothermal (b) combustion method.

The major advantages of this method were a low synthesis temperature, high purity, energy-saving, small and uniformed particle sizes as well as homogeneous distribution. From the other side, it has drawbacks, such as the fact that this approach is environmentally unfriendly due to the toxicity of some of the alcohol used. Another disadvantage of this process is the expensive cost of raw chemical components, as well as the possibility of segregation in the utilised dopants during gel formation. In addition, high temperatures are required to remove remaining hydroxides from the products [51, 52]. Akhtar et al. [53] used sol-gel technique to prepare Al-doped spinel and garnet nanostructured ferrites for microwave frequency applications. NiCuZn [54] nano ferrite was effectively manufactured employing the sol-gel method with polyvinyl alcohol as a chelating agent. The production of spinel phase at low annealing temperature (500 °C) with tiny spherical particles was observed. The study reveals that material qualities are sensitive to microstructure and can be improved by increasing the sintering temperature by 900, 950, or 1,030 degrees. M_s increases with sintering temperature up to 950 °C, with a highest value of saturation magnetization M_s of 76.76 emu/g, and thereafter diminishes to 72.73 emu/g. The enhanced grain size was due to the increased magnetism with sintering temperature (up to 950 °C). The decrease of M_s after the sintering temperature of 950 °C is due to Zn evaporation at higher sintering temperature resulting

in the formation of excess antiferromagnetic hematite ($\alpha\text{-Fe}_2\text{O}_3$) which is partly converted to magnetite (Fe_3O_4).

3.7 Microemulsion method

Over the last 30 years, microemulsion methods have been widely employed to produce high-quality metal and semiconductor nanoparticles with a narrow size distribution. Size control is also simple to achieve by making slight changes to the experimental parameters. Microemulsions are isotropic, macroscopically homogeneous, and thermodynamically stable solutions made up of at least three components: a polar phase (often water), a nonpolar phase (often oil), and a surfactant [55]. Normal micelle methods, also known as oil-in-water (o/w) techniques, and reverse micelle techniques, also known as water-in-oil (w/o) techniques, are two types of microemulsion procedures. Surfactants are utilised in both cases, and their concentrations are higher than the critical micelle concentration (CMC) **Figure 8(a)** [4]. ZnFe_2O_4 [56] nanoparticles were fabricated via using co-precipitation in water-in-oil microemulsions with a narrow size distribution.

3.8 Green synthesis

As of now, for the preparation of nanoparticles utilizing naturally occurring reagents, for example, organic products, microorganisms as reductants and capping agents, biodegradable polymers (chitosan, and so on), marine green growth, sugars, plant parts (roots, seed, leaf, stem, and latex) could be assessed as best materials for nanotechnology. Moreover, the green blend of nanoparticles offers headway over other ordinary strategies as they are one stage, straightforward, savvy, environment friendly, and often lead to preparing more stable materials and comparatively reproducible [57, 58].

3.9 Other methods

There are many other methods such as sol-gel auto-combustion method [59], standard ceramic process [60], conventional solid-state reaction method [61], citrate-gel route [62], electro spinning method [63] etc. and hybrid methods.

The average size of cobalt ferrite (CoFe_2O_4) nanoparticles produced by combustion, coprecipitation, and precipitation techniques. The average particle size of 69.5 nm for combustion, 49.5 nm for coprecipitation, and 34.7 nm for precipitation samples, which resembled SEM pictures [35]. In all three samples, XRD analysis showed a reverse cubic spinel structure with the space group $Fd-3m$. VSM data revealed a magnetic field saturation value of less than 15 kOe.

Figure 7: Preparation of ferrite using (a) sol-gel (b) co-precipitation method.

The value of magnetization saturation (M_s) was 56.7 emu/g for combustion synthesized samples, 55.8 emu/g for coprecipitation samples, and 47.2 emu/g for precipitation samples. Coercivity (H_c) was 2002 Oe for combustion synthesized samples, 850 Oe for coprecipitation samples, and 233 Oe for precipitation samples. These findings reveal that different NPs production processes can result in diverse particle sizes and magnetic properties. The combustion process has the highest H_c and M_s , whereas the precipitation approach has the lowest. One analysis revealed that the sintering process parameters and chemical compositions have a significant impact on the magnetostrictive capabilities of pure and substituted cobalt ferrites. Controlling the sintering temperature and substitution levels is essential when manufacturing magnetostrictive cobalt ferrites for specific sensors and actuators applications.

Figure 8: Synthesis of nanomaterials via (a) micro-emulsion (b) thermal decomposition method

Table1: Various synthesis techniques and applications of Ferrites.

Ferrites	Synthesis method	Solvent/acid/base used	Temp (°C)	Size	Ms	H _c	Applications	Ref.
MnFe ₂ O ₄	Water in-toluene reverse micelles.	sodium dodecyl benzene sulfonate (NaDBS)	heat treatment at 350 °C for 12 h	7.7 ± 0.7 nm			contrast enhancement agents of MRI and magnetic carriers for site-specific drug delivery	[64]
MnFe ₂ O ₄	combustion method (glycine)	tetra ethylene glycol [TEG] assisted	80°C for the dehydration reaction 300 °C for igniting combustion	30-35	46 emu/g	64G	gas sensor	[65]

MnZnFe ₂ O ₄	Microwave– Hydrothermal (M–H) method	sodium hydroxide (NaOH)	reaction. annealed at 600 °C/20 min using the microwave sintering method	40 nm.	340- 335 mT	construction of transformer with high- frequency application.	[66]
MnFe ₂ O ₄ and Mn/Fe ₃ O ₄ nanowires	Thermal decomposition of Fe–Mn–NA organometallic polymer precursors	deionized water and isopropyl alcohol, nitritotriaceticac id (NA) as a chelating agent	heated at 180 °C in an electric oven for 6 h, dried at 60 °C for 12 h in an oven, heated at 450 °C for 4 h to producing porous nanostructur es	(5–10 nm)	45.9 and 48.7 emu g ⁻¹	water treatment	[67]
NiFe ₂ O ₄	co-precipitation NaOH solution,	oleic acid	a reaction temperature of 80 °C and stirred for 40 min	8–28 nm	9 and 40.5 emu/ g		[68]
NiFe ₂ O ₄	Mechanical Milling Method		1100°C for 3 h	10–31 nm	24	0	[69]
NiFe ₂ O ₄	Hydrothermal process.	Utrica plant extract	200°C for 2 h dried at 40°C for 24 h	~56 ±1 nm	16.10 emu g ⁻¹	Therapeutic properties Cancer biomedical humidity sensors.	[70]
NiFe ₂ O ₄	Sol gel auto combustion method		heating in a water bath at 75 °C thermally treated at 500° C, 700° C, 900° C	65 nm			[71]
NiFe ₂ O ₄	thermal treatment of the precursors		>800 °C for 120 min in the studied	8.5 nm	32 emu g ⁻¹	catalyst for CO oxidation.	[72]

CoFe ₂ O ₄	co-precipitation	NH ₄ OH	pH range, from 7 (neutral) to 12 (highly alkaline). 80°C	6.0±1. 7	35.3 -41.0 emu/ g	2-5 Oe	biomedical applications	[73]
CoFe ₂ O ₄	polymer pyrolysis method.	Polyacrylate salt precursor,	calcined at temperatures of 800, 900, and 1000 °C for 3 h in air	84 to 320 nm	3.42 μB	1100 Oe	spintronic and transparent nanodevices	[74]
fcc-CaFe ₂ O ₄	sol-gel assisted combustion technique	Fuel citric acid	~125°C for approximatel y two hours	76 (±5) Å	1.16 μB	150 Oe	-	[75]
CaFe ₂ O ₄	sol-gel method		dried in the oven at 70- 80°C overnight, calcined at 550°C for 2 hours	13.59 nm	88.3 emu/ g	85.33 1 G	targeted drug delivery	[76]
CuFe ₂ O ₄	mechanochemic al treatment		3-5 h milling	10– 12 nm			catalyst	[26]
CuFe ₂ O ₄	Sonochemical method	water and ethanol,	irradiated with high- intensity ultrasound radiation under argon at room temperature (25 °C) for 3.5 or 6.5 h dried in vacuum for 10 h at 110 °C	60 nm				[77]
Zn ferrites	Co- precipitation Method	sodium hydroxide (NaOH) and acetone	(20–80 °C) At 40 °C	5– 10 nm	7.3 emu/ g			[36]

BaFe ₁₂ O ₁₉	solid-state method	-	-	1–2.5 μm	40.0 emu/g	1039 Oe	[78]
	hydrothermal synthesis						
	microwave	-	-	s 2.0–4.0 μm	53.6 emu/g	623.8 Oe	[78]
	hydrothermal synthesis						
							LTCC technology and the fabrication of chip microwave gyromagnetic devices.
SrFe ₂ O ₄ and SrFe _{0.75} M _{0.25} O _{3d} (M =Cr, Mo, W, Nb, Ti and Zr)	solid state reaction	distilled water, while the oxides WO ₃ and MoO ₃ were dissolved in diluted ammonia	powders were fired at 800°C to remove the carbonaceous species and to achieve crystallization.	-	-	-	[79]
							symmetric electrode materials for Solid Oxide Fuel Cells.

Table 2: List of methods with advantages and disadvantages.

Methods	Advantages	Disadvantages
Mechanical Milling Method:	Simple, Low cost, short time, large scale production	The requirement of high energy, Contamination by milling tool,
Thermal Decomposition Method	Small size distribution, Size control and Scalable, high crystallinity	The requirement of high temperature, long time, organic solvent, and ligand exchange
Co-precipitation Method	Aqueous media, cost-effective, simple to do and reliable method, a homogeneous powder with maximum yield, does not require any organic fuels, easily functionalized, scalable size and morphology control	Very long reaction time Required, Broad size distribution, low crystallinity
Hydrothermal Method	High yield Aqueous media, Size control, Scalable	High pressure (P2000 PSI) special reactor required High-temperature Longer reaction time
Sol-gel method	Controlled size and shape Low cost	Takes longer time Yield is

Combustion method	Less time and energy required Simple and effective method Versatile and fast Nanoparticles produced are pure and homogeneous	medium Very high temperature is required,
Thermal treatment method	Controlled size and shape, scalable	costly and complicated methodology, the high reaction temperatures and the long reaction times, the toxic reagents
Sonochemical method	Less time, Small size distribution, Size control, and Scalable	Poor shape control and medium yield
Microwave-Assisted method	uniform heating, fast reaction under a controlled environment, the product of high purity, high yield, small size distribution	Organic solvent
Microemulsion method	small size distribution, sizecontrol, highcrystallinity, low temperature	Low yield, long time, excess organic solvent
Green synthesis	one stage, straightforward, savvy, environment friendly	

Table3: Summary of characterization techniques.

Proper ties	Parameters	Ferrite	Characteriza tion Techniques	Uses	Ref.
Structural Properties	Particle size, shape	MnFe ₂ O ₄	XRD	The high intensity and well defined peaks infers the good crystallinity of the MnFe ₂ O ₄ nanoparticles diffraction peaks at 30.10°, 35.42°, 43.10°, 53.72°, 56.94° and 62.46° corresponds to the lattice planes of (220), (311), (400), (511), (440) and (444) the calculated lattice constant of 8.420 Å reveals the cubic structure of MnFe ₂ O ₄	[65]

		$(\text{Zn}_x\text{Co}_{1-x}\text{Fe}_2\text{O}_4$	SEM	The scanning electron [80] micrographs (SEM) and uniform distribution of CoFe_2O_4 and Zn-doped CoFe_2O_4 NPs (with $x = 0.0$ and $x = 0.4$) shown in Fig. 3(a & b) . The images indicate the formation of agglomerated particles with spherical shape and the grain size is affected by the dopant at nano-regime. The internal heat energy produced during combustion causes the interfacial surface friction leads to the agglomeration of particles
		$\text{Zn}_x\text{Co}_{1-x}\text{Fe}_2\text{O}_4$	TEM	TEM images of [80] $\text{Zn}_{0.4}\text{Co}_{0.6}\text{Fe}_2\text{O}_4$ NPs are represented in Fig. 3(c-d) . The images confirm the uniform distribution of particles and are in the nanometer range, it clearly shows that the spherical and agglomerated particles
Surface Area	MnFe_2O_4		BET	The total specific surface area [65] (SSA) is estimated using the Brunauer-Emmett-Teller (BET) and is found to be $33.479 \text{ m}^2 \text{ g}^{-1}$ with total pore volume of $0.1609 \text{ cm}^3 \text{ g}^{-1}$. The average pore diameter is 19.23 nm
cationic distribution	ZnFe_2O_4		Mossbauer spectroscopy	Fe^{3+} species were two which [81] demonstrated 66% occupancy of Fe^{3+} on the octahedral site

	Bonds	Li-Zn ferrite	FTIR	and 29.8% occupancy at the tetrahedral site The FTIR spectrum for each of the sample consists of two broad absorption bands: one at $\sim 510 - 800 \text{ cm}^{-1}$ corresponding to the vibrations of tetrahedral complexes (v1) and the other, at $\sim 250 - 510 \text{ cm}^{-1}$ corresponding to the vibrations of octahedral-complexes (v2) in the spinel structure of the Li-Zn ferrites [82]
	Binding energy	$\text{Mg}_x\text{Fe}_2\text{O}_4$ (x = 0.5, 0.95 and 1.0)	XPS	for x = 0.5, the Fe 2p spectra could be deconvoluted into six peaks; two $\text{Fe}^{3+}2p_{3/2}$ peaks: at $\sim 711.74 \text{ eV}$, corresponding to Fe^{3+} ions in octahedral sites and at $\sim 714.32 \text{ eV}$, corresponding to Fe^{3+} ions in tetrahedral sites, with a $2p_{3/2}$ satellite peak at $\sim 720.8 \text{ eV}$, two $\text{Fe}^{3+}2p_{1/2}$ peaks at 725.16 eV and 728.4 eV with a satellite peak at 733.5 eV for $\text{Fe}^{3+} 2p_{1/2}$. [83]
	Elemental composition	CoFe_2O_4	EDS	confirmed the presence of elements, such as cobalt, iron, and oxygen, without any additional impurities, with a ratio of 1:2 for the Co:Fe ions in CoFe_2O_4 nanoparticle annealed at 300°C [84]
		CaFe_2O_4	Raman spectroscopy	Raman spectra reveal crystallization of CaFe_2O_4 nanoparticles in the fcc type [75]

Electrical Properties			mixed spinel ferrite (space group: Fd-3) structure
		CoFe ₂ O ₄	thermogravimetric analysis (TGA)
			TGA data of the as-synthesized CoFe ₂ O ₄ . Showed Upon heating to 240 ⁰ C there occurs an initial mass loss of about 13% attributed to the desorption of the organic matter adsorbed on the surface of the nanoparticles. Another 3% of the weight was lost above 240 ⁰ C for a total of 16% during the healing process,
	Intrinsic defects vacancies	point Zn _{0.04} Fe ₂ O ₄ , Co _{0.01} Zn _{0.03} Fe ₂ O ₄ , Co _{0.02} Zn _{0.02} Fe ₂ O ₄	PL spectra
			The observed three peaks in the visible range for all J1, J2, and J3 samples are generally assigned to the charge transfer between Fe ³⁺ ion at the octahedral site, Zn ²⁺ ion at tetrahedral sites, and the surrounded O ²⁻ ions, respectively. The peak centered at 419 nm is attributed to the zinc vacancies in the lattice which corresponds to violet emission. [85]
	Permittivity and electrical resistivity measurements		LCR Meter-type impedance analyzer.
			At 20 Hz, the relative permittivity values of P1 and P2 ferrites are 31 and 22, respectively [71] for low values of relative humidity, P1 and P2 ferrites, high electrical resistivity values, i.e 4.1 10 ⁷ Um and 5.3 10 ⁷ Um, respectively,

Optical Properties	Bandgap	BiFeO ₃	UV– visible spectra	strong band-gap absorption at ~590 nm (2.1 eV) for BFO nanoparticles suggesting their potential application as visible-light response photocatalyst [22]
	saturation magnetization and coercivity	CoFe ₂ O ₄	VSM	ferromagnetic behavior (FM) of the CoFe ₂ O ₄ obtained from VSM measurements with a magnetic field of ±10 kOe at room temperature (RT). The saturation magnetization increased from 3.18 to 3.42 mB and the coercivity decreased from 1100 to 650 Oe with increasing calcination temperature 800 to 1000 ^o C [74]
Magnetic Properties		Sn _x Mn _{1-x} Fe ₂ O ₄ (x=0.00, 0.25, 0.50, 0.75, 1.00)	SQUID	At applied magnetic field (0 T - 7 T), the coercivity of as-prepared Sn _x Mn _{1-x} Fe ₂ O ₄ ferrites are about 35–110 Oe. The saturated magnetization is in the range of 22–68 emu/g [86]

4. Characterization of ferrites

There are various methods to characterize FNPs. Some techniques are selective for the investigation of a definite property, while in some cases they are combined. The microscopy-based techniques which gives information about NPs morphology, size, and crystal structure are SEM, TEM, HRTEM, AFM, etc. Numerous different techniques which uses different phenomenas like scattering, X-rays, or spectroscopy, for instance e.g., XRD, EDX, RAMAN SPECTROSCOPY, etc. give additional information of the structure, nanoscale elemental composition, the optical properties, and other common and more specific physical properties of the sample of NPs. Some methods are particular for

certain magnetic materials, e.g. SQUID, VSM, FMR, XMCD, XPS etc. [87] as summarized in **Table 3**.

4.1 Structural properties

K. Maaz et al. [88] investigated the structural properties of magnetic nanoparticles (nickel doped cobalt ferrite) produced using the co-precipitation method. The full width half maximum (FWHM) of the highest X-ray diffraction (XRD) peak and transmission electron microscopy (TEM) methods are used to obtain particle size in the range of 18–2874 nm. The presence of Co, Ni, Fe, and oxygen, as well as the necessary phases, were confirmed in the synthesized NPs using energy dispersive X-ray (EDX) analysis. The crystalline nature of the synthesized NPs was confirmed by selective area electron diffraction (SAED) analysis. The factors used to determine topography and morphology can be manually determined, as shown below.

a) Lattice Constant: The first characteristic parameter is lattice constant or lattice parameter. As Spinel ferrites possess a cubic structure, all three lattice constants possess the same value ($a = b = c$). Different methods are used by which the lattice parameter can be calculated. These days, most researchers prefer to use software approaches such as PowderX, UnitcellWin for the lattice parameter calculations. But other manual techniques are also used for the lattice constant calculation of ferrites:

i) Average lattice constant: (a) In this method, to calculate the inter-planar spacing (d), for every diffraction peak in XRD analysis Bragg's law is used, by using the formula:

$$d_{hkl} = \frac{\lambda}{2 \sin \theta_{hkl}} \quad [1]$$

And also ' a ' is calculated for each peak using the formula:

$$a = d_{hkl} \sqrt{h^2 + k^2 + l^2} \quad [2]$$

where h, k, and l are Miller indices of crystal planes.

ii) True lattice parameter: (a_0) Using the Nelson-Riley method more accurate values of lattice parameter can be calculated. In this approach, the extrapolation function $F(\theta)$, named Nelson-Riley function, is calculated for each diffraction peak using the formula[89]:

$$F(\theta) = \frac{1}{2} \left[\frac{\cos^2 \theta}{\sin \theta} + \frac{\cos^2 \theta}{\theta} \right] \quad [3]$$

Then the value of a (average lattice constant) calculated in the first method for each diffraction peak is plotted against $F(\theta)$. The straight line passing through the values gives the value of the true lattice constant.

iii) Theoretical lattice constant (a_{th}): K.A. Mohammed et al. [90] study the infrared and structural investigation of $MgZnFe_2O_4$ ferrites nanoparticles. They used the expected/ideal cationic distribution to determine the mean ionic radii of A sites (r_A) and B sites (r_B) using the formula

$$r_A = \sum \alpha_i \text{ and } r_B = \frac{1}{2} \sum \alpha_i r_i \quad [4]$$

where ' α_i ' is the concentration of the element 'i' of ionic radius ' r_i ' on the respective side. Lattice parameter is calculated using the formula:

$$a_{th} = \frac{8}{3\sqrt{3}} [(r_A + R_0) + \sqrt{3}(r_B + R_0)] \quad [5]$$

where R_0 is the radius of oxygen ion (1.32 Å)[89, 91].

b) Crystallite Size: There are two methods to calculate the crystallite size of a ferrite material:

i) Scherrer's formula: Scherrer's or X-ray diffraction line half-width method is an excellent method for calculating grain size when the grain size is smaller than 100 nm. Scherrer's equation is used to calculate the average crystallite size (D)[90]:

$$D = \frac{K\lambda}{\beta \cos \theta} \quad [6]$$

where, θ = Bragg's diffraction angle λ = wavelength of X-ray, β = line broadening measured by the full width at half maximum in radians, and K is the shape factor or Scherrer constant, depending on several factors including Miller Index of reflecting plane and shape of the crystal

ii) Williamson-Hall plot: When the grain size is more than 100 nm, this approach is utilised to determine crystallite size using XRD data. The crystallite size (D)[90] is determined using the William-Hall equation in this method:[90]:

$$B \cos \theta = \frac{k\lambda}{D} + 4\varepsilon \sin \theta \quad [7]$$

where B is full-width at half maximum (in radian) of the peaks, θ is peak position, k is Scherrer constant (0.89), λ is the wavelength of the X-ray, and is ε the lattice strain.

c) Lattice strain: Lattice strain is generally calculated using William-Hall equation[90, 92]:

$$B \cos \theta = \frac{k\lambda}{D} + 4\varepsilon \sin \theta, \quad [8]$$

where B is full-width at half maximum (in radian) of the peaks, θ is the peak position, k is Scherrer constant (0.89), λ is the wavelength of the X-ray, D is crystallite diameter and ε is the lattice strain of the structure. Simpler formula to calculate lattice strains using Williamson-Hall effect:

$$\varepsilon = \frac{B}{4 \tan \theta} \quad [9]$$

modified Williamson-Hall equation:

$$\eta = \frac{2d|k-1|}{D} \quad [10]$$

where d is the lattice spacing, D is the average crystallite size and k is the shape factor. Lattice strain, which arises in the crystal as a result of substitution, can be attributed to the distortion of the tetrahedron with doping.

d) Densities and porosity: Two types of densities are generally measured while performing structural analysis: x-ray density and actual density [90]. X-ray density is estimated using the relation:

$$D_x = \frac{\sum A}{NV} = \frac{8M}{Na^3} \quad [11]$$

where, $\sum A$ = sum of atomic weights of all atoms in the unit cell = 8M; M is the molecular weight of the particular ferrite, V= volume of the unit cell, and N Avogadro's Number. 8 is written because each primitive cell of spinel consists of eight molecules. Since spinel's have cubic structure, hence the volume a^3 , where, is lattice constant [$(a = b = c)$].The

bulk D_{exp} densities of the specimens were evaluated using the measured mass, m , and volume, V , of the samples using the following relation:

$$D_{exp} = \frac{m}{V} \quad [12]$$

In sintering and powder processing ceramics, porosity is an intrinsic phase. Sintering at a high rate with a small crystallite size decreases porosity significantly[90]. Porosity (P) can be calculated using the relation:

$$P = \frac{D_x - D_{exp}}{D_x} \times 100 \quad [13]$$

Where D_{exp} is the actual density and D_x is the X-ray density.

Grain size or particle size: Scanning electron microscopy is a technique with which the structure and size of the grains are estimated. The grain size determined using SEM analysis is always greater than the crystallite size determined using Debye Scherrer's formula in XRD analysis. This difference arises because the grain size provided by SEM analysis is the size of agglomerated particles, which are composed of several crystallites by the soft reunion. Synthesis method influences the size and shape of the grains[93].

Cationic-site distribution parameter: The ionic radii, type of bonding, and preparation procedure all influence the cation distribution between A-site and B-site. The cation distribution can be influenced by changing variables such as temperature, pressure, magneto crystalline anisotropy, and metal ion composition. The types of cation and their distribution amongst these two interstitial sites of the spinel lattice affect the magnetic properties of ferrites.

4.2 Electrical properties

Ferrites are also excellent dielectric materials, with a wide range of applications in technology from microwave to radiofrequency. The dielectric and electric properties of ferrites are essential to understand because they determine how these materials are used in the manufacture of electronic devices. The material's high resistivity and low dielectric loss made it suited for high-frequency power applications[62]. Dielectric and electric properties are usually measured using an impedance analyzer. The dielectric constant was (ϵ') measured using the relation:

$$\epsilon' = \frac{VRtS \sin \phi}{\epsilon_0 \omega R A s} \quad [14]$$

where ϵ_0 is the permittivity of free space, and t_s , A_s are the thickness and surface area of the sample respectively. This approach measures the voltage drop V_R across a standard resistance R and, phase angle φ between V_R and current I [94].

4.3 Dielectric properties

The dielectric parameters of ferrites are influenced by a variety of elements, including the technique of manufacture, sintering temperature, chemical composition, crystal structure, grain structure or size, additives, applied field frequency, and humidity. The dielectric constant is defined as “the ability to store electric charge”. High-dielectric-constant materials are of particular relevance for use in miniaturized memory devices based on capacitive components and energy storage principles. Ferrites, having very high dielectric constant, are useful in designing good microwave devices such as isolators, switches, etc. The polarisation process, or how quickly the polarizable units in a material orient themselves to keep up with the oscillations of an alternating field, determines the dielectric constant of ferrites. There are four types of polarizations: dipolar, electronic, ionic, and interfacial polarization [62]. At lower frequencies, dipolar and interfacial polarization play a significant role, while at higher frequencies, electronic and ionic polarization are the main contributors. The conduction mechanism is connected to the dielectric constant. The fundamental mechanism that triggers the conduction process is the hopping activity between the electrons of Fe^{2+} and Fe^{3+} . Because of the polarization at grain boundaries, this hopping of electrons causes local charges to be displaced [95].

Dielectric constant: The dielectric constant was determined from the formula[96].

$$\epsilon = \frac{Cd}{\epsilon_0 A} \quad [15]$$

where C is the capacitance of the pellet in farad, d the thickness of the pellet in meter, A the cross-sectional area of the flat surface of the pellet, and ϵ_0 the constant of permittivity of free space.

Dielectric loss: The term "dielectric loss" refers to the amount of energy absorbed by a dielectric material. Impurities and defects in the crystal lattice induce dielectric loss, which occurs when polarization lags behind the applied alternating field. The reduction in dielectric losses occurs as the frequency rises. According to the Maxwell-Wagner model [61] of inhomogeneous double structure, the highly conducting grains are separated by poor conducting grain boundaries, which leads to the accumulation of charge carriers at the boundaries. Grain boundaries, with a large value of resistance, are active at lower

frequencies. Therefore, more energy is required for electron exchange between ferric and ferrous ions, hence polarization within the grain boundaries is increased at low ($Fe^{2+} \leftrightarrow Fe^{3+}$) frequencies, which leads to high energy losses. On the other hand, less resistive grains are active at higher frequencies. Hence, relatively low energy is needed for the hopping of electrons, which results in low energy losses at higher frequencies. The Tangent of dielectric loss angle can be calculated using the relation:

$$\tan \delta = \frac{1}{2\pi f R_s C_s} \quad [16]$$

where δ is the loss angle, f is the frequency, R_s is the equivalent series resistance and C_s is the equivalent series capacitance. The dielectric loss factor (ϵ'') is also measured in terms of tangent loss factor ($\tan \delta$) [96] defined by the relation $\epsilon'' = \epsilon' \tan \delta$,

AC conductivity: Due to their high electrical conductivity compared to other magnetic materials, spinel ferrites are employed in magnetic devices. As a result, one of the major aspects of spinel ferrites is electrical conductivity, which provides essential information on the conduction mechanism. Measuring the frequency dependence of electrical conductivity is an informative method to understand the type and mechanism of the transport properties. The dielectric and magnetic characteristics of ferrites are substantially influenced by the order of magnitude of conductivity. The AC conductivity of ferrites samples is determined using the relationship from the dielectric constant and dielectric loss factor measurements [96]:

$$\sigma_{AC} = \omega \epsilon' \epsilon_0 \tan \delta \quad [17]$$

where σ_{AC} is the AC conductivity, ω is the angular frequency, ϵ is the permittivity of free space, ϵ_0 is the dielectric constant and $\tan \delta$ is the dielectric loss factor of the samples.

DC resistivity: The activation energy and kind of charge carriers responsible for electronic conduction are determined by DC resistivity. The ferrites' semiconductor nature is indicated by a reduction in resistance as temperature rises. DC resistivity [97], as a function of temperature, can be represented by the Arrhenius type (ρ) equation:

$$\rho = \rho_0 \exp \frac{E_a}{2k_B T} = \rho_0 \exp \frac{\Delta E}{k_B T} \quad [18]$$

Where ρ is the resistivity of the sample at room temperature, E_a is the activation energy, k_B is Boltzmann constant and T is the absolute temperature. E_a in the ferromagnetic region can be calculated from the plot using the equation. The value of activation $E_a = \text{slope} \times 4.606 \times 8.62 \times 10^{-5} \text{ eV}$ energy is observed to be higher for the sample with high electrical resistivity in comparison to that in the case of the sample with lower electrical resistivity.

4.4 Optical and absorption properties

To study the effect structure features such as defects, size, composition on the optical UV–Visible diffuse reflectance measurement and PL spectroscopy are used to investigate the effect of structure factors like as defects, size, and composition on the optical properties of ferrite materials. The band edge absorption spectra of ferrites nanoparticles may also be calculated using a diffuse UV–visible spectroscopy method. In general, the direct band-gap energy value, E_g (**table 4**) for each sample can be evaluated using the optical spectral absorption model [91].

Kubelka–Munk function: The bandgap energy can be approximately calculated from the optical reflectance data by the Kubelka–Munk function,

$$F(R) = \frac{(1-R)^2}{2R} \quad [19]$$

where R is the diffuse reflectance A graph (Tauc plot) is plotted between $[F(R)h\nu]^2$ versus $h\nu$ (eV) and the bandgap energy is calculated by extrapolating the linear region of plots until they cross with the x-axis [98].

Table 4: Bandgap energy of various ferrites.

Ferrites	Bandgap(eV)	References
NiFe ₂ O ₄	1.27 to 1.47	[99]
BiFeO ₃	2.10	[100]
NiCr _x Fe _{2-x} O ₄	1.39–2.00 eV.	[101]
Zn _{1-x} Co _x Fe ₂ O ₄ (x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5)	1.89 to 1.31 eV	[102]
Mn _x Fe _{3-x} O ₄ (0.0 ≤ x ≤ 1.0)	2.05 eV to 1.17 eV	[103]
CaFe ₂ O ₄	1.82 eV	[104]
MgFe ₂ O ₄	2.18 eV	[105]
ZnFe ₂ O ₄	1.92	[106]

4.5 Magnetic properties

The existence of irregular 3d electrons scattered in uneven amounts at the tetrahedral and octahedral sites causes magnetism in ferrites. Neel's two sublattice model describes the ferrimagnetic type ordering of spinel ferrites [107]. Ferrimagnetism is a type of anti-ferromagnetism in which magnetic moments are aligned opposite to each other, but their magnitudes are not equal. Hence, these materials have non-zero net magnetization[108]. Yafet and Kittel developed on Neel's theory, which accounted for the magnetic properties of ferrites very well [109]. Yafet and Kittel showed that in certain cases, tetrahedral and octahedral cationic sites get divided into sub-lattices in such a way that the vector resultant of the magnetic moments of sub-lattices is aligned in the opposite directions to each other, leading to ferrimagnetism.

Saturation magnetization (M_s) The saturation magnetization is the highest induced magnetic moment that can be achieved in a magnetic field (H); beyond this field, no additional magnetization can be generated. The cationic distribution of metal ions at tetrahedral (A) and octahedral (B) sites determines saturation magnetization. The magnetization of spinel ferrites can be explained using “Neel’s two sub-lattice models of ferromagnetism”. “Magnetic moments at A and B cationic sites are aligned anti-parallel to each other, and their spins have a collinear structure,” according to this model. Thus, total magnetization:

$$M = |M_B - M_A| \quad [20]$$

There are three types of exchange interactions between A and B cationic sites: A-A (inter A-site), A-B (between A and B sites), and B-B (inter B-site). All these interactions are negative i.e., anti-ferromagnetic. Among these, A-B interactions take place between Fe^{3+} ions in different sites over oxygen (i.e., $^{3+} site - A - O^{2+} - Fe^{3+} site - B$), are the strongest. ($|AB| \gg |BB| > |AA|$). These interactions render the pure spinels as ferrimagnetic with A-site moments aligned anti-parallel to B-site moments. The theoretical value of saturation magnetization for ferrites with a single-phase structure can be determined (M_s) using the expression:

$$M_s = \frac{8n\mu_B}{103a \cdot 3\rho} \quad [21]$$

where 'n' is the theoretical number of magnetic moments, μ_B is the magnitude of Bohr magneton, 'a' is the lattice parameter, ρ is the density.

Remanent magnetization: The value of magnetization that remains in the elimination of an induced magnetic field is known as remanent magnetization. According to Neel, if a group of such particles is subjected to a large magnetic field in order to overcome the dipolar field between them, their moments will line up parallel to the applied field. If the field is switched off, the magnetization should obey the following law [110]:

$$M_r = M_s \exp\left(\frac{-t}{\tau}\right) \quad [22]$$

where M_s is the saturation magnetization, t is the time after removal of the magnetic field, and τ is the relaxation time which is thermally activated and given by

$$\frac{1}{\tau} = f_0 \exp\left(\frac{-KV}{k_B T}\right) \quad [23]$$

where f_0 is a frequency factor usually taken to be 10^9 sec^{-1} , T is the temperature, and k_B is the Boltzmann constant. Consequently, if V is greater than a critical value V_P or T is smaller than the so-called blocking temperature T_B , τ is large compared to the time necessary to measure the magnetization. As the external field is decreased, the magnetic moments do not return to random directions, a remnant magnetization subsists in zero fields and the magnetization exhibits a hysteresis. In the opposite sense, if V is smaller than V_P or T is higher than T_B , τ becomes small enough for the magnetization to fluctuate during the measurement. In a zero applied field, the observed average value is zero, and an ensemble of such particles behaves similarly to a group of paramagnetic atoms in a nonzero field. The phenomenon, called “superparamagnetism”, can be described by Langevin’s theory of paramagnetism, and the magnetization is given by:

$$M(H, T) = \frac{M_s L[M_s V H]}{k_B T} \quad [24]$$

where M_s is the saturation magnetization of our sample, L is the Langevin function, V is the volume of the particle, k_B is the Boltzmann constant, T is the temperature, and H is the magnetic field. According to this Langevin function the smaller the particles, the higher is the magnetic field necessary to attain the saturation of the system.

Coercivity: (H_c) Coercive force is inversely proportional to grain size. As the size of grains decreases (grains become finer), the volume concentration of grain boundaries increases. This leads to the enhancement of the pinning possibility of magnetic domain walls, resulting in an increase in, which is the measure of reversible changes in

magnetization. Sintering temperature affects coercivity (H_c). Because lowering the sintering temperature reduces particle size, coercivity, which is proportional to grain size, will rise. Coercivity depends on magnetocrystalline anisotropy, micro-strains, magnetic particle morphology, particle size, and saturation magnetization and can be expressed as:

$$H_c = \frac{2K_1}{\mu_0 M_S} \quad [25]$$

Magneto crystalline anisotropy of samples is a sum of bulk and surface anisotropies which are related by the equation:

$$K_{eff} = \frac{K_{Bulk} + 6 K_S}{d} \quad [26]$$

where, d = particle size. Bulk anisotropy (K_{Bulk}) is proportional to ion concentration, Fe^{3+} which decreases on replacement of iron. Assuming surface anisotropies of all the samples to be the same (as are prepared in the same condition), decreases. Hence, the coercive field decreases. Surface anisotropy may sometimes change with particle morphology and size.

Curie temperature: Curie temperature is a significant parameter in the study of magnetic materials because it shows the overall strength of inter-sublattice (A-B) interactions in ferrites. It depends on the number of $Fe^{3+} A - O - Fe^{3+} B$ associations per ion per formula unit. Above this temperature, the initial permeability falls sharply and the material Fe^{3+} is no longer magnetic. At T_c , the material gets transformed from ferrimagnetic to paramagnetic. The highest value of initial permeability just beneath Curie temperature is named Hopkinson peak. The temperature where fast T_{pk} fall is observed is referred to as Curie temperature [111].

Yafet-Kittel Angle: Yafet and Kittel Model [109] also explains the magnetic properties of the ferrites: According to this model, a particular composition, the sub-lattice (A or B) starts splitting into two or four different parts and each part is at an angle, called Yafet-Kittel angle with each other. Yafet-Kittel (Y-K) angle is calculated from the magnetic moment per formula unit using the relation:

$$n_B(x) = M_B \cos \theta_{YK} - M_A \quad [27]$$

where x is the substitution content. where $n_B(x)$ is the experimental magnetic moment expressed in the units of Bohr magneton and M_A and M_B are the Bohr magneton on the A site and B sites, respectively. Y–K angles as a function of x [112].

Table 5: Magnetic, optical and electrical properties of ferrites with different methods.

S. No.	Year	Composition	Method	Properties			Refs.
				Magnetic	Optical	Electrical/di electric	
1	2015	NiFe ₂ O ₄	Sol-gel	$M_s = 45.902 \text{ emu/g}$ $M_r = 1.506 \text{ emu/g}$ $H_c = 27.374 \text{ Oe}$	–	$\sigma_{dc} = 7.7 \times 10^{-9} \Omega \text{ cm}^{-1}$	[113]
2	2015	CdFe ₂ O ₄	thermal treatment	$M_s = 23.34 \text{ emu/g}$ $M_r = 153 \text{ emu/g}$ $H_c = 3235 \text{ Oe}$	Band gap = 2.0614 eV	–	[114]
3	2016	ZnFe ₂ O ₄	microwave combustion	$M_s = 2.598 \text{ emu/g}$ $M_r = 0.014 \text{ emu/g}$ $H_c = 7.472 \text{ Oe}$	Band gap = 1.88 eV	–	[115]
4	2016	Mn _{0.8} Zn _{0.2} Fe ₂ O ₄	microwave combustion	$M_s = 48.09 \text{ emu/g}$ $M_r = 8.473 \text{ emu/g}$ $H_c = 53.93 \text{ Oe}$	Band gap = 1.95 to 2.35 eV	–	[115]
5	2017	CoFe ₂ O ₄ NiFe ₂ O ₄ ZnFe ₂ O ₄	Co-precipitation method	–	Band gap = 2.44 eV 3.54 eV 3.25 eV	Resistivity (Ω) = 0.2344×10^6 0.1153×10^6 0.2063×10^6	[116]
6	2017	ZnFe ₂ O ₄	Sol-gel	$M_s = 12.81 \text{ emu/g}$ $M_r = 0.483 \text{ emu/g}$ $H_c = 16.17 \text{ Oe}$	Band gap = 1.90 eV	$\sigma_{ac} = 1.32 \times 10^{-9} \text{ Scm}^{-1}$	[117]

7	2018	$\text{Co}_{1-x}\text{Ca}_x\text{Fe}_2\text{O}_4$ ($x=0.05$)	Sol-Gel Auto combustion	$M_s=18.86 \text{ emu/g}$ $M_r=54.91 \text{ emu/g}$ $H_c=858.14 \text{ Oe}$	—	—	[118]
8	2019	CoFe_2O_4	co- precipitation	$M_s=45.16 \text{ emu/g}$ $M_r=10.75 \text{ emu/g}$ $H_c=0.1 \text{ Oe}$	Band gap $=1.5 \text{ eV}$	—	[119]
9	2019	$\text{Ni}_{0.4}\text{Co}_{0.6}\text{Fe}_2\text{O}_4$	co- precipitation	$M_s=31.45 \text{ emu/g}$ $M_r=13.48 \text{ emu/g}$ $H_c=0.8 \text{ Oe}$	Band gap $=1.36 \text{ eV}$	—	[119]
10	2020	$\text{Ni}_{0.4}\text{Co}_{0.6}\text{ErFe}_2\text{O}_4$	co- precipitation	$M_s=35.99 \text{ emu/g}$ $M_r=12.21 \text{ emu/g}$ $H_c=0.16 \text{ Oe}$	—	Resistivity(Ω) $=6.20 \times 10^7$	[120]
11	2020	$\text{Ni}_{0.4}\text{Co}_{0.6}\text{Er}_{0.015}\text{Fe}_{1.98}\text{O}_4$	co- precipitation	$M_s=41.1 \text{ emu/g}$ $M_r=10.93 \text{ emu/g}$ $H_c=0.4 \text{ Oe}$	—	Resistivity(Ω) $=1.93 \times 10^7$	[120]

5. Applications

Because of the efficient magnetic, electrical, and optical properties of FNPs, researchers are paying considerable attention in the synthesis of FNPs and making their use in a number of applications that include the medical field [14], electronic devices [6], and environment remediation [121].

Figure 9: Applications of FNPs.

5.1 Biomedical application

Low toxicity, superparamagnetic, and high magnetization are some essential conditions that demanded the use of magnetic NPs in the field biomedical. In addition, concerns about the nanoparticle's size have to be considered. Therefore, FNPs must have these requirements to be useful [70].

Hyperthermia: Magnetic fluid hyperthermia is a non-invasive treatment that destroys cancer cells by heating up a ferrofluid-impregnated malignant tissue with an AC magnetic field at the same time causing minimal harm to the neighboring healthy tissue [122]. This physical therapy was originated from the observation of some patients with high fever leading to reduction or destruction of the cancer cells. hyperthermia would damage, kill or make the cancerous cells very sensitive to the radiation effects and some certain anticancer drugs. Some techniques like ultrasound, Solid State Phenomena microwave, radiofrequency, and others are currently available to induce the heat. However, the need of homogeneous heat distribution and deepness of the therapeutic temperatures ($\sim 45^{\circ}\text{C}$) is the key problem for these thermal methodologies [123, 124]. In this sense, the thermal process based on MNPs is a great candidate to solve as mentioned problems. The quantity of induced heat by MNPs is computed in conditions of specific loss power which also depends upon several physical, magnetic properties of the NPs including particle size distribution, size, magneto crystalline anisotropy (K) in addition

of several extrinsic factors including the frequency (f) and amplitude magnetic field externally applied. Ferrites nanoparticles (MFe_2O_4 where $M = Mn, Co, Zn, Ni$) have required magnetic properties because of their ease of synthesis, low toxicity, physical as well as chemical stabilities [125] they are appropriate as hyperthermia agents. At low magnetic field range hyperthermia applications, maghemite and copper-ferrite NPs are promising materials, whereas in the high field amplitude cobalt-ferrite is the best magnetic hyperthermia agent.

Magnetic resonance imaging MRI: MRI is very important powerful medical imaging methods to get a diagnosis for clinical purposes. This is a non-invasive technique essentially developed on the bases of the interaction of protons and biological tissues in an applied magnetic field. However, the detection of diseased tissue is not easy. Sometimes, the contrast distinction between the target and normal tissue is negligible. Thus, it make complex to detect the disease, which causes the decrease in the cure chances for the patient. To solve this problem, contrast agents were developed to enhance the signal distinction improving the contrast between pathological lesions and normal tissues. However, the requirement of specificity is a problem for MRI contrast agents. Their poor sensitivity becomes unfeasible in accurate detection of small targets for instance tumors in the early stage of cancer, for example. In this consideration, magnetic ferrite NPs appear as an excellent candidate. Their magnetic properties and the easy surface modification and control of parameters like size, composition and shape make them an attractive platform as contrast agents [126, 127] for MRI.

Drug delivery: The growth and development of nanostructured systems for the transport of the active agent (anti-cancer drug, for example) to the target has been the goal of many researchers worldwide. The MNPs applications in drug delivery has gained much attention in the last two decades. The advantages provided by magnetism allow designing a nanosystem easily controlled by an applied magnetic field. This strongly affects selectivity. Several researches have established the specific accumulation in/on the target by enjoying the magnetic and surface properties of NPs. Additionally, a possibility to track the MNPs using the MRI as stated before, which also makes them a potential candidate for carrier drug [128, 129].

5.2 Electronics device application

Ferrite nanoparticles are used in making many electronic devices because of their enhanced electrical properties for instances the high resistivity, low ac conductivity, low power losses, etc. [6].

Gas sensors: Due to sensing properties [130, 131] ferrites are can be used as gas sensors, the response of Mg ferrite ($MgFe_2O_4$) for methane (CH_4), hydrogen sulfide (H_2S),

liquefied petroleum gas (LPG), and ethanol gas (C_2H_5OH) [132]. Cu- ferrite ($CuFe_2O_4$) [133] and Zn ferrite ($ZnFe_2O_4$) [134,135] showed a good response for hydrogen sulfide (H_2S) reported by many researchers.

Biosensors: Biosensors have been extensively researched and developed as a tool for the medical, food, pharmaceutical and environmental field. Biosensors are gadgets that consolidate a biological component to identify an analyte and a physicochemical segment to create a quantifiable signal. The biosensors are intended to create a computerized electronic signal which is depending upon the concentration of a particular biochemical or a bunch of biochemicals within the sight of a few meddling species [136].

Humidity sensors: The estimation of humidity has gotten incredible consideration because of the perceived significance of water vapour concentration in several areas for instance medicine, meteorology, industry, and agriculture. The humidity sensors must have required properties like good chemical, and thermal stability, high sensitivity, and short response time. The relative humidity (RH) is ratio of actual vapor pressure to the saturated vapor pressure at a given temperature, is frequently used parameter to specify humidity.

Microwave or high-frequency devices: In alternating magnetic field ferrites are used, as a result of their high value electrical resistivity and less eddy current losses, and in high frequency they also have outstanding magnetic property than the magnetic metallic materials. Ferrites are magnetic iron oxides, and gives the best obtainable combination of magnetic materials and electrical insulators and provides the extraordinary flexibility to control the magnetic, conductive properties with crystal lattice parameters. At high frequency magnetic materials properties are considerably different from low-frequency behavior, which leads to a number of microwave phenomena. At higher frequencies self biased hexaferrite is used to reduce the requirement of a huge external bias magnet [137]. Ferrites have applications in magnetostatic (MSW) devices, offering a better alternative to surface acoustic wave (SAW) circuits. Nonlinear ferrite devices uses the high-power instabilities of ferrites. Dispersed ferrites are used in thin EM wave absorbers [138].

LTCC (low temperature co-fired ceramic) devices: Low temperature co-fired ceramic technology is perhaps the most encouraging incorporated innovations. In this innovation passive components, for instances capacitors, inductors, and filters, are used to integrate the substrate of multilayer LTCC. The telecommunication industry nowadays requires high-volume and low-cost circuit fabrication, whereas at the same time it also require reliability, circuit miniaturization, surface mounting methods and exceptional electrical

performance. LTCCs for example NiZnCu ferrite [139] and M-type barium ferrite [78] have been studied intensively for such practical applications.

Supercapacitor applications: Swiftly increasing in requirement for energy conversion devices, energy-storage devices have become significantly attractive in electronic devices. Certainly, supercapacitors are well thought-out mainly capable energy storage devices, due to their outstanding reversibility, high power density, swift charge/discharge. Supercapacitor also have cyclic stability and long-life than the analogous (electrochemical) energy storage devices. Many ferrites for instances Co ferrites, Sn ferrites etc. are largely used for energy storage application because of their electrochemical activity. Various morphologies influence the surface area resulting to the different supercapacitance values. The higher the surface area higher is the storage capacity of charge. Normally, supercapacitors have three basic types, pseudocapacitors, battery-like, and electrochemical double-layer capacitors (EDLC). The fabricated nanoneedles showed narrow pore size distribution, high surface area, and mesoporous nanostructure. MnZnFe₂O₄ [140] nanoneedles-based supercapacitorselectrodes display high value of specific capacitance (783 F g⁻¹) in 0.5 M H₂SO₄ and high columbic efficiency through the stability test on the bases of pseudocapacitance faradaic mechanism.

5.3 Environmental applications

Catalytic applications: Ferrites can convey lattice oxygen to fuel, in some extend they recover it within the air. Copper ferrite seems to possess the best performance, since it can transport the highest amount of lattice O, than the other materials tested, is very active in CH₄ oxidation with initial conversion greater than 99% and its selectivity towards CO and H₂ is very low. In addition, it is quite stable, and ranked first, still after five redox cycles, and therefore it is appropriate as an oxygen carrier[141-143]

Photocatalytic applications: Photocatalysts are important materials employing which solar energy is used in oxidation and reduction processes. Photocatalysis is apt in numerous areas including the eradication of contaminants from water and air, odor control, bacterial inactivation, production of H₂ by water splitting, inactivation of cancer cells, and many others [144-148]. Organic compounds that are introduced in environment because contaminants are of major concern and the contaminants can be degraded photocatalytically, ideally to CO₂ and water, with no additional waste or by-products. Photocatalysts utilize light energy (hν) to carry out oxidation and reduction reactions. In the photocatalyst an electron (e) get excited from the valence band (VB) to the conduction band (C_B) when exposed to light energy, create a photogenerated hole (h⁺). The total solar energy that arrives at the Earth's surface is ultraviolet (UV), visible, and

infrared (IR) irradiation. It can be observed that visible light accounts for 46% while UV only accounts for 5% of the total energy from the sun, with the remaining portion belongs to the infrared region. Many of the photocatalysts that are generally used have large band gaps (>3.1 eV) and are only able to utilize a small portion of sunlight. It is ideal to use visible solar energy because the large amount of this light that is received by Earth's surface annually, which is approximately 10,000 times more than the current yearly energy consumption. For that reason, development of photocatalysts which can be capable for using protected and economical solar energy successfully and productively is significant. The development of such material which have a narrow bandgap less than 3.1 eV, which allows for photocatalytic activity in visible light exposer. Ferrites nanomaterial such as CaFe_2O_4 [104], MgFe_2O_4 [105], ZnFe_2O_4 [106], can be efficiently used in visible light because of small band gaps (**Table 4**).

Wastewater treatment: Water pollution is mainly caused by releasing of a heavy number of different category of harmful and toxic metals in the water stream beyond their acceptable limits. The occurrence of such heavy metals in water can create a serious danger for the environment because they are non-degradable and toxic in nature [149-151]. Of the available technologies, SFNPs are applied in water treatment industries are becoming extremely important for the immediate removal of contaminants through the adsorption or degradation process. For example, SFNPs are used in industries for wastewater treatment to remove dyes, phenols, and toxic trace metals. By the external magnetic field they can be recovered easily from their reaction mixture and the chance of several times reuse are other additional advantage of SFNPs [121, 152]

Radar absorbing devices: The emission of radiation from radar increases pollution of electromagnetic radiation in surrounding environment and reduces the effectiveness and performance rate of the electronic instruments, therefore decrease their life span and safety [153]. Radar absorbing material RAM has the property to change electromagnetic radiation energy by thermal energy. These materials are used in numerous areas, for instances in cellular telephones and (reception/transmission) antennas in telecommunication. The most commonly used ferrites spinels ferrites used for microwave absorption. Among the various ferrites CoZn [63], MnZn (2–18 GHz) [154], and NiZn -ferrites [155] are appropriate in the high frequency range (3–30 GHz) microwave absorption.

Conclusions

The synthesis and characterization of FNPs are becoming a popular research subject. This is primarily due to the high demand for high-quality FNPs for biomedical applications and appropriate materials for electronic devices. FNPs generated using excellent

synthesis methods can hold up the conditions under which they are synthesized and perform better. The most frequently used synthesis techniques with their advantages and some limitations are also discussed. One important field that needs further attention is to make use of FNPs in electronic materials as sensors and biosensors. As a consequence of doping ferrites with transition metals or rare earth metals, many novel FNPs with various and advanced properties are emerging, as evidenced by recent research studies. The capability to prepare new and improved FNPs by doping Mn, Ni, Co, or Zn into Fe_3O_4 has been established in research. Researchers have not yet completely exploited the rare earth metals doping of ferrite, but progress is being made and results are expected soon. Doping of first-row transition metals for instances manganese, iron, cobalt, and copper appears to be one of the main active research fields, according to the most recent published literature. They are broadly studied for their structural, electrical, magnetic, adsorptive, and catalytic properties to achieve the best quality ferrites for biomedical, electronics devices, and in environmental remediation applications. This chapter briefly summarizes types of ferrites, different synthesis and characterization techniques with their respective applications.

Conflict of Interest

The authors declare that they have no conflict of interest.

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