Chapter 2

Recent Advances in Processing, Characterizations and Biomedical Applications of Spinel Ferrite Nanoparticles

Gaurav Katoch¹, Garima Rana², M. Singh³, Alberto García-Peñas⁶, Sumit Bhardwaj¹,
Indu Sharma⁴, Pankaj Sharma⁵, Gagan Kumar^{1*}

¹Department of Physics, Chandigarh University, Gharuan, Mohali, Punjab, India

²School of Physics and Materials Science, Shoolini University, Bajhol, Solan, India

³Department of Physics, Himachal Pradesh University, Shimla, India

⁴Department of Physics, Career Point University, Hamirpur, HP, India

⁵Department of Applied Sciences, National Institute of Technical Teachers Training and Research, Sector 26, Chandigarh, 160019, India

⁶Departamento de Ciencia e Ingeniería de Materiales e Ingeniería Química (IAAB), Universidad Carlos III de Madrid, 28911, Leganés, Madrid, Spain

*physics.bhargava@gmail.com

Abstract

Many researchers are interested in investigating ceramic materials because of the potential for their use in nanotechnology. Spinel ferrites are a diverse group of materials with many applications. Electronic devices such as inductors, power, information storage, microwave, and induction tuners are only a few examples. As ferrite materials exhibit super-paramagnetic activity, their potential for biological applications such as drug delivery, hyperthermia, and resonance magnetic imaging. As a result, super-paramagnetism is a highly desirable property in spinel ferrites. Due to the size dependence, the methodologies used to synthesis of these materials have emerged as a critical step in achieving the desired properties. Many synthesis strategies have been developed in this regard such as sol-gel, co-precipitation, solid-state, solution combustion method and so on. As a result, this study provides a historical overview of spinel ferrites, as well as key principles for comprehending their various characterization techniques and properties. Recent developments in the synthesis and applications of spinel ferrites are also discussed.

Keywords

Spinel Structure, Synthesis Routes, Characterization, Biomedical Applications

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1. Introduction

Thanks to their unique design and promising applications such as high-quality data storage, catalysts, gas sensors, rechargeable lithium batteries, data storage systems, magnetic bulk cores, magnetic fluids, microwave absorbers, and medical and therapeutic diagnostics, spinel ferrite nanomaterials (SFNMs) have received a lot of attention in recent years from a fundamental science perspective [1-5]. Besides, spinel ferrite-based NPs have potential antimicrobial properties against certain microorganisms that cause disease[6]. Hilpert synthesized diverse spinel ferrites at the start of the century and attributed their chemical composition to their magnetic houses [7]. Kato and Takei [8], two Japanese scholars, made significant contributions to the field of ferrite in 1932. The first discovery was a low magnetism in Fe_3O_4 and CoFe_2O_4 solid solutions at 300 degrees Celsius. At room temperature, the same sample showed strong magnetization [8]. Another breakthrough was the development of industrial magnetic core materials. They combined two spinel ferrites, one inverse and the other normal, one with high magnetization and the other with almost no magnetization. The permeability of the composite was establish to multiply by more than ten times [9]. These significant discoveries prepared the path for the industrialization of these fabricated samples, exposing the electronic industry's potential for ferrites-based materials. Apart from significant commercial progress, the fundamental knowledge about the magnetic behavior of spinel ferrites was unknown. To demonstrate this, in 1945, Néel [10] employed exchange interactions and cation distribution to introduce the idea of ferrimagnetism into the scientific community. The advancement of electronic items such as television, computers, and electronic devices were aided by a greater accepting of the magnetic properties of ferrites [11]. So, the fundamental information connected with the market for electronic goods, the researchers decided to concentrate on ferrites-based electronic devices and circuits. As a result, the ferrite industry grew around the world [12-16]. On the other side, biochemists demonstrated why Fe_3O_4 was found within the

bodies of certain species, such as pigeons [17], honey bees [18], and bacteria [19]. This showed that this material has a lot of promise in biomedical applications including drug delivery [20], magnetic hyperthermia [21], and diagnostics [22].

Figure 1: As per Scopus data, the number of publications for the keyword “Spinel ferrites” from 2011-2020.

Scale, shape, synthesis process, and dopant amount all affect these desirable properties. The surface area to volume ratio of nanoparticles increases dramatically as particle size decreases. For a particle with a diameter of 1 μm , 6 nm, and 1.6 nm, approximately 0.15, 20, and 60% of the atoms in the composition are found on the surface, respectively [23, 24]. As compared to their bulk counterparts, these size differences result in specific physical, chemical, and mechanical properties. Among these unique properties of spinel ferrite nanoparticles, and negligible inter-particle interactions are important attributes of SFNPs [25, 26] and to make use of such unique properties, spinel ferrite nanoparticles have been briefly studied by several researchers to address and solve the existing health and environmental problems. The most interesting discoveries and novel applications

over time are perfectly described in **Figure 2**. Low toxicity, super-paramagnetism, and high magnetization are only a few of the requirements for using magnetic nanoparticles in biomedical applications [27]. Synthetic processes are essential in this observation because they can regulate the magnetic, structural, and morphological properties of MNPs. We will study the basic principles to better understand the properties of spinel ferrites and their methods in this paper. Finally, MNPs will be addressed concerning MRI, hyperthermia, drug delivery, and other applications. **Figure1** depicts the number of research paper publication by the research community for spinel ferrite from 2011 to 2020.

Figure 2: Time-line of main findings and new applications of spinel ferrite nanoparticles(Reproduced with permission from reference [9]).

2. Structure of spinel ferrite nanoparticles

Spinel ferrites are compliant with the common chemical formula AB_2O_4 , where A and B are metals in two different crystallographic, tetrahedral (A sites) and octahedral (B sites), and one of the key components in their formation is Fe. Three potential properties of spinel ferrite are known in the formula AFe_2O_4 , depending on the site selection site A (II) and Fe (III). They are known as normal, inverse, and mixed structures. A (II) is present at tetrahedral sites in a normal spinel structure, while Fe(III) is present at octahedral sites. Fe (III) is uniformly scattered at both sites in an inverse spinel structure, while A (II) occupies only the octahedral sites. Both ions occupy the tetrahedral and

octahedral sites at random in a mixed spinel structure. Normal spinel is ZnFe_2O_4 as an example. Inverse spinel ferrites including Fe_3O_4 and NiFe_2O_4 are a popular example, while $\text{Mn}_{0.8}\text{Fe}_{0.2}(\text{Mn}_{0.2}\text{Fe}_{1.8})\text{O}_4$ are a good example of mixed spinel ferrite. **Figure 3** shows the structure of spinel ferrite. Spinel ferrites are a large class of materials that have the same structure as natural spinel i.e. MgAl_2O_4 . According to the literature [28], there were already over 140 oxides and 80 sulphides, and their physicochemical properties were investigated after they were synthesized. Spinel ferrites have an extensive range of properties due to their ability to integrate cations of various charges into their structure. To balance the charge of the anions, the total positive charge should not be greater than 8. The cation radii are also a necessity. The values must be between 0.4 and 0.9 Å. The general formula for magnetic spinel is $\text{A}^{2+}\text{Fe}_2\text{O}_4$ (or $\text{AO}.\text{Fe}_2\text{O}_3$), where the divalent cation can be Mn, Ni, Fe, Co, Zn, Mg, and so on. Natural Fe_3O_4 (or $\text{FeO}.\text{Fe}_2\text{O}_3$) is the most essential and abundant [29]. In 1915, Bragg [30] was the first to discover the crystalline structure of spinel ferrites. The space group of the spinel ferrite is $\text{Fd}\bar{3}\text{m}$, and the unit cell comprises eight units of AB_2O_4 , a total of 56 ions (16 in A sites, 32 in B sites, and 32 oxygen directly bonded to the cations) are present. The lattice parameter variation based on the cations in A or B sites, and it can be determined theoretically using equation 1.

$$a_{\text{th}} = \frac{8}{3\sqrt{3}}[(r_a + r_o) + \sqrt{3}(r_b + r_o)] \quad (1)$$

where r_o is the oxygen anions of ionic radii, and r_a and r_b are the A and B sites ionic radii, respectively. Each spinel ferrites has a unique physicochemical property.

Figure 3: Spinel structure of ferrite nanoparticles.

For example, inverse spinel ferrites are ferrimagnetic, while normal spinel ferrites are paramagnetic [31]. As a result, it's critical to comprehend which factors influence site occupancy, as well as the cationic distribution on structural and magnetic properties.

For example, the average cation radii at the tetrahedral and octahedral sites, r_A and r_B , for the $Zn_{1-x}Co_xFe_2O_4$ system [32], were determined using the following cation distribution:

$$(Zn_{1-x}^{2+}Fe_{x+y}^{3+}Co_y^{2+})_A[Co_{x-y}^{2+}Fe_{2-x-y}^{3+}]_B(O_4^{2-})_O \quad (2)$$

$$r_A = C(Zn_A^{2+}) \cdot r(Zn_A^{2+}) + C(Fe_A^{3+}) \cdot r(Fe_A^{3+}) + C(Co_A^{2+}) \cdot r(Co_A^{2+}) \quad (3)$$

$$r_B = C(Co_B^{2+}) \cdot r(Co_B^{2+}) + C(Fe_B^{3+}) \cdot r(Fe_B^{3+}) / 2 \quad (4)$$

where $r(Zn_A^{2+})$, $r(Fe_A^{3+})$, and $r(Co_A^{2+})$ denote the ionic concentration at tetrahedral and octahedral sites, respectively; C denotes the ionic concentration. $r(Co_B^{2+})$, $r(Fe_B^{3+})$ are the ionic radii of Co^{2+} (0.745 Å) and Fe^{3+} (0.645 Å) ions in the octahedral sites and Zn^{2+} (0.60 Å), Fe^{3+} (0.49 Å), and Co^{2+} (0.58 Å) ions in the tetrahedral sites, respectively [32]. With decrease the ionic radii $r(A)$ at tetrahedral site, while $r(B)$ increases with increasing Co^{2+} concentration because Zn^{2+} ions (0.60 Å) with larger ionic radius are replaced by Co^{2+} ions (0.58 Å) with smaller ionic radius [33]. Kane et al. prepared $Zn_{0.85-x}Ni_xMg_{0.05}Cu_{0.1}Fe_2O_4$ ferrites by sol-gel method and studied the cation distribution. Since there is a clear correlation between the magnetic properties and the cation distribution of spinel ferrites, cationic distribution will help us better understand the magnetic interactions of these elements [34, 35]. Table 1 shows the chemical composition and chemical parameters of several ferrites in a cubic spinel structure. The constant lattice decrease in spinel ferrite systems can be explained in several ways: a decrease in ionic radius due to low ionic surface of the doping cation relative to that of the parent cation

- (i) a potential redistribution of Me^{2+} and Me^{3+} ions within the tetrahedral/octahedral ionic sites, due to substantial changes in magnetic properties
- (ii) a fraction of Me^{2+} ions occupying the octahedral sites, driving Me^{3+} to the tetrahedral sites against their chemical preferences [34].

Table 1: Composition and crystal-chemical parameters for several ferrites with a spinel structure.

S.No.	Composition	Synthesis Methods	Size(nm)	Lattice Constant (Å)	Strain (ε)	References
1	ZnFe ₂ O ₄	microwave combustion	5–15	8.4410	0.034	[34]
2	Co _{1-x} Zn _x Fe ₂ O ₄	microwave combustion	45–32	8.3799–8.3959	0.035–0.043	[35]
3	Mg _x Zn _{1-x} Fe ₂ O ₄ (x = 0.5, 0.6, 0.7)	Co-precipitation	6.3–14.6	8.422–8.438	~0.005	[36]
4	Zn _{1-x} Mg _x Fe ₂ O ₄ (x=0.0, 0.1, 0.2, 0.3 0.4, 0.5, 0.6, 0.7, and 0.8)	microwave combustion	41.20–15.87	8.443–8.427	0.067–0.047	[37]
5	Zn _{1-x} Cu _x Fe ₂ O ₄ (x = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5)	microwave combustion	43–54	8.443–8.413	0.067–0.056	[38]
6	Mn _{0.5} Zn _{0.5} Fe ₂ O ₄	Sol–gel	25	8.4339	0.0009	[39]
7	Mn _{1-x} Ni _x Fe ₂ O ₄ (x = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5)	microwave combustion	-	8.477–8.419	0.412–0.200	[40]
8	Co _{1-x} Ca _x Fe ₂ O ₄ (x=0.0, 0.01, 0.015, 0.02, 0.05, 0.1, and 0.15)	sol–gel	22-9	8.376-8.399	1.26-9.6	[41]
9	NiGd _x Fe _{2-x} O ₄ (x=0,0.025,0.050,0.075and 0.1)	Sol-gel	25.02-11.1	8.303-8.309	0.00148-0.00262	[42]
10	Al _x ZnFe _{2-x} O ₄ , (x = 0.0, 0.04, 0.08, 0.12, 0.16, 0.20)	co-precipitation	36.1-31.4	8.44-8.425	0.00117-0.000121	[43]
11	CoFe _{1.95} Ho _{0.05} O ₄	mechanical alloyed	50	8.3745	0.463	[44]

12	$\text{Ni}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ($x=0.5, 0.6$ and 0.7)	Coprecipitated	10.6-12.3	8.381-8.346	-	[45]
13	$\text{Co}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$	sol-gel	21.68	8.411	0.577	[46]
14	$\text{Co}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$	ball-mill	18.99	8.409	0.702	[46]
15	MgFe_2O_4	sol-gel auto combustion	17.5	8.301	-	[47]
16	ZnFe_2O_4	sol-gel auto combustion	21.3	8.366	-	[47]
17	MnFe_2O_4	sol-gel auto combustion	23.3	8.434	-	[47]
18	$\text{Ni}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ($x=0.1, 0.3, 0.5$)	co-precipitation	11.85-16.76	8.4271-8.4093	0.003539-0.002166	[48]
19	$\text{NiCe}_x\text{Fe}_{2-x}\text{O}_4$ ($x=0, 0.025, 0.050, 0.075$ and 1.0)	Sol-gel	35.02-15.33	8.303-8.319	0.00124-0.00293	[49]
20	$\text{Ni}_{0.9}\text{Cd}_{0.1}\text{Gd}_x\text{Fe}_{2-x}\text{O}_4$ ($x=0, 0.1, 0.2$ and 0.3)	sol-gel	17.5 ± 1.2 - 19.3 ± 0.8	0.8402-0.8363	-	[50]
21	$\text{Cu}_{0.5}\text{Ni}_{0.5}\text{In}_x\text{Fe}_{2-x}\text{O}_4$ ($x=0.00$ - 0.32)	sol-gel	33.21-17.78	8.3349 to 8.3723	0.054-0.094	[51]

3. Synthesis methods of spinel ferrite nanoparticles

To synthesize nanoparticles there is two techniques: top-down and bottom-up shown in **Figure 4**. In the first technique, mass material is separated to get nano estimated particles. This technique has many breaking points at particles like commonly metal oxides are utilized, a prerequisite of extremely high temperature for the response, items are inhomogeneous, presence of pollutions, gem abandons, expansive size appropriation and defect in surface design. In the second technique, nanoparticles are produced from small atomic building blocks. To synthesize nanoparticles there are various methods to produce the product uniform and pure. Tremendous procedures are utilized to plan nano ferrites, for example, solution combustion method, co-precipitation method, sol-gel method, microemulsions method, solid-state reaction method, thermal method. Top-down synthesis techniques include solid-state and other are bottom-up techniques various properties improved with various procedures.

Figure 4: shows the top-down and bottom-up approach spinel ferrite nanoparticles.

3.1 Co-precipitation method

This method is easy to integrate nanomaterials. To get homogenous construction and small size this method is used. The ferrites arranged utilizing this technique are of controlled size, profoundly unadulterated, and have a homogeneous construction. For making a homogenous solution different materials are dissolved in H_2O and may be other medium and here basic material that is used like (chloride, sulphate, nitrate, etc.) as the initial material. Set the pH range 7-10 to get nanoparticles. In the end, materials are together after precipitation. After the precipitation, the material should be calcined. Thakur et al. [52] utilized this technique to prepare MnZn ferrite. For starting materials $FeCl_3$, $MgCl_3$ and $ZnCl_2$ were utilized. In 60 ml of refined D.I. water the 3M arrangement was prepared. Then this arrangement was filled with a bubbling sodium hydroxide (NaOH) arrangement although mixing for 60 min at different temperatures 355-359 K, keeping up pH somewhere in the range of 10 and 11. For getting the nanoparticles to settle down the stirring process is allowed to precipitates and after this, with the help of distilled water, the final sample was washed many times. Using mortar pestle the crushing process was started while before this the sample washed properly and dried in a hot air oven. Anwar et al. [53] more over prepared MnZn ferrites, $Mn(NO_3)_2 \cdot 4H_2O$, $Zn(NO_3)_2 \cdot H_2O$, and $Fe_2(NO_3)_3 \cdot 9H_2O$ as the initial materials. At 355K homogenous solution prepared when these were assorted. CPT has successfully synthesized MFe_2O_4 (M=Fe, Co, Mn) NPs with sizes ranging from 4 to 12 nm in high yields using alkanolamines instead of sodium hydroxide, ammonia, and tetra alkyl-ammonium

hydroxides. When compared to NaOH-prepared nanoparticles, this method produced nanoparticles with higher colloidal stability, smaller particle sizes, and improved magnetic properties [54]. The CPT method was used to make spinel-type CuFeMnO_4 with an average size of 100 nm, which was achieved by calcinating the precipitate at 500–900 °C. Cu^+ ions at tetrahedral sites and Mn^{4+} at octahedral sites turned into Cu^{2+} and Mn^{3+} during calcinations, according to X-ray photoelectron spectroscopy (XPS) study [55]. $\text{Mn}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_4$ [56], $\text{Ni}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_4$ [57,58], MnFe_2O_4 [59], CoFe_2O_4 [60], $\text{Ni}_{0.53}\text{Cu}_{0.12}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4$ and $\text{Mg}_{0.2}\text{Cu}_{0.3}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ [61] has been prepared by CPT method.

3.2 Sol-gel method

It is a method for producing solid materials from small particles. In this compound methodology, a "sol" (a colloidal arrangement) is shaped and also, gelation of the sol in a nonstop fluid stage (gel) to shape a three-dimensional organization structure. For this method, metal ferrite is prepared by a sol-gel method like nickel ferrite, cobalt ferrite, zinc ferrite. The salt precursors (oxidizer) and complexing agents (reductant) are added to form a gel in these processes. Citric acid is widely used as a chelating agent and a reductant in the auto combustion sol-gel process, where it is oxidised by nitrate ions and thus acts as a fuel [62]. To make ferrite powder, the solution is heated and self-ignited [63]. After that, the ferrite is annealed at temperatures ranging from 400 to 1000 degrees Celsius. The sol-gel method [64] allows for more precise control of elemental composition, structure, homogeneity, and powder morphology. The key drawback of sol-gel techniques is that they are expensive and produce poor yields [65].

It has been possible to monitor the stability, crystallinity, particle size, and electromagnetic properties of SF products by selecting an acceptable complexing agent, the heating source, and the atmosphere [66]. The sol-gel method was used to synthesize NiFe_2O_4 NPs [67]. The chelating agent was polyacrylic acid. The average particle size ranged from 5 to 30 nm. Particle sizes decreased and crystallinity increased as the molar ratio of PAA to total metal ions was increased. The findings revealed that PAA not only acts as a chelating agent but also aids in increasing the crystallinity of nanoparticles through its combustion heat. R.H. Kadam et al. [68] prepared Gd_3+ doped Mn-Cr nanoferrites in the form of sol-gel auto combining and then investigate the structural properties and magnetic fields.

Figure 5: Flow chart for the synthesis of spinel ferrite nanoparticles by different methods.

3.3 Microemulsion method

Microemulsions are macroscopically homogeneous and thermodynamically stable solutions made up of at least three components: a polar phase (typically water), a nonpolar phase (typically oil), and a surfactant [69]. Oil-in-water (O/W) (normal micelle), water-in-oil (W/O) (reverse micelle), and water-in-supercritical CO₂ (W/sc-CO₂) are all examples of microemulsion systems. For the most part, the reverse micelle process is used to make ferrite nanoparticles. A surfactant is dissolved in organic solvents, and tiny droplets of water are encircled by surfactant molecules, creating so-called "water ponds." These reverse micelle water pools serve as nanoreactors, allowing inorganic and organic materials to precipitate [69, 70]. This method produces nanoparticles that are uniform and homogeneous, with a small size distribution. Small modifications to the synthesis will easily regulate the size. On the other hand, the process is costly and low yield. Furthermore, significant amounts of organic solvents are used, which is not environmentally friendly [58, 71]. In a W/O microemulsion device [water–

isooctane–AOT (sodium di 2ethylhexylsulfosuccinate)] [72], nanocrystalline Mn-Zn ferrite was synthesized. The particles ranged in size from 20 to 80 nanometres. The effect of synthesis temperature on the size of the micelles was investigated in this analysis. At 15°C, the smallest particles were collected. CoFe_2O_4 [73], MgFe_2O_4 [74], ZnFe_2O_4 [75], $\text{Co}_{0.5}\text{Ni}_{0.5}\text{Fe}_2\text{O}_4$ [76], CoeSn substituted barium ferrite [77], and other mixed ferrites have all been synthesised using the microemulsion technique. As previously mentioned, the method of preparation used may affect the structural and physical properties of ferrite nanoparticles [78].

3.4 Solution combustion method

SCS is a thrilling phenomenon, which includes engendering of self-supported exothermic responses along with fluid or sol-gel media. This method is very simple and synthesizes nanomaterial especially complexing oxides, alloys, etc. It is a method that is used to prepared nanocrystalline powder viz ceramic oxides, which are extremely pure and uniform powders [79]. In SCS there are numerous initial materials are used viz nitrates, metal sulfates, and carbonates, as oxidants and reducing reagents, fuels such as glycine, sucrose, urea [80, 81]. During combustion reaction, the nitrate acts as an oxidizer fuel. In the end, the powder that is obtained from this method of a single-phase meanwhile is a combination of metal oxides and required heat treatment to form a single phase. SCS is a technique dependent on the rule that once a response is started under warming, an exothermic response happens that gets self-supporting inside a specific period, bringing about a powder as the result. The exothermic response starts at the start temperature and creates a specific measure of warmth that is shown in the greatest temperature or temperature of burning. Arrangement ignition blend has the benefit of quickly creating the powder homogenous. Since it is an exothermic, auto-spread cycle, and with a high warmth discharge rate, it tends to be hazardous and ought to be attempted with additional safeguards. Arrangement burning blend is a speedy and simple cycle, with as primary favorable circumstances the saving of time and energy.

3.5 Solid-state method

Grinding of iron and metal salts is accompanied by a direct reaction at high temperatures in the solid-state synthesis of the ceramic process. The ceramic technique can be influenced by the particle size of the reactants, the gas environment, and international additives [82]. The procedure is straightforward and low-cost, with high efficiency and selectivity [83]. Since the reaction takes place without the use of a solvent, contamination from solvents is avoided. It's difficult to keep track of the reaction's progress and find the right conditions for the reaction to finish. Furthermore, it is difficult to separate the target product from a mixture of reactants and products. Furthermore, even though the reaction

continues almost to completion, the solid-state reaction makes it impossible to obtain a homogeneous pure product [84]. Nb⁵⁺/Ti³⁺-doped NiFe₂O₄, MnFe₂O₄, and NiZnFe₂O₄ have been synthesized using the solid-state reaction [85]. As the concentration of dopant ions increased, the particle diameters shrank. The ferrite grain size had a big impact on saturation magnetization and coercive area. Zinc ferrite [86], spinel cobalt ferrite [87], and LiZn ferrite (Li_{0.4}Zn_{0.2}Fe_{2.4}O₄) [88] have all been synthesized using the solid-state method.

There are the following steps we followed after fabrication of samples by different methods:

a) Calcination

Calcination enables the neighbouring grains to react by inter-diffusion of their ions in the furnace, to obtain a new stable process the diffusion must be reduced during sintering. Controlling the shrinkage of the sample during the sintering of the calcination is an important process. Calcination is a process to heat the solid material in the absence of oxygen and air. The powder to be calcined is not normally pressed. Escaping gases often produces extra porosity, and the reactions do not go to completion partly owing to small contact areas at interfaces between grains. Repeated mixing, pressing, and grinding are needed to form a homogeneous product.

b) Pelletization

The simplest way to shape a ceramic is using pelletization. The sample is ground uniformly by mixing with a suitable binder, and then the powder is pressed by hydraulic pressing which is used for the shaping of the materials. Unidirectional pressing is carried out in a die with movable top and bottom punches. The bottom punch is used for free-flowing of powder in which cavity is formed and the other side top punch is used to compress the powder and determine the volume of the sample. These punches are moved upwards when the top punch is clear from the powder and the bottom punch level with the die. The bottom punch is cleared when the compact is removed. Under this method, the dry powder is pressed in a metal die at a sufficiently high pressure of 10 tons to form a dense, strong piece. Pressing ensures a large area of surface contact between the grains. This increases the reaction rates, density, and strength of final products.

Macroscopic pressure gradients that develop across the pellet during pressurization can result in cracking and therefore they should be minimized.

- i) Friction at die wall
- ii) Die surfaces are not flat, and

iii) Die edges are not perfect

After pressing, pellets need to be handled carefully to avoid mechanical stress. A metal die of 1.5 cm. diameter opening is used for pelletization purposes. Pressure usually used was nearly equal to 10 tons.

c) Sintering

It is interaction as the expulsion of the pores between the underlying fine particles joined by shrinkage of the calcined item joined with development together and arrangement of solid connections between adjacent particles.

In ceramics, this increases mechanical strength, density, and thermal conductivity. These are correlated to the grain size, grain shape, pore size, and pore shape. During heat treatment, the average grain size increases due to grain growth in this process. Some grain ought to shrink and disappear when the average grain size increases. While overpowering is the driving force in all systems, the main difference in the behavior of different types of systems must be related to different asset conversion processes. Some of these processes are evaporation, condensing, visible flow, expansion of the earth, and the deterioration of plastic.

Material transformation by evaporation and condensation arises from the difference in surface curvature and consequently of the vapour pressure at the various parts of the system. (Vapour phase material requires heating of the material to a temperature sufficiently high for vapour pressure to be appreciable). The diffusion can occur in many ways, e.g. at surfaces, grain boundaries, or in bulk involving migration of vacancies. The sintering temperature is chosen so that solid-state diffusion predominates over vapour transport.

To carry out sintering in the present case, a high-temperature programmable furnace (Heraeus Make) is used with a chromal-alumal thermocouple. For this furnace, the upper-temperature limit was 1400°C. High-temperature alumina boats were used to place the powder/ samples in the furnace.

d) Finishing

Sintered samples are then lapped using micro grit powder to reduce the thickness of the pellet and finally silver metallization is done for electrical and magnetic characterization. **Figure 5** shows the flow chart for the synthesis of spinel ferrite nanoparticles by different methods. **Table 2** summarizes the composition of various spinel ferrites synthesized with different methods and study their magnetic and dielectric properties. Their magnetic properties, as well as the ease with which they can be modified and regulated in terms of size, shape, and composition, make them an appealing medium for biomedical

applications [89, 90]. Their high saturation magnetization, high coercivity and low curie temperature are ideal for a variety of biomedical applications.

4. Characterizations of spinel ferrite nanoparticles

The nano ferrites are characterized using a variety of techniques. These techniques provide high-quality details about the sample. The structure, morphological, magnetic, and dielectric properties of spinel ferrite nanoparticles have been defined using a variety of characterization methods. The following are some of them:

4.1 X-ray diffraction

For characterizing crystalline materials, X-ray diffraction (XRD) is an effective non-destructive technique. Structures, phases, desired crystal orientations (texture), and other structural parameters such as average grain size, crystallinity, strain, and crystal defects, provided all the information. The constructive distortion of the monochromatic X-ray beam is dispersed at certain angles from each set of lattice planes in the sample producing X-ray diffraction peaks. The distribution of atoms within the lattice determines the maximum force. For extracting XRD patterns from samples, XRD used CuK as a radiation source. The parameters of the site radii structure, bond hopping length, shared and unallocated edges are all determined using distribution X-ray data. X-ray beam with a length of $\lambda = 1.5406\text{\AA}$ is directed at an angle to the sample in this process. The X-ray power shown is recorded as the sample and detector rotate. The Debye-Scherrer equation can be used to determine the crystallite size [91]:

$$D = \frac{0.9\lambda}{\beta \cos \theta} \quad (5)$$

where D is the crystallite size in nm, λ is the wavelength, β is the highest Bragg's peak, and θ is the diffraction angle.

The lattice parameter is determined using the equation:

$$a = d\sqrt{h^2 + k^2 + l^2} \quad (6)$$

where d is the interplanar distance and the miller indices are “h,” “k,” and “l.”

The Williamson–Hall method [92] was used to measure the induced strain

$$\beta \cos \theta = 4 \epsilon \sin \theta \frac{\lambda}{D} \quad (7)$$

Where D is the particle size, X-ray wavelength is λ , FWHM is measured in radians, induced lattice strain is ϵ , and Bragg Angle is θ . The above-mentioned formula yielded an induced lattice strain.

Figure 6: shows the XRD pattern of the prepared ferrite sample (a) NiFe_2O_4 , (b) CoFe_2O_4 , (c) MnFe_2O_4 , (d) MgFe_2O_4 and (e) ZnFe_2O_4 [93] (copyright permission with license number: 5056370206855).

Darshane et al. published an XRD pattern that fits well with JCPDC data (card no. 10-0325) for NiFe_2O_4 calcined at 700°C , with an average crystallite size of 20 nm, and crystal studies show the formation of a large number of distinct uniform nanoparticles, confirming the position of NaCl as a growth inhibitor [94]. As grain size increases from nano to micro-scale during annealing at temperatures ranging from 900°C to 1300°C , Sutka et al. reported big differences in the impact of grain size on electrical resistivity between p-type and n-type materials [95]. Wang et al. found that the XRD pattern of cubic NiFe_2O_4 (JCPDS file no. 44-1485) has no other iron or nickel oxide phases and that the formation of spherical nanoparticles is dependent on the precursor concentration. Ethylene glycol is used as a solvent, reducing agent, complex agent, and stabilizing agent, according to Wang et al. [96]. Figure 6 shows that the XRD results show that powders made with AFe_2O_4 have a spinel structure without any phase impurities [93].

4.2 Morphological study

Scanning electron microscopy and transmission electron microscopy were used to examine the surface morphology of spinel ferrite nanoparticles. These methods are used on a wide scale to calculate the diameter of ferrite nanoparticles and to visualize their morphology. TEM is a more useful technique for determining the morphology, structure, and crystallite of ferrite nanoparticles. The TEM has a better resolution down to the atomic level. Scanning electron microscopy (SEM) is a method for imaging surfaces with high sensitivity. Its use of the electrons generated by the interaction of the beam with the sample surface. It's widely used to investigate nanoparticles aggregation and surface morphology. SEM is more commonly used than TEM, but SEM resolution is lower than TEM. Zhu et al. documented a porous brick-like structure of nickel-ferrite with numerous nanoparticles agglomerated on it [96]. Zhang et al. discovered a rod-like morphology with an average diameter of 100 nm and a 5 mm average length. Amorphous precursor rods have a very smooth surface [97]. Wang et al. described the elemental composition of aggregated nickel ferrite nanoparticles. Wang et al. published aggregated spheres of nickel ferrite nanoparticles, and EDS analysis revealed that the products only contain O, Fe, and Ni, with no contamination elements found. According to a TEM analysis, the average particle size is 90 nm [98]. **Figure 7** shows the TEM and SEM images of nickel spinel ferrite nanoparticles [99].

Figure 7: SEM(a,b) and TEM(c,d) image of NFSF NPs [99] (copyright permission with license number:5056401432599).

4.3 Fourier transform infrared study

FTIR analysis has been used by several researchers to determine the structure of ferrite nanoparticles. The FTIR spectra reveal the ions' locations in the crystal structure and their vibration modes, which reflect the effects of different ordering positions on the structural properties of synthesized compounds. Zhu et al. found that calcination temperature affects the FTIR and that all of the bands that appeared in the spectra of the NiFe_2O_4 samples gradually became weaker as the calcination temperature of the samples increases [99]. By removing the presence of unwanted ions, the FTIR spectrum is an effective tool for determining the temperature of nickel ferrite [100]. FTIR spectroscopic evidence published by Baykal et al. suggests that magnetic particle migration from aqueous to organic phase is followed by CTAB, which acts as a transfer agent [101]. Waldron suggested [102] that the $\text{Fe}^{3+}\text{O}^{2-}$ complex at the tetrahedral site is connected to the vibrational frequency (1) about $600\text{--}500\text{ cm}^{-1}$ (A). **Figure 8** shows FTIR peaks of LiZn ferrite nanoparticles [103].

Figure 8: FTIR spectra of $\text{Li}_{(0.5-0.5x)}\text{Zn}_x\text{Fe}_{(2.5-0.5x)}\text{O}_4$ samples ($x = 0.0, 0.2, 0.4, 0.6, 0.8$ and 1.0). For clarity, the transmittance values of samples with $x = 0.0, 0.2, 0.4, 0.6$ and 0.8 are shifted by 200, 140, 75, 35 and 30 units, respectively [103] (copyright permission with license number:5056430338199).

4.4 Magnetic properties

The investigation and analysis of magnetic properties were carried out using standard methods i.e. SQUID and VSM. The SQUID was employed where highly sensitive magnetisation measurements are required, and VSM was employed where the sensitivity maximum is approximately 10^{-6} emu [104]. The Saturation Magnetization (M_s), the Squareness ratio (SQR), coercivity (H_c), remanence (M_r) investigated in the VSM research. SQUID can calculate crystals, powders, thin films, gases, and liquids. The samples that are being investigated are packed into capsules made of gelatine. It is possible to calculate M_s , H_s , and residual magnetisation of ferrite nanoparticles using the SQUID technique when an external magnetic field and temperature are applied.

Figure 9: The magnetic hysteresis loops of the as-prepared $(Ni, Cu, Co)Fe_2O_4$ calcined at different temperatures and (b) H_c values of the products [105] (copyright permission with license number: 5056880383838).

Figure 9 shows the hysteresis loops of the prepared sample and it observes that the value of magnetic saturation was increased with increasing the temperature [105]. According to Naseri et al. the temperature of the calcinations is one of the most important factors that can increase or decrease the saturation of nickel ferrite when the sample is prepared by the heat treatment process. If the heating rate is slow, the crystallization and magnetic phases will emerge, resulting in higher saturation magnetization [100]. According to Maaz et al. the coercivity of nickel ferrite increases with particle size (for small particles)

due to the transition from a superparamagnetic to a blocked/unblocked condition. This happens when thermal energy triumphs over volume-dependent anisotropy in small particles [106].

4.5 Dielectric properties

One of the most important characteristics of ferrites is the dielectric behavior, which is highly dependent on the preparation conditions, such as sintering time and temperature, as well as the type and quantity of additives. Analysis of dielectric structures reveals useful information on the behavior of energy-carrying companies, leading to a better understanding of the dielectric separation of ferrite samples under investigation. The dielectric properties of spinel ferrites were investigated as a function of temperature, frequency, and composition [107]. While dielectric loss decreased as frequency increased, hopping resonance was discovered at higher frequencies and this research indicates that these soft ferrite nanoparticles may be used in a variety of advanced technical devices [108]. Dar et al. prepared $\text{Cu}_{1-x}\text{Co}_x\text{Fe}_2\text{O}_4$ ($x = 0.0, 0.1, 0.2, 0.4, 0.6, 1.0$) nanoparticles and reported that with increasing frequency, both the dielectric constant and the dielectric loss decrease. Furthermore, it is observe that with increase the concentration of Co^{2+} , dielectric constant also increases shown in **Figure 10** [109]. The dielectric constant in MnZn ferrite is found to decrease with the composition of Mn^{2+} using sol-gel auto combustion and co-precipitation techniques. The dependency of boundary charges located in the shell region of nanoparticles, which causes surface charge polarisation, is thought to be the cause of the dielectric constant variation. In the current series of samples, the hopping mechanism for electrical conduction is very different, and it is determined by the presence of a specific metal ion at B-site in the spinel structure. In this analysis, the method of preparation is important for achieving spinel structure [110]. The high dc resistivity of Gd-Mg ferrite makes it suitable for high frequency applications where eddy current losses are important. At 3 MHz, the dielectric loss in the currently studied ferrite is just 0.003 at room temperature. This ferrite's low dielectric constant and dielectric losses mean that it may be useful in microwave communications [83].

Figure 10: Room temperature variation of (a) real part of dielectric constant (ϵ') (b) imaginary part of dielectric constant (c) dielectric Loss (d) ac conductivity with applied frequency (f) for different Co²⁺ substitution in Cu_{1-x}Co_xFe₂O₄ ($x = 0.0 - 1.0$) ferrite samples [109] (copyright permission with license number: 5057020073404).

Table2: Magnetic and electrical properties of spinel ferrites with different methods.

S. No.	Composition	Methods	Size (nm)	Calcinations Temperature (°)	Magnetic Properties	Dielectric Properties	Refs.
1	$\text{Ni}_{0.65}\text{Zn}_{0.35}\text{Fe}_{2-x}\text{Mn}_x\text{O}_4$ ($x=0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30$ and 0.40)	Conventional ceramic processing	-	-	$M_r = 3475\text{--}3180$ emu/g $M_s = 5287\text{--}4476$ emu/g $H_c = 1.1$ Oe	$\rho = 1.7\text{--}1.9 \times 10^{-3}$ Ωcm $\tan \delta = <10^{-3}$	[111]
2	$\text{NiCr}_{0.2}\text{Ga}_x\text{Fe}_{1.8-x}\text{O}_4$ ($x=0.00, 0.02, 0.04, 0.06, 0.08$)	Co precipitation	23.01–17.48	800–7h	$M_r = 7.41\text{--}0.16$ emu/g $M_s = 27.83\text{--}7.01$ emu/g $H_c = 162.7\text{--}41.9$ Oe	-	[112]
3	$\text{Ni}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ($x=0.1, 0.2, 0.3, 0.4$ and 0.5)	Combustion	71–53	-	$M_s = 2.90\text{--}67.62$ emu/g $H_c = 14.61\text{--}81.09$ Oe	$\rho = 9.56\text{--}10.62 \times 10^x$ Ωcm	[113]
4	$\text{Co}_{1.2-x}\text{Mn}_x\text{Fe}_{1.8}\text{O}_4$ ($0 \leq x \leq 0.4$)	Chemical Autocombustion	-	700–4h	$M_r = 93.02\text{--}108.17$ emu/g $M_s = 106.50\text{--}97.78$ emu/g $H_c = 1520.82\text{--}1165.36$ Oe	-	[114]
5	$\text{NiHo}_x\text{Fe}_{2-x}\text{O}_4$ ($x=0.0\text{--}0.15$)	sol–gel auto-combustion	600–4h	$14\text{--}25 \pm 2$	$M_s = 21.23\text{--}11.57$ $M_r = 8.718\text{--}2.567$ $H_c = 253.47\text{--}707$	$\rho(\Omega\text{cm}^{-1}) = 8.9 \times 10^7$ $\epsilon = 7.748$	[115]
6	$\text{NiFe}_{1.5}\text{Sm}_{0.5}\text{O}_4$	Sol-gel	67.43	900–2h	-	$\sigma_{AC} = 5.203 \times 10^{-7}$	[116]
7	$\text{Ni}_{0.5}\text{Co}_{0.5-x}\text{Cd}_x\text{Fe}_{1.78}\text{Nd}_{0.02}\text{O}_4$ ($x \leq 0.25$)	Electro spinning	18.5–10.5	600–2h	-	$\epsilon = 0.360\text{eV}$	[117]

8	NiFe _{1.925} Sm _{0.075} O ₄	Solid-state	-	1250-12h	M _s =42.5 emu/g	$\dot{\epsilon}=4.9 \times 10^4$	[118]
9	NiFe ₂ O ₄	Sol-gel	35	800-2h	M _s =45.902 emu/g M _r =1.506 emu/g H _c = 27.374 Oe	$\sigma_{dc} = 7.7 \times 10^{-9} \Omega$ cm ⁻¹	[119]
10	CoFe ₂ O ₄ NiFe ₂ O ₄ ZnFe ₂ O ₄	Co- precipitation method	~14 ~ 9 ~12	600-4h	-	Resistivity (Ω)= 0.2344×10 ⁶ 0.1153×10 ⁶ 0.2063×10 ⁶	[120]
11	ZnFe ₂ O ₄	Sol-gel	16	500	M _s =12.01e mu/g M _r =0.345 emu/g H _c =20.83O e	$\sigma_{ac}=0.42 \times 10^{-9}$ Scm ⁻¹	[121]
12	Ni _{0.4} Co _{0.6} ErFe ₂ O ₄	Co- precipitation	14.833 6	600-5h	M _s =35.99e mu/g M _r =12.21 emu/g H _c = 0.16 Oe	Resistivity(Ω)= 6.20 ×10 ⁷	[122]
13	Ni _{0.5} Zn _{0.3} Cd _{0.2} La _y Fe _{2-y} O ₄ (y = 0.00–0.21)	Sol-gel	54.05- 38.69	1023 K for 6 h	M _s =40.31- 34.1 emu/g M _r =5.2- 3.25 emu/g H _c = 71.85- 54.37 Oe	-	[123]
14	Co _{1-x} Zr _x Fe ₂ O ₄ (x = 0, 0.25, 0.5, 0.75 and 1)	Co- precipitation	17-26	700-4h	M _s = 47.09 - 0.33 emu/g M _r = 18.22 - 0.06 emu/g H _c =1144.10 - 1225.34 Oe	-	[124]
15	CoFe ₂ O ₄ CoFe _{1.9} Nd _{0.1} O ₄	Co- precipitation	38.59	600-2h	M _s =73.58 emu/g	(Ω^{-1} cm ⁻¹) (10 ⁻⁶)=	[125]

	CoFe _{1.9} Sm _{0.1} O ₄	n	34.23		M _s =48.75	5.095	
	CoFe _{1.9} Gd _{0.1} O ₄		32.43		emu/g	(Ω ⁻¹ cm ⁻¹)	
			31.15		M _s =54.36	(10 ⁻⁶	
					emu/g	)=5.885	
					M _s =61.64	(Ω ⁻¹ cm ⁻¹)	
					emu/g	(10 ⁻⁶	
						)=5.678	
						(Ω ⁻¹ cm ⁻¹)	
						(10 ⁻⁶	
						)=6.016	
16	Cu _{0.8} Zn _{0.2} Cr _x Fe _{2-x} O ₄ ; (0≤x≤0.1)	Citrate– nitrate combustion	37.7– 47	-	M _s =33.22– 30.31 emu/g M _r =6.3– 4.07 emu/g H _c =265.23– 158.58 Oe	-	[126]
17	Ni _{0.6} Mg _{0.4} Fe ₂ O ₄	Sol-gel	-	1050 - 48 h	M _s = 41 emu/g M _r = 1.9 emu/g H _c = 18Oe	R _g (Ω)= 2249	[127]
18	Co _{0.7} Zn _{0.3} La _x Fe _{2-x} O ₄ (x = 0, 0.025, 0.05, 0.075 and 0.1)	Sol-gel	20-29	450-4h	M _s =63-51 emu/g H _c =481– 420 Oe M _r =24– 15emu/g	-	[128]
19	Mg _{1+x} Mn _x Fe _{2-2x} O ₄ (0 ≤ x ≤ 0.9)	Ceramic technique	-	1050-24h	M _s = 17.99– 8.08 emu/g	-	[129]
20	Ni _{0.2} Mg _{0.8-x} Zn _x Fe ₂ O ₄ (x = 0.0–0.8)	Sol-gel	8.6– 48.6	400-5h	M _s = 25.6 - 45.5 emu/g	ε' (1 MHz)= 18.1 - 47.4 σ _{ac} (1 MHz) = 2.57E-6 - 1.11E-5 ε''(1 MHz) = 4.62 - 20.1	[130]

5. Biomedical applications of SFNPs

In the last few decades, MNPs have been thoroughly studied. Their magnetic properties have always attracted the attention of scientists all over the world. Catalysis [131], information technology [132], biosensor [133, 134], and medicine [135], have produced a wide range of applications. SFNPs are used in a variety of biomedical applications, the most popular of which are disease detection, cancer treatment, and drug delivery. Non-toxic Superparamagnetic NPs with high M_s , high coercivity, and low Curie temperature are ideal for a variety of biomedical applications [136]. Spinel ferrite NPs with all these properties at room temperature, are clearly supported and are actually one of the priority areas of research to address and solve some of the health issues. Early identification of diseases before they cause significant harm and systematic delivery of medication at the targeted area that need surgent attention.

Figure 11: As per Scopus data, the number of publication for the keyword “Biomedical applications of spinel ferrites” from 2011-2020.

Advanced diagnostics and imaging are required for the former, while a targeted drug delivery system is required for the latter. All of these possibilities are available with SFNPs if they are coated with biocompatible polymeric chemicals. They have innovative and impressive uses in magnetically driven drug delivery, hyperthermia, and imaging techniques [137-142]. Traditional diagnostic and imaging methods are unable to identify tumour cells in the early stages of development and have little ability to distinguish

between normal and malignant cells [142]. Researchers from all over the world are interested in the special properties of SFNPs for resolving health issues, as well as their excellent properties in imaging, cancer care, and drug delivery. As a result, this section will provide a summary of the evolution of spinel ferrite biomedical applications. **Figure 11** shows the number of published papers in the field of biomedical application of spinel ferrite nanoparticles from 2011 to 2020.

5.1 Magnetic resonance imaging (MRI)

One of the most effective medical imaging methods for obtaining diagnosis for clinical purposes is magnetic resonance imaging (MRI). It's a non-invasive technique that relies on the interaction of protons & biological tissues in the presence of a magnetic field. Briefly, ^1H , ^{11}B , ^{13}C , ^{19}F , or ^{31}P can be used as MRI signal sources because of its sensitivity and abundance in biological tissues, the water proton (^1H) is the most commonly used for clinical purposes [143, 144]. As the proton nuclear spin is affected by an external magnetic field, longitudinal magnetization can be observed for imaging purposes. Radiofrequency pulses are used to excite the spin. The longitudinal magnetization decreases in this process, while a transverse magnetization is created. The pulse is removed, and the spin emits energy to return to the ground state. Relaxation is the term for this operation, which is recorded by MRI. The relaxation times T1 (longitudinal: spin–lattice relaxation) and T2 (transverse: spin–spin relaxation), which enable protons to return to their original state, can be used to create an MRI image. The complementation of the NP's magnetic field and its magnetic field and the protons from water molecules are required for T1 and T2. Reducing the resting time limits of water by following tissue separation, using different speeds of tissue regeneration and comparison agents [145]. Presence of cobalt nanoparticles Ms. (1422 emu cm^{-3}) has a much higher at room temperature than iron oxides (395 emu cm^{-3}), which could result in a stronger proton relaxation effect. This improves MRI contrast and allows for the use of smaller magnetic nanoparticles core without sacrificing sensitivity. Water-soluble Cobalt nanoparticles are difficult to make since [145] they are resistant to oxidation.

Figure12: Schematic representation of multifunctional MRI-contrast agents and their applications.

Larger magnetic particles have a higher r_1 relaxivity than shorter size. Field strength and particle size have little impact on r_2 relaxivity, but the relatively high value of r_2 makes Co nanoparticles useful as a negative contrast agent. Other metallic nanoparticles (Fe, Fe//Ni, Fe//Co and Fe//Pt), in addition to Co, can be used as MRI contrast agents. At the same particle size, the r_2 and r_2^* relaxivity of Fe is significantly higher than that of iron oxide [146]. The r_2/r_1 relaxivity ratio of FePt magnetic nanoparticles is 3–14 times greater than that of standard iron-oxide dependent contrast agents [147]. The lack of specificity in MRI contrast agents is still an issue. Their low sensitivity makes successful identification of tiny targets like tumours in the early stages of cancer [148]. MNPs tend to be an outstanding candidate in this regard. Their magnetic properties, as well as the ease with which they can be modified and regulated in terms of scale, shape, and composition, make them an appealing medium for MRI contrast agents [89, 90]. MNPs have proven to be effective contrast agents. The accumulation of MNPs in the target tissue will alter the local physiochemical properties. They looked at the magnetic properties of a series of spinel structures with the general formula MFe_2O_4 , where M can

be Mn^{2+} , Fe^{2+} , Co^{2+} , or Ni^{2+} , as well as their effect on MRI signals. In the range 85–110 emu.g^{-1} ($\text{Fe} + \text{M}$), there is high saturation magnetization, which has a big impact on the T2 relaxation time. MnFe_2O_4 outperformed as compared to other ferrites in terms of MR imaging sensitivity, being able to unambiguously detect small size cancers (~50 mg) in vivo documented by Jae-Hyun et al. [149]. Zhenghuan et al. [150] used octapod and spherical magnetic NPs for high-performance T2 contrast agents to successfully detect liver cancer in vivo. Both MNPs were able to detect liver cancer in vivo, but the octapod magnetic NPs were clearly better at distinguishing between healthy and diseased tissue.

5.2 Drug delivery

Because of their efficacy, simplicity, ease of preparation, and ability to adapt their properties for particular biological applications, the use of spinel ferrite nanoparticles as a drug delivery agent under the control of an external magnetic field has gotten a lot of attention [151-154]. About a century ago, German scientist Paul Ehrlich (1854-1915) proposed the concept of a "magic bullet" that would destroy only diseased tissue [155]. In 1950s the modern history of drug delivery can be work on micro-encapsulated drug particles [156]. Since then, the number of publications in this biomedical area has increased dramatically. Many analyses and research papers involving nanoparticles derived from silica [157-159], gold [160-162], polymers [163, 164], and other materials are currently available in the literature [157, 165-168]. As a result, it's easy to see that magnetism isn't a necessary feature when designing a drug delivery nano system, since a wide range of nano materials can be used. However, in recent decades, the use of MNPs in drug delivery has gotten a lot of attention [167]. The traditional method of drug delivery from nonspecific cell and tissue distributions with metabolic instability resulting in whole body toxicity and reduced therapeutic efficacy [169]. Another intriguing feature of SFNPs is their ability to encapsulate cytotoxic drugs within the polymer matrix and deliver them to cells [170-173]. SFNPs can hold drugs and circulate without spilling, and with the help of an external magnetic field, they can easily travel to the target tumour site and assist in delivering successful therapeutic care to cancer cells by bypassing normal cells [174]. The medication will be released and have therapeutic effects until it reaches the site of action [151]. Multifunctional NPs/NCs, which are made up of spinel ferrite nanoparticles, anti-cancer drugs, semiconductors (for cell imaging), and biocompatible coating agents, are particularly valuable for cancer therapy. Shen et al. [175] used in situ assembly to create multifunctional chitosan-based magnetic hybrid NCs with folate-conjugated tetrapeptide composite.

Figure13: Schematic representation of a SPION-liposome hybrid drug delivery system specifically designed for the triggered release of an encapsulated hydrophilic drug (Reproduced with permission from reference [176] Copyright 2014).

Chitosan, CdTe quantum dots, SPM Fe_3O_4 , anticancer agent camptothecin, and folate are the key components of synthesised NCs. $\text{MnFe}_2\text{O}_4@\text{graphene oxide}$ NC with SPM properties was recently synthesised using a sono-chemical process, and the NC has a high DOX loading potential [177]. The higher DOX loading ability has been due to hydrogen bonding and π -interactions between graphene oxide and DOX, according to the author's observations. In addition, under acidic rather than alkaline conditions, DOX sensitivity and release were found to be higher. As a result, the $\text{MnFe}_2\text{O}_4@\text{GO}$ is a promising candidate for DOX drug delivery to the tumour site and due to the acidic microenvironment of cancer tissue, the drug could be easily released at the tumour site. It has also been documented that lauric acid capped CoFe_2O_4 nanoparticles could be used as a promising drug delivery agent with pH sensitive release [178]. Furthermore, capping or coating SFNPs with biocompatible materials may help to improve their stability and reduce their toxicity in cells. To be used for magnetically driven drug delivery, SFNPs must have no residual magnetisation after the external magnet field has been removed, which means they must be SPM. This also allows them to preserve colloidal stability and prevent aggregation, allowing them to be used in biomedical applications [179]. Magnetic attraction between the particles is one of the predicted reasons for SFNP

agglomeration [180]. Targeted drug delivery with SFNPs has a number of benefits, including minimising drug waste, reducing drug administration frequency, reducing side effects, removing side effects on other organs due to site-specific drug delivery, improving treatment efficacy in a limited amount of time, and being safe and efficient due to drug delivery to preferred target organs. Hyperthermia, drug delivery and release at the target organs, where an increase in temperature to 42 to 46°C has no direct negative impact on the body (**Figure 13**). The reader is recommended to read the following reviews [89, 139, 151, 181-185] for more detail.

5.3 Hyperthermia

The basic principle of hyperthermia treatment is to generate heat locally by using an external system to pass energy to the tissue, thus increasing the temperature of the local atmosphere. Observation of certain patients with high fevers led to the development of this physical therapy. Surprisingly, the cancer cells were found to be significantly reduced or completely destroyed. Furthermore, other experiments using radiation-resistant cancer cells revealed a promising treatment combination capable of increasing the radiotherapy's efficacy [186]. As a result, hyperthermia will damage, destroy, or make cancerous cells more vulnerable to the effects of radiation and anticancer drugs [187]. To induce heat, various techniques such as ultrasound, microwave, radiofrequency, and others are currently available. The key issue with these thermal methodologies [188] is the absence of homogeneous heat distribution and the depth of therapeutic temperatures (45°C). In this regard, a thermal process based on MNPs is an excellent candidate for addressing these issues. As previously mentioned, their scale, magnetism, and ease of tuning surface properties to accumulate MNPs in tumour tissue are significant advantages. Both of these factors may contribute to the development of a cancer-treatment thermal therapy. Gordon et al. [189] were the first to describe a "*modern multidisciplinary "intracellular" biophysical treatment of cancer*" in 1979.

After an external high frequency or pulsed electromagnetic field was applied to colloidal magnetic submicron particles phagocytized by cancer cells, local heat was generated. As a result, a highly specific intracellular heat would be produced. Chan and his colleagues published Chan et al. in 1993. As a result, a highly specific intracellular heat would be produced. Chan et al. [155] created an aqueous magnetic fluid with dextran-modified SPM iron oxides in 1993. It was investigated how well they could absorb energy from an external magnetic field of varying intensity and frequency and convert it to heat. Jung-tak et al. [160] investigated the use of mixed ferrites (metal-doped MNPs). The authors investigated the magnetic influence of Zn^{2+} in the spinel structure of Fe_3O_4 and $MnFe_2O_4$ in their research. In addition, the Zn doped-MNPs ($(Zn_xMn_{1-x}) Fe_2O_4$ and (Zn_xFe_{1-x})

$x\text{Fe}_2\text{O}_4$, x ranging from 0.0 to 0.8) were tested for MRI and hyperthermia treatment. Since high values of saturation magnetization were observed for x equal to 0.4, it was possible to observe the mostly positive effect of Zn in the spinel structure of the MNPs studied. For $(\text{Zn}_{0.4}\text{Fe}_{0.6})\text{Fe}_2\text{O}_4$ and $(\text{Zn}_{0.4}\text{Mn}_{0.6})\text{Fe}_2\text{O}_4$, the values were 161 and 175 emu.g^{-1} , respectively. HeLa cells were used in an vitro trial, and 84.4 percent of those treated with $(\text{Zn}_{0.4}\text{Mn}_{0.6})\text{Fe}_2\text{O}_4$ died after 10 minutes, compared to just 13.5 percent of those treated with Feridex®. With all of these findings, it's easy to see how hyperthermia for cancer care has progressed rapidly over time. Jae-Hyun et al. [136] developed a core-shell structure compound consisting of MnFe_2O_4 (Shell) and CoFe_2O_4 (core) for in vivo hyperthermia treatment. In comparison to common antitumor drugs like doxorubicin, the antitumor study in mice showed higher efficacy. Tanmoy et al. [165] investigated magnetic hyperthermia therapy. According to the findings, hyperthermia was found to have an important in vivo inhibitory effect on tumour development. Noriyasu et al. [159] investigated the anticancer effects of Fe_3O_4 cationic liposomes (MCLs) in syngeneic rats with prostate cancer. The findings in this study strongly suggest that MCLs may be a useful tool in the treatment of prostate cancer. Not only do the MCLs appear to destroy cancerous cells by heating them, but they also appear to cause an immune response.

Figure14: Timeline of the development of hyperthermia using magnetic nanoparticles.

5.4 Other applications

5.4.1 Inductors and transformers for small-signal applications

A major use of high quality pot-core inductors is in combination with capacitors in filter circuits. They were extensively used in telephone systems but solid state switched systems have replaced them to a large extent. The value of Snoek's constant for cubic (standard) ferrites is around 7 GHz for a high-quality NiZn ferrite and around 4 GHz for a MnZn ferrite. If capacitance and line-length effects are ignored, most ferrites for EMC filters or transformers have similar HF efficiency [190]. The soft MnZn and NiZn ferrite systems are dominant for pot-core manufacture, although metal 'dust cores' are used for certain applications.

5.4.2 Transformers for power applications

There are many high-frequency (typically 1 kHz to 1 MHz) applications where a high saturation flux density is the prime requirement. Examples are power transformers to transmit a single frequency, those required to transmit over a narrow frequency band, as in the power unit of an ultrasonic generator and wide-band matching transformers to feed transmitting aerials. Television line output transformers are, commercially speaking, very important examples of power transformers and although not a transformer, the beam deflection yoke falls into the same category. At 300 kHz/70 mT, the total loss of the Mn Zn Co Fe O ferrite core did not exceed 420 mW/cm. This shows that it has a lot of scope for use in high-frequency power electronics circuits [191].

5.4.3 Information storage

Computer memory systems are classified as 'volatile' or 'non-volatile', the latter are of the type which retains the stored information if the power supply fails. Non-volatility is, of course, a very desirable feature, but other factors such as size, speed and cost all have to be considered. Two decades ago ferrite cores were dominant in random access memories; since then they have been almost completely superseded in commercial computers by the inherently volatile semiconductor memory elements. Sharma et al. reported that the moderate coercivity (maximum coercivity is 125.58 Oe) and saturation magnetization (decreases from 57.84 emu/gm to 25.30 emu/gm as Ni²⁺ content increases) suggest that these materials may be used in high density information storage devices [192].

5.4.4 Ferrite core memory

A material with a ‘square’ hysteresis loop has the important property that its remanent state is very little altered by the application or removal of small fields such as $+1/2 H_m$. If the field greater than $+H_c$ are applied, the remanent state switches to the opposite sense. This is the basis of operation of a ferrite core memory, where the $+B_r$ states represent the digits 0 and 1.

5.4.4.1 Magnetic bubble memory

Magnetic bubble memories are based on the mobility and stability of magnetic domains under certain conditions. If a thin transparent layer of anisotropic magnetic garnet is viewed through a crossed polarizer and analyzer system in a microscope.

5.4.5 Microwave devices

The elementary description of microwave propagation in magnetically saturated ferrites provides a basis for an understanding of the principles of operation of devices such as circulators, isolators and phase shifters, all of which find extensive use in microwave engineering. For example, a circulator might be used in a radar system where a single antenna is employed for both transmitting microwave power and receiving a reflected signal. Because of its high specific resistance (10^8 - $10^{10} \Omega\text{cm}$), Mg ferrite is well suited for microwave applications [193].

Faraday rotation isolator

Essential parts of a Faraday rotation isolator. The electric field of the forward wave is perpendicular to the plane of the resistive card and so it passes it with little attenuation.

Y-junction circulators

The most frequently used ferrite device is a three port circulator in waveguide or strip line configuration. In the waveguide configuration a ferrite cylindrical disc is located symmetrically with respect to three ports. In the strip line configuration two ferrite discs are placed on each side of the strips. In both cases a magnetic field is applied perpendicular to the planes of the discs.

Phase shifters

The phase of a microwave passing along a guide can be shifted by inserting pieces of ferrite at appropriate positions. For example, in a rectangular guide along which the simplest microwave field configuration is propagating, the magnetic field component is circularly polarized in the plane of the broad face of the waveguide at a distance

approximately a quarter of the way across the guide; on the opposite side of the guide the magnetic field component is circularly polarized in the opposite sense.

Microwave Ferrite Types

Most other examples that can be cited of materials exploitation, designing a ferrite for a particular microwave application is a compromise: a desire value for a particular parameter is generally achieved at the expense of the optimum values of other parameters. Nevertheless, a select number of spinel and garnet compositions have become favoured for microwave applications.

Permanent Magnets

Permanent magnet materials are required to give a maximum flux in the surrounding medium for a minimum volume of material and to be resistant to demagnetization. A material's suitability for a particular application is judged by its B_r , H_c and $(BH)_{max}$ values. The hexaferrites have the advantage of lower-cost raw materials their metal counterparts; both cobalt and the rare earths are expensive. They also have higher coercive field relative to those for the mass-produced metal magnet types and this allows them to be made into shapes involving high demagnetizing fields. According to the hysteresis loop, $Co_{0.5}Nd_{0.5}Fe_2O_4$ has a maximum energy product $(BH)_{max}$ of 0.431 MG Oe (3.434 KJ/m^3) at room temperature, which is a 7 percent increase above pure cobalt ferrites nanoparticles, confirming the material's performance in permanent magnet applications [194].

Wastewater treatment

Colours are distinguished as most noteworthy chemical contaminants that cause wastewater contamination [195, 196, 197, 198]. There has been developing exploration interests on photocatalytic decomposition using magnetic nanoparticles for environmental remediation because of the capability of these materials for enormous-scope application and compatibility with current innovations [199, 200, 201]. Magnetic ferrites and spinel structure have a restricted band gap ($\sim 1.9 \text{ eV}$) and that's why they are able for the engrossing visible light [202]. Photocatalytic degradation of colors in wastewater utilizing zinc ferrite and its spinel are exceptionally alluring as it is a zero waste procedure, and the impetuses can be reused [203-207]. The dye decomposition efficiency and kinetics of the pristine catalyst under direct and diffused sunlight was studied. Mandal S. et al. reported that direct sunlight works better than diffused light dye rot and more than 95%, can be found in the concentration of the first dye under the sun [206]. A second pseudonym for kinetics. $AgBr / ZF / NG$, $AgBr / CF / NG$ and NG demonstrated significant adsorption potential for MO and MG elimination while $AgBr$, ZF and CF showed optimal image performance under 12 % and 10%, respectively. The adsorption

strength of AgBr / CF / NG, AgBr / ZF / NG, and NG of MG was recorded as 64.00, 62.56 and 63.00 mg / g, respectively. 65.12, 66.00, and 67.10 mg / g of MO were extracted from AgBr / CF / NG, AgBr / ZF / NG, and NG, respectively. Claiming to reuse experiments, AgBr / ZF / NG and AgBr / CF / NG achieved 85% and 83% degradation efficacy, respectively, after ten consecutive cycles [207].

6. Future prospects

The use of SFNPs in biomedicine for diagnostics, hyperthermia, cancer gene therapy, and selective drug delivery and release has piqued the scientific community's interest. Despite the availability of several synthesis methods, the existing methods for the preparation of pure SFNPs with all of the required properties and in the desired quantities still need improvement. As a result, finding simple standard synthesis methods for SFNPs with the necessary scale, shape, and properties requires advanced technology that improves SFNP quality at a scalable production level. The ability to prepare new and improved SFNPs by doping or substituting transition or rare earth metals into SFNPs has been demonstrated in research. Doping of transition metals such as manganese, iron, cobalt, nickel, copper, and zinc has been found to be one of the most active research areas right now. On the other hand, the impact of incorporating rare earth metals into first-row transition metal ferrites hasn't been thoroughly investigated. As a result, we conclude that selective doping of low-concentration rare earth metals would most likely aid in the development of new SFNPs that have the potential to solve current health problems. To modified the structure and properties of SFNPs can be changing their size, synthesis methods, and doping them with transition metals or rare earth metals. As it has been observed in recent studies, doping of metals into ferrites has resulted in the variety of new SFNPs with various useful properties. SFNPs' multipurpose applications in biomedical fields like drug delivery, drug release, MRI, and cancer therapy are very promising. However, efficiency of synthesised SFNPs, optimisation of heating properties, concentrations of anticancer agents and spinel ferrite NPs, reproducibility of the synthesis system, and process parameters are all important. More research and attention are still required. Furthermore, the optimum size of SFNPs that can generate optimal heat and the alternative magnetic field needed to produce optimal heating are areas that should be investigated further.

Conclusions

Spinel ferrites have emerged as a promising material for the advancement of nanotechnology and nanomedicine. Spinel ferrite NPs have a variety of medical applications, including cancer diagnostics, cancer gene therapy, and drug administration. In biomedical applications, the efficacy of spinel ferrite NPs is more dependent on

synthesis procedures; good synthesis methods provide SFNPs that can endure the circumstances for which they are synthesised while also boosting their efficiency. The ease with which they may be manipulated and managed in terms of size, form, and composition, as well as their magnetic properties (high M_s and coercivity), make them an interesting medium for biomedical applications. In general, the excellent properties of SFNPs observed, as well as the ease with which they can be functionalized by coating their surfaces with non-toxic chemicals, provide an exciting opportunity for future generations to solve environmental and medical problems. SFNPs, in particular, are highly beneficial in the treatment of cancer. Recent conventional methodologies and approaches to spinel ferrites synthesis are discussed in this study. In addition, an overview of the issue was attempted, highlighting significant applications and discussing their characterisation methodologies, which provide high-quality details on the sample.

Conflict of Interest

The authors declare that they have no conflict of interest.

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References

- [1] Z. Yan, J. Gao, Y. Li, M. Zhang, M. Guo, Hydrothermal synthesis and structure evolution of metal-doped magnesium ferrite from saprolite laterite, *RSC Advances*, 5 (2015) 92778-92787. <https://doi.org/10.1039/C5RA17145H>
- [2] R.T. Olsson, G. Salazar-Alvarez, M.S. Hedenqvist, U.W. Gedde, F. Lindberg, S.J. Savage, Controlled synthesis of near-stoichiometric cobalt ferrite nanoparticles, *Chemistry of Materials*, 17 (2005) 5109-5118. <https://doi.org/10.1021/cm0501665>
- [3] A.H. Latham, M.E. Williams, Controlling transport and chemical functionality of magnetic nanoparticles, *Accounts of chemical research*, 41 (2008) 411-420. <https://doi.org/10.1021/ar700183b>
- [4] H. El Moussaoui, T. Mahfoud, S. Habouti, K. El Maalam, M.B. Ali, M. Hamedoun, O. Mounkachi, R. Masrour, E. Hlil, A. Benyoussef, Synthesis and magnetic properties of tin spinel ferrites doped manganese, *Journal of magnetism and magnetic materials*, 405 (2016) 181-186. <https://doi.org/10.1016/j.jmmm.2015.12.059>

- [5] D.S. Mathew, R.-S. Juang, An overview of the structure and magnetism of spinel ferrite nanoparticles and their synthesis in microemulsions, *Chemical engineering journal*, 129 (2007) 51-65. <https://doi.org/10.1016/j.cej.2006.11.001>
- [6] M.A. Maksoud, G.S. El-Sayyad, A. Ashour, A.I. El-Batal, M.S. Abd-Elmonem, H.A. Hendawy, E. Abdel-Khalek, S. Labib, E. Abdeltwab, M. El-Okr, Synthesis and characterization of metals-substituted cobalt ferrite [$M_x Co_{(1-x)} Fe_2O_4$; (M= Zn, Cu and Mn; x= 0 and 0.5)] nanoparticles as antimicrobial agents and sensors for Anagrelide determination in biological samples, *Materials Science and Engineering: C*, 92 (2018) 644-656. <https://doi.org/10.1016/j.msec.2018.07.007>
- [7] S. Hilpert, V. Verf, Genetische und konstitutive Zusammenhänge in den magnetischen Eigenschaften bei Ferriten und Eisenoxyden, *Berichte der deutschen chemischen Gesellschaft*, 42 (1909) 2248-2261. <https://doi.org/10.1002/cber.190904202121>
- [8] Y. Kato, T. Takei, Characteristics of metallic oxide magnetic, *Journal of the Institute Eletronic Engineering of Japan*, 53 (1933) 408-412.
- [9] W.S. Galvão, D. Neto, R.M. Freire, P.B. Fechine, Super-paramagnetic nanoparticles with spinel structure: a review of synthesis and biomedical applications, in: *solid state phenomena*, Trans Tech Publ, 2016, pp. 139-176. <https://doi.org/10.4028/www.scientific.net/SSP.241.139>
- [10] L. Néel, Théorie du traînage magnétique des ferromagnétiques en grains fins avec applications aux terres cuites, *Ann. géophys.*, 5 (1949) 99-136.
- [11] M. Sugimoto, The past, present, and future of ferrites, *Journal of the American Ceramic Society*, 82 (1999) 269-280. <https://doi.org/10.1111/j.1551-2916.1999.tb20058.x>
- [12] E. Albers-Schoenberg, Ferrites for microwave circuits and digital computers, *Journal of Applied Physics*, 25 (1954) 152-154. <https://doi.org/10.1063/1.1721594>
- [13] A. Bobeck, Properties and device applications of magnetic domains in orthoferrites, *The bell system technical journal*, 46 (1967) 1901-1925. <https://doi.org/10.1002/j.1538-7305.1967.tb03177.x>
- [14] A. Bobeck, R. Fischer, A. Perneski, J. Remeika, L. Van Uitert, Application of orthoferrites to domain-wall devices, *IEEE Transactions on Magnetics*, 5 (1969) 544-553. <https://doi.org/10.1109/TMAG.1969.1066480>

- [15] J. Dillon Jr, E. Gyorgy, J. Remeika, Photoinduced magnetic anisotropy and optical dichroism in silicon-doped yttrium iron garnet, *Physical Review Letters*, 22 (1969) 643. <https://doi.org/10.1103/PhysRevLett.22.643>
- [16] C.L. Hogan, The ferromagnetic Faraday effect at microwave frequencies and its applications: the microwave gyrator, *The Bell System Technical Journal*, 31 (1952) 1-31. <https://doi.org/10.1002/j.1538-7305.1952.tb01374.x>
- [17] C. Walcott, J.L. Gould, J. Kirschvink, Pigeons have magnets, *Science*, 205 (1979) 1027-1029. <https://doi.org/10.1126/science.472725>
- [18] J.L. Gould, J. Kirschvink, K. Deffeyes, Bees have magnetic remanence, *Science*, 201 (1978) 1026-1028. <https://doi.org/10.1126/science.201.4360.1026>
- [19] R.B. Frankel, R.P. Blakemore, R.S. Wolfe, Magnetite in freshwater magnetotactic bacteria, *Science*, 203 (1979) 1355-1356. <https://doi.org/10.1126/science.203.4387.1355>
- [20] K.J. Widder, A.E. Senyei, D.G. Scarpelli, Magnetic microspheres: a model system for site specific drug delivery in vivo, *Proceedings of the Society for Experimental Biology and Medicine*, 158 (1978) 141-146. <https://doi.org/10.3181/00379727-158-40158>
- [21] R. Gilchrist, R. Medal, W.D. Shorey, R.C. Hanselman, J.C. Parrott, C.B. Taylor, Selective inductive heating of lymph nodes, *Annals of surgery*, 146 (1957) 596. <https://doi.org/10.1097/00000658-195710000-00007>
- [22] P. Fannin, Measurement of the Neel relaxation of magnetic particles in the frequency range 1 kHz to 160 MHz, *Journal of Physics D: Applied Physics*, 24 (1991) 76. <https://doi.org/10.1088/0022-3727/24/1/013>
- [23] A.H. Lu, E.e.L. Salabas, F. Schüth, Magnetic nanoparticles: synthesis, protection, functionalization, and application, *Angewandte Chemie International Edition*, 46 (2007) 1222-1244. <https://doi.org/10.1002/anie.200602866>
- [24] B. Issa, I.M. Obaidat, B.A. Albiss, Y. Haik, Magnetic nanoparticles: surface effects and properties related to biomedicine applications, *International journal of molecular sciences*, 14 (2013) 21266-21305. <https://doi.org/10.3390/ijms141121266>
- [25] K.L. Pisane, E.C. Despeaux, M.S. Seehra, Magnetic relaxation and correlating effective magnetic moment with particle size distribution in maghemite nanoparticles, *Journal of Magnetism and Magnetic Materials*, 384 (2015) 148-154. <https://doi.org/10.1016/j.jmmm.2015.02.038>

- [26] S. Ruta, R. Chantrell, O. Hovorka, Unified model of hyperthermia via hysteresis heating in systems of interacting magnetic nanoparticles, *Scientific reports*, 5 (2015) 1-7. <https://doi.org/10.1038/srep09090>
- [27] P. Tartaj, M. del Puerto Morales, S. Veintemillas-Verdaguer, T. González-Carreño, C.J. Serna, The preparation of magnetic nanoparticles for applications in biomedicine, *Journal of physics D: Applied physics*, 36 (2003) R182. <https://doi.org/10.1088/0022-3727/36/13/202>
- [28] R.J. Hill, J.R. Craig, G. Gibbs, Systematics of the spinel structure type, *Physics and chemistry of minerals*, 4 (1979) 317-339. <https://doi.org/10.1007/BF00307535>
- [29] V.G. Harris, Modern microwave ferrites, *IEEE Transactions on Magnetics*, 48 (2011) 1075-1104. <https://doi.org/10.1109/TMAG.2011.2180732>
- [30] W. Bragg, The structure of magnetite and the spinels, *Nature*, 95 (1915) 561-561. <https://doi.org/10.1038/095561a0>
- [31] B. Cullity, C. Graham, *Introduction to Magnetic Materials*, A John Wiley & Sons, Inc., Hoboken, New Jersey, (2009) 361.
- [32] T. Tatarchuk, M. Bououdina, N. Paliychuk, I. Yaremiy, V. Moklyak, Structural characterization and antistructure modeling of cobalt-substituted zinc ferrites, *Journal of Alloys and Compounds*, 694 (2017) 777-791. <https://doi.org/10.1016/j.jallcom.2016.10.067>
- [33] M.P. Leal, S. Rivera-Fernández, J.M. Franco, D. Pozo, M. Jesús, M.L. García-Martín, Long-circulating PEGylated manganese ferrite nanoparticles for MRI-based molecular imaging, *Nanoscale*, 7 (2015) 2050-2059. <https://doi.org/10.1039/C4NR05781C>
- [34] G. Manjari, Green synthesis of silver and copper nanoparticles using *Aglaia elaeagnoidea* and its catalytic application on dye degradation, in, Department of Ecology and Environmental Sciences, Pondicherry University, 2018.
- [35] M. Sundararajan, V. Sailaja, L.J. Kennedy, J.J. Vijaya, Photocatalytic degradation of rhodamine B under visible light using nanostructured zinc doped cobalt ferrite: kinetics and mechanism, *Ceramics International*, 43 (2017) 540-548. <https://doi.org/10.1016/j.ceramint.2016.09.191>
- [36] S. Singh, C. Srinivas, B. Tirupanyam, C. Prajapat, M. Singh, S. Meena, P. Bhatt, S. Yusuf, D. Sastry, Structural, thermal and magnetic studies of $\text{Mg}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ nanoferrites: study of exchange interactions on magnetic anisotropy, *Ceramics International*, 42 (2016) 19179-19186. <https://doi.org/10.1016/j.ceramint.2016.09.081>

- [37] A. Manikandan, L.J. Kennedy, M. Bououdina, J.J. Vijaya, Synthesis, optical and magnetic properties of pure and Co-doped ZnFe_2O_4 nanoparticles by microwave combustion method, *Journal of magnetism and magnetic materials*, 349 (2014) 249-258. <https://doi.org/10.1016/j.jmmm.2013.09.013>
- [38] A. Manikandan, J.J. Vijaya, L.J. Kennedy, M. Bououdina, Structural, optical and magnetic properties of $\text{Zn}_{1-x}\text{Cu}_x\text{Fe}_2\text{O}_4$ nanoparticles prepared by microwave combustion method, *Journal of molecular structure*, 1035 (2013) 332-340. <https://doi.org/10.1016/j.molstruc.2012.11.007>
- [39] V.J. Angadi, A. Anupama, H.K. Choudhary, R. Kumar, H. Somashekarappa, M. Mallappa, B. Rudraswamy, B. Sahoo, Mechanism of γ -irradiation induced phase transformations in nanocrystalline $\text{Mn}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ ceramics, *Journal of Solid State Chemistry*, 246 (2017) 119-124. <https://doi.org/10.1016/j.jssc.2016.11.017>
- [40] S. Jesudoss, J.J. Vijaya, L.J. Kennedy, P.I. Rajan, H.A. Al-Lohedan, R.J. Ramalingam, K. Kaviyarasu, M. Bououdina, Studies on the efficient dual performance of $\text{Mn}_{1-x}\text{Ni}_x\text{Fe}_2\text{O}_4$ spinel nanoparticles in photodegradation and antibacterial activity, *Journal of Photochemistry and Photobiology B: Biology*, 165 (2016) 121-132. <https://doi.org/10.1016/j.jphotobiol.2016.10.004>
- [41] R. Kumar, M. Kar, Correlation between lattice strain and magnetic behavior in non-magnetic Ca substituted nano-crystalline cobalt ferrite, *Ceramics International*, 42 (2016) 6640-6647. <https://doi.org/10.1016/j.ceramint.2016.01.007>
- [42] M.M.L. Sonia, S. Anand, V.M. Vinosel, M.A. Janifer, S. Pauline, A. Manikandan, Effect of lattice strain on structure, morphology and magneto-dielectric properties of spinel $\text{NiGd}_x\text{Fe}_{2-x}\text{O}_4$ ferrite nano-crystallites synthesized by sol-gel route, *Journal of Magnetism and Magnetic Materials*, 466 (2018) 238-251. <https://doi.org/10.1016/j.jmmm.2018.07.017>
- [43] S. Gul, M.A. Yousuf, A. Anwar, M.F. Warsi, P.O. Agboola, I. Shakir, M. Shahid, Al-substituted zinc spinel ferrite nanoparticles: Preparation and evaluation of structural, electrical, magnetic and photocatalytic properties, *Ceramics International*, 46 (2020) 14195-14205. <https://doi.org/10.1016/j.ceramint.2020.02.228>
- [44] I.P. Muthuselvam, R. Bhowmik, Mechanical alloyed Ho^{3+} doping in CoFe_2O_4 spinel ferrite and understanding of magnetic nanodomains, *Journal of Magnetism and Magnetic Materials*, 322 (2010) 767-776. <https://doi.org/10.1016/j.jmmm.2009.10.057>
- [45] C. Srinivas, B. Tirupanyam, S. Meena, S. Yusuf, C.S. Babu, K. Ramakrishna, D. Potukuchi, D. Sastry, Structural and magnetic characterization of co-precipitated

- $\text{Ni}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ferrite nanoparticles, *Journal of Magnetism and Magnetic Materials*, 407 (2016) 135-141. <https://doi.org/10.1016/j.jmmm.2016.01.060>
- [46] R.S. Yadav, J. Havlica, M. Hnatko, P. Šajgalík, C. Alexander, M. Palou, E. Bartoníčková, M. Boháč, F. Frajkorová, J. Masilko, Magnetic properties of $\text{Co}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_4$ spinel ferrite nanoparticles synthesized by starch-assisted sol-gel autocombustion method and its ball milling, *Journal of Magnetism and Magnetic Materials*, 378 (2015) 190-199. <https://doi.org/10.1016/j.jmmm.2014.11.027>
- [47] S. Prasad, M. Deepty, P. Ramesh, G. Prasad, K. Srinivasarao, C. Srinivas, K.V. Babu, E.R. Kumar, N.K. Mohan, D. Sastry, Synthesis of MFe_2O_4 ($\text{M} = \text{Mg}^{2+}, \text{Zn}^{2+}, \text{Mn}^{2+}$) spinel ferrites and their structural, elastic and electron magnetic resonance properties, *Ceramics International*, 44 (2018) 10517-10524. <https://doi.org/10.1016/j.ceramint.2018.03.070>
- [48] M. Gabal, R.M. El-Shishtawy, Y. Al Angari, Structural and magnetic properties of nano-crystalline Ni-Zn ferrites synthesized using egg-white precursor, *Journal of Magnetism and Magnetic Materials*, 324 (2012) 2258-2264. <https://doi.org/10.1016/j.jmmm.2012.02.112>
- [49] M.M.L. Sonia, S. Anand, V.M. Vinosel, M.A. Janifer, S. Pauline, Effect of lattice strain on structural, magnetic and dielectric properties of sol-gel synthesized nanocrystalline Ce^{3+} substituted nickel ferrite, *Journal of Materials Science: Materials in Electronics*, 29 (2018) 15006-15021. <https://doi.org/10.1007/s10854-018-9639-2>
- [50] B.P. Jacob, S. Thankachan, S. Xavier, E. Mohammed, Effect of Gd^{3+} doping on the structural and magnetic properties of nanocrystalline Ni-Cd mixed ferrite, *Physica Scripta*, 84 (2011) 045702. <https://doi.org/10.1088/0031-8949/84/04/045702>
- [51] M. Junaid, M.A. Khan, M.N. Akhtar, A. Hussain, M.F. Warsi, Impact of indium substitution on dielectric and magnetic properties of $\text{Cu}_{0.5}\text{Ni}_{0.5}\text{Fe}_{2-x}\text{O}_4$ ferrite materials, *Ceramics International*, 45 (2019) 13431-13437. <https://doi.org/10.1016/j.ceramint.2019.04.042>
- [52] A. Thakur, P. Thakur, J.-H. Hsu, Structural, Magnetic and Electromagnetic Characterization of In^{3+} Substituted Mn-Zn Nanoferrites, *Zeitschrift für Physikalische Chemie*, 228 (2014) 663-672. <https://doi.org/10.1515/zpch-2014-0477>
- [53] H. Anwar, A. Maqsood, Effect of sintering temperature on structural, electrical and dielectric parameters of Mn-Zn nano ferrites, in: *Key Engineering Materials*, Trans Tech Publ, 2012, pp. 163-170. <https://doi.org/10.4028/www.scientific.net/KEM.510-511.163>

- [54] C. Pereira, A.M. Pereira, C. Fernandes, M. Rocha, R. Mendes, M.P. Fernández-García, A. Guedes, P.B. Tavares, J.-M. Grenèche, J.o.P. Araújo, Superparamagnetic MFe_2O_4 (M= Fe, Co, Mn) nanoparticles: tuning the particle size and magnetic properties through a novel one-step coprecipitation route, *Chemistry of Materials*, 24 (2012) 1496-1504. <https://doi.org/10.1021/cm300301c>
- [55] H. Ni, Z. Gao, X. Li, Y. Xiao, Y. Wang, Y. Zhang, Synthesis and characterization of CuFeMnO_4 prepared by co-precipitation method, *Journal of Materials Science*, 53 (2018) 3581-3589. <https://doi.org/10.1007/s10853-017-1800-4>
- [56] K. Hoshi, H. Kato, T. Fukunaga, S. Furusawa, H. Sakurai, Synthesis of MnZn-Ferrite Using Coprecipitation Method, in: *Key Engineering Materials*, Trans Tech Publ, 2013, pp. 22-25. <https://doi.org/10.4028/www.scientific.net/KEM.534.22>
- [57] K. Velmurugan, V.S.K. Venkatachalapathy, S. Sendhilnathan, Synthesis of nickel zinc iron nanoparticles by coprecipitation technique, *Materials Research*, 13 (2010) 299-303. <https://doi.org/10.1590/S1516-14392010000300005>
- [58] N. Kaur, M. Kaur, Comparative studies on impact of synthesis methods on structural and magnetic properties of magnesium ferrite nanoparticles, *Processing and Application of Ceramics*, 8 (2014) 137-143. <https://doi.org/10.2298/PAC1403137K>
- [59] A. Lungu, I. Malaescu, C. Marin, P. Vlazan, P. Sfirloaga, The electrical properties of manganese ferrite powders prepared by two different methods, *Physica B: Condensed Matter*, 462 (2015) 80-85. <https://doi.org/10.1016/j.physb.2015.01.025>
- [60] M. Houshiar, F. Zebhi, Z.J. Razi, A. Alidoust, Z. Askari, Synthesis of cobalt ferrite (CoFe_2O_4) nanoparticles using combustion, coprecipitation, and precipitation methods: A comparison study of size, structural, and magnetic properties, *Journal of Magnetism and Magnetic Materials*, 371 (2014) 43-48. <https://doi.org/10.1016/j.jmmm.2014.06.059>
- [61] Y. Kannan, R. Saravanan, N. Srinivasan, K. Praveena, K. Sadhana, Synthesis and characterization of some ferrite nanoparticles prepared by co-precipitation method, *Journal of Materials Science: Materials in Electronics*, 27 (2016) 12000-12008. <https://doi.org/10.1007/s10854-016-5347-y>
- [62] P. Dhiman, J. Chand, A. Kumar, R.K. Kotnala, K.M. Batoo, M. Singh, Synthesis and characterization of novel Fe@ZnO nanosystem, *Journal of Alloys and Compounds*, 578 (2013) 235-241. <https://doi.org/10.1016/j.jallcom.2013.05.015>
- [63] S. Bhukal, S. Mor, S. Bansal, J. Singh, S. Singhal, Influence of Cd_{2+} ions on the structural, electrical, optical and magnetic properties of Co–Zn nanoferrites prepared

- by sol gel auto combustion method, *Journal of Molecular Structure*, 1071 (2014) 95-102. <https://doi.org/10.1016/j.molstruc.2014.04.073>
- [64] N. Sanpo, J. Wang, C.C. Berndt, Influence of chelating agents on the microstructure and antibacterial property of cobalt ferrite nanopowders, *Journal of the Australian Ceramic Society*, 49 (2013) 84-91.
- [65] G.J. Owens, R.K. Singh, F. Foroutan, M. Alqaysi, C.-M. Han, C. Mahapatra, H.-W. Kim, J.C. Knowles, Sol-gel based materials for biomedical applications, *Progress in Materials Science*, 77 (2016) 1-79. <https://doi.org/10.1016/j.pmatsci.2015.12.001>
- [66] A. Sutka, G. Mezinskis, Sol-gel auto-combustion synthesis of spinel-type ferrite nanomaterials, *Frontiers of Materials Science*, 6 (2012) 128-141. <https://doi.org/10.1007/s11706-012-0167-3>
- [67] D.-H. Chen, X.-R. He, Synthesis of nickel ferrite nanoparticles by sol-gel method, *Materials Research Bulletin*, 36 (2001) 1369-1377. [https://doi.org/10.1016/S0025-5408\(01\)00620-1](https://doi.org/10.1016/S0025-5408(01)00620-1)
- [68] R. Kadam, K. Desai, V.S. Shinde, M. Hashim, S.E. Shirsath, Influence of Gd³⁺ ion substitution on the MnCrFeO₄ for their nanoparticle shape formation and magnetic properties, *Journal of Alloys and Compounds*, 657 (2016) 487-494. <https://doi.org/10.1016/j.jallcom.2015.10.164>
- [69] M.A. Malik, M.Y. Wani, M.A. Hashim, Microemulsion method: A novel route to synthesize organic and inorganic nanomaterials: 1st Nano Update, *Arabian journal of Chemistry*, 5 (2012) 397-417. <https://doi.org/10.1016/j.arabjc.2010.09.027>
- [70] A. Košak, D. Makovec, A. Žnidaršič, M. Drofenik, Preparation of MnZn-ferrite with microemulsion technique, *Journal of the European Ceramic Society*, 24 (2004) 959-962. [https://doi.org/10.1016/S0955-2219\(03\)00524-7](https://doi.org/10.1016/S0955-2219(03)00524-7)
- [71] K. Pemartin, C. Solans, J. Alvarez-Quintana, M. Sanchez-Dominguez, Synthesis of Mn-Zn ferrite nanoparticles by the oil-in-water microemulsion reaction method, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 451 (2014) 161-171. <https://doi.org/10.1016/j.colsurfa.2014.03.036>
- [72] D.O. Yener, H. Giesche, Synthesis of Pure and Manganese-, Nickel-, and Zinc-Doped Ferrite Particles in Water-in-Oil Microemulsions, *Journal of the American Ceramic Society*, 84 (2001) 1987-1995. <https://doi.org/10.1111/j.1151-2916.2001.tb00947.x>

- [73] V. Pillai, D. Shah, Synthesis of high-coercivity cobalt ferrite particles using water-in-oil microemulsions, *Journal of Magnetism and Magnetic Materials*, 163 (1996) 243-248. [https://doi.org/10.1016/S0304-8853\(96\)00280-6](https://doi.org/10.1016/S0304-8853(96)00280-6)
- [74] P. Holec, J. Plocek, D. Nižňanský, J.P. Vejpravová, Preparation of MgFe_2O_4 nanoparticles by microemulsion method and their characterization, *Journal of sol-gel science and technology*, 51 (2009) 301-305. <https://doi.org/10.1007/s10971-009-1962-x>
- [75] F. Grasset, N. Labhsetwar, D. Li, D. Park, N. Saito, H. Haneda, O. Cador, T. Roisnel, S. Mornet, E. Duguet, Synthesis and magnetic characterization of zinc ferrite nanoparticles with different environments: powder, colloidal solution, and zinc ferrite-silica core-shell nanoparticles, *Langmuir*, 18 (2002) 8209-8216. <https://doi.org/10.1021/la020322b>
- [76] Y. Gao, Y. Zhao, Q. Jiao, H. Li, Microemulsion-based synthesis of porous Co-Ni ferrite nanorods and their magnetic properties, *Journal of alloys and compounds*, 555 (2013) 95-100. <https://doi.org/10.1016/j.jallcom.2012.12.057>
- [77] X. Gao, Y. Du, X. Liu, P. Xu, X. Han, Synthesis and characterization of Co-Sn substituted barium ferrite particles by a reverse microemulsion technique, *Materials Research Bulletin*, 46 (2011) 643-648. <https://doi.org/10.1016/j.materresbull.2011.02.002>
- [78] B.P. Jacob, A. Kumar, R. Pant, S. Singh, E. Mohammed, Influence of preparation method on structural and magnetic properties of nickel ferrite nanoparticles, *Bulletin of Materials Science*, 34 (2011) 1345-1350. <https://doi.org/10.1007/s12034-011-0326-7>
- [79] P. Dhiman, J. Chand, S. Verma, Sarveena, M. Singh, Ni, Fe Co-doped ZnO nanoparticles synthesized by solution combustion method, *AIP Conference Proceedings*, 1591 (2014) 1443-1445. <https://doi.org/10.1063/1.4872990>
- [80] P. Dhiman, M. Patial, A. Kumar, M. Alam, M. Naushad, G. Sharma, D.-V.N. Vo, R. Kumar, Environmental friendly and robust $\text{Mg}_{0.5-x}\text{Cu}_x\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ spinel nanoparticles for visible light driven degradation of Carbamazepine: Band shift driven by dopants, *Materials Letters*, 284 (2021) 129005. <https://doi.org/10.1016/j.matlet.2020.129005>
- [81] P. Dhiman, K.M. Batoo, R.K. Kotnala, J. Chand, M. Singh, Room temperature ferromagnetism and structural characterization of Fe,Ni co-doped ZnO nanocrystals, *Applied Surface Science*, 287 (2013) 287-292. <https://doi.org/10.1016/j.apsusc.2013.09.144>

- [82] C. Rao, J. Gopalakrishnan, E. Banks, New Directions in Solid State Chemistry: Structures, Synthesis, Properties, Reactivity and Materials Design, Physics Today, 41 (1988) 112. <https://doi.org/10.1063/1.2811679>
- [83] J. Chand, M. Singh, Electric and dielectric properties of $\text{MgGd}_{0.1}\text{Fe}_{1.9}\text{O}_4$ ferrite, Journal of alloys and compounds, 486 (2009) 376-379. <https://doi.org/10.1016/j.jallcom.2009.06.150>
- [84] N. Chaibakhsh, Z. Moradi-Shoeili, Enzyme mimetic activities of spinel substituted nanoferrites (MFe_2O_4): A review of synthesis, mechanism and potential applications, Materials Science and Engineering: C, 99 (2019) 1424-1447. <https://doi.org/10.1016/j.msec.2019.02.086>
- [85] T. Kundu, S. Mishra, Nanocrystalline spinel ferrites by solid state reaction route, Bulletin of Materials Science, 31 (2008) 507-510. <https://doi.org/10.1007/s12034-008-0079-0>
- [86] S. Bera, A. Prince, S. Velmurugan, P. Raghavan, R. Gopalan, G. Panneerselvam, S. Narasimhan, Formation of zinc ferrite by solid-state reaction and its characterization by XRD and XPS, Journal of materials science, 36 (2001) 5379-5384. <https://doi.org/10.1023/A:1012488422484>
- [87] V. Berbenni, C. Milanese, G. Bruni, A. Girella, A. Marini, Mechanochemical solid-state synthesis of cobalt (II) ferrite and determination of its heat capacity by MTDSC, Zeitschrift für Naturforschung B, 65 (2010) 1434-1438. <https://doi.org/10.1515/znB-2010-1204>
- [88] E.N. Lysenko, E.V. Nikolaev, A.P. Surzhikov, TG study of the $\text{Li}_{0.4}\text{Fe}_{2.4}\text{Zn}_{0.2}\text{O}_4$ ferrite synthesis, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2016, pp. 012092. <https://doi.org/10.1088/1757-899X/110/1/012092>
- [89] C. Sun, J.S. Lee, M. Zhang, Magnetic nanoparticles in MR imaging and drug delivery, Advanced drug delivery reviews, 60 (2008) 1252-1265. <https://doi.org/10.1016/j.addr.2008.03.018>
- [90] J. Wang, Y. Huang, A. E David, B. Chertok, L. Zhang, F. Yu, V. C Yang, Magnetic nanoparticles for MRI of brain tumors, Current pharmaceutical biotechnology, 13 (2012) 2403-2416. <https://doi.org/10.2174/138920112803341824>
- [91] A. Rana, V. Kumar, O. Thakur, R. Pant, Structural and Electrical Properties of Gd^{3+} Ion Substituted $\text{CoGd}_x\text{Fe}_{2-x}\text{O}_4$ Nano-Ferrites, Journal of nanoscience and nanotechnology, 12 (2012) 6355-6358. <https://doi.org/10.1166/jnn.2012.6418>

- [92] Y.-L. Liu, Z.-M. Liu, Y. Yang, H.-F. Yang, G.-L. Shen, R.-Q. Yu, Simple synthesis of MgFe_2O_4 nanoparticles as gas sensing materials, *Sensors and Actuators B: Chemical*, 107 (2005) 600-604. <https://doi.org/10.1016/j.snb.2004.11.026>
- [93] S. Phumying, S. Labuayai, E. Swatsitang, V. Amornkitbamrung, S. Maensiri, Nanocrystalline spinel ferrite (MFe_2O_4 , M= Ni, Co, Mn, Mg, Zn) powders prepared by a simple aloe vera plant-extracted solution hydrothermal route, *Materials Research Bulletin*, 48 (2013) 2060-2065. <https://doi.org/10.1016/j.materresbull.2013.02.042>
- [94] N. Gupta, P. Jain, R. Rana, S. Shrivastava, Current development in synthesis and characterization of nickel ferrite nanoparticle, *Materials Today: Proceedings*, 4 (2017) 342-349. <https://doi.org/10.1016/j.matpr.2017.01.031>
- [95] A. Šutka, R. Pärna, T. Käämbre, V. Kisand, Synthesis of p-type and n-type nickel ferrites and associated electrical properties, *Physica B: Condensed Matter*, 456 (2015) 232-236. <https://doi.org/10.1016/j.physb.2014.09.013>
- [96] Z. Zhu, X. Li, Q. Zhao, H. Li, Y. Shen, G. Chen, Porous “brick-like” NiFe_2O_4 nanocrystals loaded with Ag species towards effective degradation of toluene, *Chemical Engineering Journal*, 165 (2010) 64-70. <https://doi.org/10.1016/j.cej.2010.08.060>
- [97] D. Zhang, Z. Tong, G. Xu, S. Li, J. Ma, Templated fabrication of NiFe_2O_4 nanorods: characterization, magnetic and electrochemical properties, *Solid State Sciences*, 11 (2009) 113-117. <https://doi.org/10.1016/j.solidstatesciences.2008.05.001>
- [98] J. Wang, F. Ren, R. Yi, A. Yan, G. Qiu, X. Liu, Solvothermal synthesis and magnetic properties of size-controlled nickel ferrite nanoparticles, *Journal of Alloys and Compounds*, 479 (2009) 791-796. <https://doi.org/10.1016/j.jallcom.2009.01.059>
- [99] Z. Gao, F. Cui, S. Zeng, L. Guo, J. Shi, A high surface area superparamagnetic mesoporous spinel ferrite synthesized by a template-free approach and its adsorptive property, *Microporous and mesoporous materials*, 132 (2010) 188-195. <https://doi.org/10.1016/j.micromeso.2010.02.019>
- [100] M.G. Naseri, E.B. Saion, H.A. Ahangar, M. Hashim, A.H. Shaari, Simple preparation and characterization of nickel ferrite nanocrystals by a thermal treatment method, *Powder Technology*, 212 (2011) 80-88. <https://doi.org/10.1016/j.powtec.2011.04.033>
- [101] A. Baykal, N. Kasapoğlu, Y. Köseoğlu, M.S. Toprak, H. Bayrakdar, CTAB-assisted hydrothermal synthesis of NiFe_2O_4 and its magnetic characterization, *Journal*

- of Alloys and Compounds, 464 (2008) 514-518.
<https://doi.org/10.1016/j.jallcom.2007.10.041>
- [102] R. Waldron, Infrared spectra of ferrites, *Physical review*, 99 (1955) 1727.
<https://doi.org/10.1103/PhysRev.99.1727>
- [103] V. Rathod, A. Anupama, R.V. Kumar, V. Jali, B. Sahoo, Correlated vibrations of the tetrahedral and octahedral complexes and splitting of the absorption bands in FTIR spectra of Li-Zn ferrites, *Vibrational Spectroscopy*, 92 (2017) 267-272.
<https://doi.org/10.1016/j.vibspec.2017.08.008>
- [104] D. Chaudhari, D. Choudhary, K. Rewatkar, *Spinel Ferrite Nanoparticles: Synthesis, Characterization and Applications*, (2020).
- [105] Y.-j. Sun, Y.-f. Diao, H.-g. Wang, G. Chen, M. Zhang, M. Guo, Synthesis, structure and magnetic properties of spinel ferrite (Ni, Cu, Co) Fe₂O₄ from low nickel matte, *Ceramics International*, 43 (2017) 16474-16481.
<https://doi.org/10.1016/j.ceramint.2017.09.029>
- [106] K. Maaz, S. Karim, A. Mumtaz, S. Hasanain, J. Liu, J. Duan, Synthesis and magnetic characterization of nickel ferrite nanoparticles prepared by co-precipitation route, *Journal of Magnetism and Magnetic Materials*, 321 (2009) 1838-1842.
<https://doi.org/10.1016/j.jmmm.2008.11.098>
- [107] A. Abdeen, Dielectric behaviour in Ni–Zn ferrites, *Journal of magnetism and magnetic materials*, 192 (1999) 121-129. [https://doi.org/10.1016/S0304-8853\(98\)00324-2](https://doi.org/10.1016/S0304-8853(98)00324-2)
- [108] M.A. Yousuf, M.M. Baig, N.F. Al-Khalli, M.A. Khan, M.F.A. Aboud, I. Shakir, M.F. Warsi, The impact of yttrium cations (Y³⁺) on structural, spectral and dielectric properties of spinel manganese ferrite nanoparticles, *Ceramics International*, 45 (2019) 10936-10942. <https://doi.org/10.1016/j.ceramint.2019.02.174>
- [109] M. Dar, D. Varshney, Effect of d-block element Co²⁺ substitution on structural, Mössbauer and dielectric properties of spinel copper ferrites, *Journal of Magnetism and Magnetic Materials*, 436 (2017) 101-112.
<https://doi.org/10.1016/j.jmmm.2017.04.046>
- [110] M. Deepty, S. Ch, P. Ramesh, N.K. Mohan, M.S. Singh, C. Prajapat, A. Verma, D. Sastry, Evaluation of structural and dielectric properties of Mn²⁺-substituted Zn-spinel ferrite nanoparticles for gas sensor applications, *Sensors and Actuators B: Chemical*, 316 (2020) 128127. <https://doi.org/10.1016/j.snb.2020.128127>

- [111] G.F. Dionne, R.G. West, Magnetic and dielectric properties of the spinel ferrite system $\text{Ni}_{0.65}\text{Zn}_{0.35}\text{Fe}_{2-x}\text{Mn}_x\text{O}_4$, *Journal of Applied Physics*, 61 (1987) 3868-3870. <https://doi.org/10.1063/1.338623>
- [112] M. Ajmal, M.U. Islam, G.A. Ashraf, M.A. Nazir, M. Ghouri, The influence of Ga doping on structural magnetic and dielectric properties of $\text{NiCr}_{0.2}\text{Fe}_{1.8}\text{O}_4$ spinel ferrite, *Physica B: Condensed Matter*, 526 (2017) 149-154. <https://doi.org/10.1016/j.physb.2017.05.044>
- [113] R. Kambale, N. Adhate, B. Chougule, Y. Kolekar, Magnetic and dielectric properties of mixed spinel Ni–Zn ferrites synthesized by citrate–nitrate combustion method, *Journal of Alloys and Compounds*, 491 (2010) 372-377. <https://doi.org/10.1016/j.jallcom.2009.10.187>
- [114] R. Kambale, P. Shaikh, C. Bhosale, K. Rajpure, Y. Kolekar, The effect of Mn substitution on the magnetic and dielectric properties of cobalt ferrite synthesized by an autocombustion route, *Smart Materials and structures*, 18 (2009) 115028. <https://doi.org/10.1088/0964-1726/18/11/115028>
- [115] E. Pervaiz, I. Gul, High frequency AC response, DC resistivity and magnetic studies of holmium substituted Ni-ferrite: a novel electromagnetic material, *Journal of magnetism and magnetic materials*, 349 (2014) 27-34. <https://doi.org/10.1016/j.jmmm.2013.08.011>
- [116] M. Khan, S. Bisen, J. Shukla, A. Mishra, P. Sharma, Investigations on the Structural and Electrical Properties of Sm^{3+} -Doped Nickel Ferrite–Based Ceramics, *Journal of Superconductivity and Novel Magnetism*, (2020) 1-18. <https://doi.org/10.1007/s10948-020-05754-1>
- [117] F. Alahmari, M. Almessiere, B. Ünal, Y. Slimani, A. Baykal, Electrical and optical properties of $\text{Ni}_{0.5}\text{Co}_{0.5-x}\text{Cd}_x\text{Nd}_{0.02}\text{Fe}_{1.78}\text{O}_4$ ($x \leq 0.25$) spinel ferrite nanofibers, *Ceramics International*, 46 (2020) 24605-24614. <https://doi.org/10.1016/j.ceramint.2020.06.249>
- [118] K.K. Bharathi, G. Markandeyulu, C. Ramana, Structural, magnetic, electrical, and magnetoelectric properties of Sm-and Ho-substituted nickel ferrites, *The Journal of Physical Chemistry C*, 115 (2011) 554-560. <https://doi.org/10.1021/jp1060864>
- [119] L. Chauhan, A. Shukla, K. Sreenivas, Dielectric and magnetic properties of Nickel ferrite ceramics using crystalline powders derived from DL alanine fuel in sol–gel auto-combustion, *Ceramics International*, 41 (2015) 8341-8351. <https://doi.org/10.1016/j.ceramint.2015.03.014>

- [120] P. Chand, S. Vaish, P. Kumar, Structural, optical and dielectric properties of transition metal (MFe_2O_4 ; $\text{M} = \text{Co, Ni and Zn}$) nanoferrites, *Physica B: Condensed Matter*, 524 (2017) 53-63. <https://doi.org/10.1016/j.physb.2017.08.060>
- [121] R.S. Yadav, I. Kuřitka, J. Vilcakova, P. Urbánek, M. Machovsky, M. Masař, M. Holec, Structural, magnetic, optical, dielectric, electrical and modulus spectroscopic characteristics of ZnFe_2O_4 spinel ferrite nanoparticles synthesized via honey-mediated sol-gel combustion method, *Journal of Physics and Chemistry of Solids*, 110 (2017) 87-99. <https://doi.org/10.1016/j.jpcs.2017.05.029>
- [122] M.F. Warsi, A. Iftikhar, M.A. Yousuf, M.I. Sarwar, S. Yousaf, S. Haider, M.F.A. Aboud, I. Shakir, S. Zulfiqar, Erbium substituted nickel–cobalt spinel ferrite nanoparticles: Tailoring the structural, magnetic and electrical parameters, *Ceramics International*, 46 (2020) 24194-24203. <https://doi.org/10.1016/j.ceramint.2020.06.199>
- [123] S. Ikram, J. Jacob, M.I. Arshad, K. Mahmood, A. Ali, N. Sabir, N. Amin, S. Hussain, Tailoring the structural, magnetic and dielectric properties of $\text{Ni-Zn-CdFe}_2\text{O}_4$ spinel ferrites by the substitution of lanthanum ions, *Ceramics International*, 45 (2019) 3563-3569. <https://doi.org/10.1016/j.ceramint.2018.11.015>
- [124] S. Kavitha, M. Kurian, Effect of zirconium doping in the microstructure, magnetic and dielectric properties of cobalt ferrite nanoparticles, *Journal of Alloys and Compounds*, 799 (2019) 147-159. <https://doi.org/10.1016/j.jallcom.2019.05.183>
- [125] A. Nikumbh, R. Pawar, D. Nighot, G. Gugale, M. Sangale, M. Khanvilkar, A. Nagawade, Structural, electrical, magnetic and dielectric properties of rare-earth substituted cobalt ferrites nanoparticles synthesized by the co-precipitation method, *Journal of Magnetism and Magnetic Materials*, 355 (2014) 201-209. <https://doi.org/10.1016/j.jmmm.2013.11.052>
- [126] S. Mansour, M. Abdo, F. Kzar, Effect of Cr dopant on the structural, magnetic and dielectric properties of Cu-Zn nanoferrites, *Journal of Magnetism and Magnetic Materials*, 465 (2018) 176-185. <https://doi.org/10.1016/j.jmmm.2018.05.104>
- [127] N. Hamdaoui, Y. Azizian-Kalandaragh, M. Khelifi, L. Beji, Structural, magnetic and dielectric properties of $\text{Ni}_{0.6}\text{Mg}_{0.4}\text{Fe}_2\text{O}_4$ ferromagnetic ferrite prepared by sol gel method, *Ceramics International*, 45 (2019) 16458-16465. <https://doi.org/10.1016/j.ceramint.2019.05.177>
- [128] A.B. Mugutkar, S.K. Gore, U.B. Tumberphale, V.V. Jadhav, R.S. Mane, S.M. Patange, S.F. Shaikh, M. Ubaidullah, A.M. Al-Enizi, S.S. Jadhav, The role of La^{3+} substitution in modification of the magnetic and dielectric properties of the

- nanocrystalline Co-Zn ferrites, *Journal of Magnetism and Magnetic Materials*, 502 (2020) 166490. <https://doi.org/10.1016/j.jmmm.2020.166490>
- [129] A. Pandit, A. Shitre, D. Shengule, K. Jadhav, Magnetic and dielectric properties of $\text{Mg}_{1+x}\text{Mn}_x\text{Fe}_{2-2x}\text{O}_4$ ferrite system, *Journal of materials science*, 40 (2005) 423-428. <https://doi.org/10.1007/s10853-005-6099-x>
- [130] T.V. Sagar, T.S. Rao, K.C.B. Naidu, Effect of calcination temperature on optical, magnetic and dielectric properties of sol-gel synthesized $\text{Ni}_{0.2}\text{Mg}_{0.8-x}\text{Zn}_x\text{Fe}_2\text{O}_4$ ($x=0.0-0.8$), *Ceramics International*, 46 (2020) 11515-11529. <https://doi.org/10.1016/j.ceramint.2020.01.178>
- [131] N. Rezlescu, E. Rezlescu, L. Sachelarie, P. Popa, C. Doroftei, Structural and catalytic properties of mesoporous nanocrystalline mixed oxides containing magnesium, *Catalysis Communications*, 46 (2014) 51-56. <https://doi.org/10.1016/j.catcom.2013.11.021>
- [132] X. Huang, J. Zhang, S. Xiao, T. Sang, G. Chen, Unique electromagnetic properties of the zinc ferrite nanofiber, *Materials Letters*, 124 (2014) 126-128. <https://doi.org/10.1016/j.matlet.2014.03.049>
- [133] E.R. Kumar, R. Jayaprakash, G.S. Devi, P.S.P. Reddy, Synthesis of Mn substituted CuFe_2O_4 nanoparticles for liquefied petroleum gas sensor applications, *Sensors and Actuators B: Chemical*, 191 (2014) 186-191. <https://doi.org/10.1016/j.snb.2013.09.108>
- [134] Y. Liu, M. Yuan, L. Qiao, R. Guo, An efficient colorimetric biosensor for glucose based on peroxidase-like protein- Fe_3O_4 and glucose oxidase nanocomposites, *Biosensors and Bioelectronics*, 52 (2014) 391-396. <https://doi.org/10.1016/j.bios.2013.09.020>
- [135] D. Ling, N. Lee, T. Hyeon, Chemical synthesis and assembly of uniformly sized iron oxide nanoparticles for medical applications, *Accounts of chemical research*, 48 (2015) 1276-1285. <https://doi.org/10.1021/acs.accounts.5b00038>
- [136] A. Yadollahpour, S. Rashidi, Magnetic nanoparticles: a review of chemical and physical characteristics important in medical applications, *Orient J Chem*, 31 (2015) 25-30. <https://doi.org/10.13005/ojc/31.Special-Issue1.03>
- [137] A. Akbarzadeh, M. Samiei, S. Davaran, Magnetic nanoparticles: preparation, physical properties, and applications in biomedicine, *Nanoscale research letters*, 7 (2012) 1-13. <https://doi.org/10.1186/1556-276X-7-144>
- [138] D. Psimadas, G. Baldi, C. Ravagli, M.C. Franchini, E. Locatelli, C. Innocenti, C. Sangregorio, G. Loudos, Comparison of the magnetic, radiolabeling, hyperthermic and

- biodistribution properties of hybrid nanoparticles bearing CoFe_2O_4 and Fe_3O_4 metal cores, *Nanotechnology*, 25 (2013) 025101. <https://doi.org/10.1088/0957-4484/25/2/025101>
- [139] M. Colombo, S. Carregal-Romero, M.F. Casula, L. Gutiérrez, M.P. Morales, I.B. Böhm, J.T. Heverhagen, D. Prosperi, W.J. Parak, Biological applications of magnetic nanoparticles, *Chemical Society Reviews*, 41 (2012) 4306-4334. <https://doi.org/10.1039/c2cs15337h>
- [140] H. Ersoy, F.J. Rybicki, Biochemical safety profiles of gadolinium-based extracellular contrast agents and nephrogenic systemic fibrosis, *Journal of Magnetic Resonance Imaging: An Official Journal of the International Society for Magnetic Resonance in Medicine*, 26 (2007) 1190-1197. <https://doi.org/10.1002/jmri.21135>
- [141] L. Huang, L. Ao, W. Wang, D. Hu, Z. Sheng, W. Su, Multifunctional magnetic silica nanotubes for MR imaging and targeted drug delivery, *Chemical Communications*, 51 (2015) 3923-3926. <https://doi.org/10.1039/C4CC09382H>
- [142] W. Lin, Introduction: nanoparticles in medicine, *Chemical reviews*, 115 (2015) 10407-10409. <https://doi.org/10.1021/acs.chemrev.5b00534>
- [143] C.P. Slichter, *Principles of magnetic resonance*, Springer Science & Business Media, 2013.
- [144] N. Lee, T. Hyeon, Designed synthesis of uniformly sized iron oxide nanoparticles for efficient magnetic resonance imaging contrast agents, *Chemical Society Reviews*, 41 (2012) 2575-2589. <https://doi.org/10.1039/C1CS15248C>
- [145] Q. Pankhurst, N. Thanh, S. Jones, J. Dobson, Progress in applications of magnetic nanoparticles in biomedicine, *Journal of Physics D: Applied Physics*, 42 (2009) 224001. <https://doi.org/10.1088/0022-3727/42/22/224001>
- [146] C.G. Hadjipanayis, M.J. Bonder, S. Balakrishnan, X. Wang, H. Mao, G.C. Hadjipanayis, Metallic iron nanoparticles for MRI contrast enhancement and local hyperthermia, *Small*, 4 (2008) 1925-1929. <https://doi.org/10.1002/sml.200800261>
- [147] S. Maenosono, T. Suzuki, S. Saita, Superparamagnetic FePt nanoparticles as excellent MRI contrast agents, *Journal of Magnetism and Magnetic Materials*, 320 (2008) L79-L83. <https://doi.org/10.1016/j.jmmm.2008.01.026>
- [148] T.-H. Shin, Y. Choi, S. Kim, J. Cheon, Recent advances in magnetic nanoparticle-based multi-modal imaging, *Chemical Society Reviews*, 44 (2015) 4501-4516. <https://doi.org/10.1039/C4CS00345D>

- [149] J.-H. Lee, Y.-M. Huh, Y.-w. Jun, J.-w. Seo, J.-t. Jang, H.-T. Song, S. Kim, E.-J. Cho, H.-G. Yoon, J.-S. Suh, Artificially engineered magnetic nanoparticles for ultra-sensitive molecular imaging, *Nature medicine*, 13 (2007) 95-99.
<https://doi.org/10.1038/nm1467>
- [150] J. Gao, X. Chen, Z. Zhao, Octapod iron oxide nanoparticles as high performance T2 contrast agents for magnetic resonance imaging, in, *Google Patents*, 2018.
- [151] V.V. Mody, A. Cox, S. Shah, A. Singh, W. Bevins, H. Parihar, Magnetic nanoparticle drug delivery systems for targeting tumor, *Applied Nanoscience*, 4 (2014) 385-392. <https://doi.org/10.1007/s13204-013-0216-y>
- [152] J. Estelrich, E. Escribano, J. Queralt, M.A. Busquets, Iron oxide nanoparticles for magnetically-guided and magnetically-responsive drug delivery, *International journal of molecular sciences*, 16 (2015) 8070-8101. <https://doi.org/10.3390/ijms16048070>
- [153] A.K. Hauser, R.J. Wydra, N.A. Stocke, K.W. Anderson, J.Z. Hilt, Magnetic nanoparticles and nanocomposites for remote controlled therapies, *Journal of Controlled Release*, 219 (2015) 76-94. <https://doi.org/10.1016/j.jconrel.2015.09.039>
- [154] H. Guo, W. Chen, X. Sun, Y.-N. Liu, J. Li, J. Wang, Theranostic magnetoliposomes coated by carboxymethyl dextran with controlled release by low-frequency alternating magnetic field, *Carbohydrate polymers*, 118 (2015) 209-217.
<https://doi.org/10.1016/j.carbpol.2014.10.076>
- [155] D.C. Chan, D.B. Kirpotin, P.A. Bunn Jr, Synthesis and evaluation of colloidal magnetic iron oxides for the site-specific radiofrequency-induced hyperthermia of cancer, *Journal of Magnetism and Magnetic Materials*, 122 (1993) 374-378.
[https://doi.org/10.1016/0304-8853\(93\)91113-L](https://doi.org/10.1016/0304-8853(93)91113-L)
- [156] A. Jordan, P. Wust, H. Fählin, W. John, A. Hinz, R. Felix, Inductive heating of ferrimagnetic particles and magnetic fluids: physical evaluation of their potential for hyperthermia, *International journal of hyperthermia*, 9 (1993) 51-68.
<https://doi.org/10.3109/02656739309061478>
- [157] A. Jordan, R. Scholz, P. Wust, H. Fähling, R. Felix, Magnetic fluid hyperthermia (MFH): Cancer treatment with AC magnetic field induced excitation of biocompatible superparamagnetic nanoparticles, *Journal of Magnetism and Magnetic materials*, 201 (1999) 413-419. [https://doi.org/10.1016/S0304-8853\(99\)00088-8](https://doi.org/10.1016/S0304-8853(99)00088-8)
- [158] A. Jordan, R. Scholz, K. Maier-Hauff, M. Johannsen, P. Wust, J. Nadobny, H. Schirra, H. Schmidt, S. Deger, S. Loening, Presentation of a new magnetic field therapy system for the treatment of human solid tumors with magnetic fluid

- hyperthermia, *Journal of magnetism and magnetic materials*, 225 (2001) 118-126.
[https://doi.org/10.1016/S0304-8853\(00\)01239-7](https://doi.org/10.1016/S0304-8853(00)01239-7)
- [159] N. Kawai, A. Ito, Y. Nakahara, M. Futakuchi, T. Shirai, H. Honda, T. Kobayashi, K. Kohri, Anticancer effect of hyperthermia on prostate cancer mediated by magnetite cationic liposomes and immune-response induction in transplanted syngeneic rats, *The prostate*, 64 (2005) 373-381. <https://doi.org/10.1002/pros.20253>
- [160] J.t. Jang, H. Nah, J.H. Lee, S.H. Moon, M.G. Kim, J. Cheon, Critical enhancements of MRI contrast and hyperthermic effects by dopant-controlled magnetic nanoparticles, *Angewandte Chemie International Edition*, 48 (2009) 1234-1238.
<https://doi.org/10.1002/anie.200805149>
- [161] K. Maier-Hauff, R. Rothe, R. Scholz, U. Gneveckow, P. Wust, B. Thiesen, A. Feussner, A. von Deimling, N. Waldoefner, R. Felix, Intracranial thermotherapy using magnetic nanoparticles combined with external beam radiotherapy: results of a feasibility study on patients with glioblastoma multiforme, *Journal of neuro-oncology*, 81 (2007) 53-60. <https://doi.org/10.1007/s11060-006-9195-0>
- [162] P. Wust, U. Gneveckow, P. Wust, U. Gneveckow, M. Johannsen, D. Böhmer, T. Henkel, F. Kahmann, J. Sehouli, R. Felix, Magnetic nanoparticles for interstitial thermotherapy—feasibility, tolerance and achieved temperatures, *International Journal of Hyperthermia*, 22 (2006) 673-685. <https://doi.org/10.1080/02656730601106037>
- [163] B. Thiesen, A. Jordan, Clinical applications of magnetic nanoparticles for hyperthermia, *International journal of hyperthermia*, 24 (2008) 467-474.
<https://doi.org/10.1080/02656730802104757>
- [164] J.-H. Lee, J.-t. Jang, J.-s. Choi, S.H. Moon, S.-h. Noh, J.-w. Kim, J.-G. Kim, I.-S. Kim, K.I. Park, J. Cheon, Exchange-coupled magnetic nanoparticles for efficient heat induction, *Nature nanotechnology*, 6 (2011) 418-422.
<https://doi.org/10.1038/nnano.2011.95>
- [165] T. Sadhukha, T.S. Wiedmann, J. Panyam, Inhalable magnetic nanoparticles for targeted hyperthermia in lung cancer therapy, *Biomaterials*, 34 (2013) 5163-5171.
<https://doi.org/10.1016/j.biomaterials.2013.03.061>
- [166] R. Di Corato, A. Espinosa, L. Lartigue, M. Tharaud, S. Chat, T. Pellegrino, C. Ménager, F. Gazeau, C. Wilhelm, Magnetic hyperthermia efficiency in the cellular environment for different nanoparticle designs, *Biomaterials*, 35 (2014) 6400-6411.
<https://doi.org/10.1016/j.biomaterials.2014.04.036>

- [167] O. Veiseh, J.W. Gunn, M. Zhang, Design and fabrication of magnetic nanoparticles for targeted drug delivery and imaging, *Advanced drug delivery reviews*, 62 (2010) 284-304. <https://doi.org/10.1016/j.addr.2009.11.002>
- [168] D. Singh, J.M. McMillan, X.-M. Liu, H.M. Vishwasrao, A.V. Kabanov, M. Sokolsky-Papkov, H.E. Gendelman, Formulation design facilitates magnetic nanoparticle delivery to diseased cells and tissues, *Nanomedicine*, 9 (2014) 469-485. <https://doi.org/10.2217/nnm.14.4>
- [169] N. Lee, D. Yoo, D. Ling, M.H. Cho, T. Hyeon, J. Cheon, Iron oxide based nanoparticles for multimodal imaging and magnetoresponsive therapy, *Chemical reviews*, 115 (2015) 10637-10689. <https://doi.org/10.1021/acs.chemrev.5b00112>
- [170] S.J. Mattingly, M.G. O'Toole, K.T. James, G.J. Clark, M.H. Nantz, Magnetic nanoparticle-supported lipid bilayers for drug delivery, *Langmuir*, 31 (2015) 3326-3332. <https://doi.org/10.1021/la504830z>
- [171] Y. Ding, S.Z. Shen, H. Sun, K. Sun, F. Liu, Y. Qi, J. Yan, Design and construction of polymerized-chitosan coated Fe₃O₄ magnetic nanoparticles and its application for hydrophobic drug delivery, *Materials Science and Engineering: C*, 48 (2015) 487-498. <https://doi.org/10.1016/j.msec.2014.12.036>
- [172] Y. Chen, J. Nan, Y. Lu, C. Wang, F. Chu, Z. Gu, Hybrid Fe₃O₄-poly (acrylic acid) nanogels for theranostic cancer treatment, *Journal of biomedical nanotechnology*, 11 (2015) 771-779. <https://doi.org/10.1166/jbn.2015.2001>
- [173] Y. Yang, L. Yang, Q.-y. Sun, Archaeal and bacterial communities in acid mine drainage from metal-rich abandoned tailing ponds, Tongling, China, *Transactions of Nonferrous Metals Society of China*, 24 (2014) 3332-3342. [https://doi.org/10.1016/S1003-6326\(14\)63474-9](https://doi.org/10.1016/S1003-6326(14)63474-9)
- [174] B. Bahrami, M. Hojjat-Farsangi, H. Mohammadi, E. Anvari, G. Ghalamfarsa, M. Yousefi, F. Jadidi-Niaragh, Nanoparticles and targeted drug delivery in cancer therapy, *Immunology letters*, 190 (2017) 64-83. <https://doi.org/10.1016/j.imlet.2017.07.015>
- [175] J.-M. Shen, X.-M. Guan, X.-Y. Liu, J.-F. Lan, T. Cheng, H.-X. Zhang, Luminescent/magnetic hybrid nanoparticles with folate-conjugated peptide composites for tumor-targeted drug delivery, *Bioconjugate chemistry*, 23 (2012) 1010-1021. <https://doi.org/10.1021/bc300008k>
- [176] C.A. Monnier, D. Burnand, B. Rothen-Rutishauser, M. Lattuada, A. Petri-Fink, Magnetoliposomes: opportunities and challenges, *European Journal of Nanomedicine*, 6 (2014) 201-215. <https://doi.org/10.1515/ejnm-2014-0042>

- [177] G. Wang, Y. Ma, L. Zhang, J. Mu, Z. Zhang, X. Zhang, H. Che, Y. Bai, J. Hou, Facile synthesis of manganese ferrite/graphene oxide nanocomposites for controlled targeted drug delivery, *Journal of Magnetism and Magnetic Materials*, 401 (2016) 647-650. <https://doi.org/10.1016/j.jmmm.2015.10.096>
- [178] Y. Teng, P.W. Pong, One-Pot Synthesis and Surface Modification of Lauric-Acid-Capped CoFe_2O_4 Nanoparticles, *IEEE Transactions on Magnetics*, 54 (2018) 1-5. <https://doi.org/10.1109/TMAG.2018.2834524>
- [179] T. Indira, P. Lakshmi, Magnetic nanoparticles—a review, *International Journal of Pharmaceutical sciences and nanotechnology*, 3 (2010) 1035-1042. <https://doi.org/10.1016/j.jmmm.2014.01.016>
- [180] Z. Karimi, Y. Mohammadifar, H. Shokrollahi, S.K. Asl, G. Yousefi, L. Karimi, Magnetic and structural properties of nano sized Dy-doped cobalt ferrite synthesized by co-precipitation, *Journal of Magnetism and Magnetic Materials*, 361 (2014) 150-156. <https://doi.org/10.1016/j.jmmm.2014.01.016>
- [181] K.M. Krishnan, Biomedical nanomagnetism: a spin through possibilities in imaging, diagnostics, and therapy, *IEEE transactions on magnetics*, 46 (2010) 2523-2558. <https://doi.org/10.1109/TMAG.2010.2046907>
- [182] H. Dong, S.-R. Du, X.-Y. Zheng, G.-M. Lyu, L.-D. Sun, L.-D. Li, P.-Z. Zhang, C. Zhang, C.-H. Yan, Lanthanide nanoparticles: from design toward bioimaging and therapy, *Chemical reviews*, 115 (2015) 10725-10815. <https://doi.org/10.1021/acs.chemrev.5b00091>
- [183] H. Markides, M. Rotherham, A. El Haj, Biocompatibility and toxicity of magnetic nanoparticles in regenerative medicine, *Journal of Nanomaterials*, 2012 (2012). <https://doi.org/10.1155/2012/614094>
- [184] A. Koner, D. Krndija, Q. Hou, D. Sherratt, M. Howarth, *Acs Nano* 2013, 7, 1137–1144; b) AB Chinen, CM Guan, JR Ferrer, SN Barnaby, TJ Merkel, CA Mirkin, *Chem. Rev.*, 115 (2015) 10530-10574.
- [185] Z. Ma, H. Liu, Synthesis and surface modification of magnetic particles for application in biotechnology and biomedicine, *China Particuology*, 5 (2007) 1-10. <https://doi.org/10.1016/j.cpart.2006.11.001>
- [186] A.B. Salunkhe, V.M. Khot, S. Pawar, Magnetic hyperthermia with magnetic nanoparticles: a status review, *Current topics in medicinal chemistry*, 14 (2014) 572-594. <https://doi.org/10.2174/1568026614666140118203550>

- [187] J. Lagendijk, Hyperthermia treatment planning, *Physics in Medicine & Biology*, 45 (2000) R61. <https://doi.org/10.1088/0031-9155/45/5/201>
- [188] A. Jordan, R. Scholz, K. Maier-Hauff, F.K. van Landeghem, N. Waldoefner, U. Teichgraeber, J. Pinkernelle, H. Bruhn, F. Neumann, B. Thiesen, The effect of thermotherapy using magnetic nanoparticles on rat malignant glioma, *Journal of neuro-oncology*, 78 (2006) 7-14. <https://doi.org/10.1007/s11060-005-9059-z>
- [189] R. Gordon, J. Hines, D. Gordon, Intracellular hyperthermia a biophysical approach to cancer treatment via intracellular temperature and biophysical alterations, *Medical hypotheses*, 5 (1979) 83-102. [https://doi.org/10.1016/0306-9877\(79\)90063-X](https://doi.org/10.1016/0306-9877(79)90063-X)
- [190] N. Hamilton, The small-signal frequency response of ferrites, *High frequency electronics*, (2011) 36-52.
- [191] T.-J. Liang, H.-H. Nien, J.-F. Chen, Investigating the characteristics of cobalt-substituted MnZn ferrites by equivalent electrical elements, *IEEE transactions on magnetics*, 43 (2007) 3816-3820. <https://doi.org/10.1109/TMAG.2007.903383>
- [192] R. Sharma, P. Thakur, P. Sharma, V. Sharma, Ferrimagnetic Ni²⁺ doped Mg-Zn spinel ferrite nanoparticles for high density information storage, *Journal of Alloys and Compounds*, 704 (2017) 7-17. <https://doi.org/10.1016/j.jallcom.2017.02.021>
- [193] M. Pardavi-Horvath, Microwave applications of soft ferrites, *Journal of Magnetism and Magnetic Materials*, 215 (2000) 171-183. [https://doi.org/10.1016/S0304-8853\(00\)00106-2](https://doi.org/10.1016/S0304-8853(00)00106-2)
- [194] O. Mounkachi, R. Lamouri, B. Abraime, H. Ez-Zahraouy, A. El Kenz, M. Hamedoun, A. Benyoussef, Exploring the magnetic and structural properties of Nd-doped Cobalt nano-ferrite for permanent magnet applications, *Ceramics International*, 43 (2017) 14401-14404. <https://doi.org/10.1016/j.ceramint.2017.07.209>
- [195] M.T. Yagub, T.K. Sen, S. Afroze, H.M. Ang, Dye and its removal from aqueous solution by adsorption: a review, *Advances in colloid and interface science*, 209 (2014) 172-184. <https://doi.org/10.1016/j.cis.2014.04.002>
- [196] G. Sharma, A. Kumar, S. Sharma, M. Naushad, P. Dhiman, D.-V.N. Vo, F.J. Stadler, Fe₃O₄/ZnO/Si₃N₄ nanocomposite based photocatalyst for the degradation of dyes from aqueous solution, *Materials Letters*, 278 (2020) 128359. <https://doi.org/10.1016/j.matlet.2020.128359>
- [197] A. Kumar, G. Sharma, M. Naushad, A.a.H. Al-Muhtaseb, A. García-Peñas, G.T. Mola, C. Si, F.J. Stadler, Bio-inspired and biomaterials-based hybrid photocatalysts for

- environmental detoxification: A review, *Chemical Engineering Journal*, 382 (2020) 122937. <https://doi.org/10.1016/j.cej.2019.122937>
- [198] A. Kumar, S.K. Sharma, G. Sharma, C. Guo, D.-V.N. Vo, J. Iqbal, M. Naushad, F.J. Stadler, Silicate glass matrix@Cu₂O/Cu₂V₂O₇ p-n heterojunction for enhanced visible light photo-degradation of sulfamethoxazole: High charge separation and interfacial transfer, *Journal of Hazardous Materials*, 402 (2021) 123790. <https://doi.org/10.1016/j.jhazmat.2020.123790>
- [199] E. Casbeer, V.K. Sharma, X.-Z. Li, Synthesis and photocatalytic activity of ferrites under visible light: a review, *Separation and Purification Technology*, 87 (2012) 1-14. <https://doi.org/10.1016/j.seppur.2011.11.034>
- [200] P. Dhiman, A. Kumar, M. Shekh, G. Sharma, G. Rana, D.-V.N. Vo, N. AlMasoud, M. Naushad, Z.A. Allothman, Robust magnetic ZnO-Fe₂O₃ Z-scheme heterojunctions with in-built metal-redox for high performance photo-degradation of sulfamethoxazole and electrochemical dopamine detection, *Environmental Research*, 197 (2021) 111074. <https://doi.org/10.1016/j.envres.2021.111074>
- [201] A. Kumar, G. Sharma, M. Naushad, T. Ahamad, R.C. Veses, F.J. Stadler, Highly visible active Ag₂CrO₄/Ag/BiFeO₃@RGO nano-junction for photoreduction of CO₂ and photocatalytic removal of ciprofloxacin and bromate ions: The triggering effect of Ag and RGO, *Chemical Engineering Journal*, 370 (2019) 148-165. <https://doi.org/10.1016/j.cej.2019.03.196>
- [202] K. Harish, H.B. Naik, R. Viswanath, Synthesis, enhanced optical and photocatalytic study of Cd-Zn ferrites under sunlight, *Catalysis Science & Technology*, 2 (2012) 1033-1039. <https://doi.org/10.1039/c2cy00503d>
- [203] A. Di Paola, E. García-López, G. Marci, L. Palmisano, A survey of photocatalytic materials for environmental remediation, *Journal of hazardous materials*, 211 (2012) 3-29. <https://doi.org/10.1016/j.jhazmat.2011.11.050>
- [204] N.M. Mahmoodi, Zinc ferrite nanoparticle as a magnetic catalyst: synthesis and dye degradation, *Materials Research Bulletin*, 48 (2013) 4255-4260. <https://doi.org/10.1016/j.materresbull.2013.06.070>
- [205] X. Guo, H. Zhu, Q. Li, Visible-light-driven photocatalytic properties of ZnO/ZnFe₂O₄ core/shell nanocable arrays, *Applied Catalysis B: Environmental*, 160 (2014) 408-414. <https://doi.org/10.1016/j.apcatb.2014.05.047>
- [206] P. Xiong, J. Zhu, X. Wang, Cadmium sulfide-ferrite nanocomposite as a magnetically recyclable photocatalyst with enhanced visible-light-driven

photocatalytic activity and photostability, Industrial & Engineering Chemistry Research, 52 (2013) 17126-17133. <https://doi.org/10.1021/ie402437k>

- [207] P. Dhiman, N. Dhiman, A. Kumar, G. Sharma, M. Naushad, A.A. Ghfar, Solar active nano- $\text{Zn}_{1-x}\text{Mg}_x\text{Fe}_2\text{O}_4$ as a magnetically separable sustainable photocatalyst for degradation of sulfadiazine antibiotic, Journal of Molecular Liquids, 294 (2019) 111574. <https://doi.org/10.1016/j.molliq.2019.111574>