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Polymeric Ferrites: A Novel Approach for Sustainable Waste Water Treatment; A Critical Review of Current Trends, Applications, Challenges and Future Prospects

Zobia Liaqat[1*], Hamza Farooq[2], Sadaf Mushtaq[3], Yamna Zaeem Sair[4], Rabiya Bashir[5], Rida Muhammad Rasheed[6], Nazia Tanveer[7], Malik Salman Tariq[8], Aqsa Bashir[9]

[1]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan
[2]Department of Physics, Comsats University Islamabad, Lahore campus, Punjab Pakistan
[3]Department of Chemistry, Government College University Lahore, Punjab Pakistan
[4]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan
[5]Department of Botany, University of Agriculture Faisalabad, Punjab Pakistan
[6]Department of Center of Excellence of Solid State Physics, Punjab university Lahore, Punjab Pakistan
[7]Department of chemistry, Islamia University Bahawalpur, Punjab Pakistan
[8]Department of Physics, The Islamia University of Bahawalpur, Punjab Pakistan
[9]Department of Chemistry, Government College University Lahore, Punjab Pakistan

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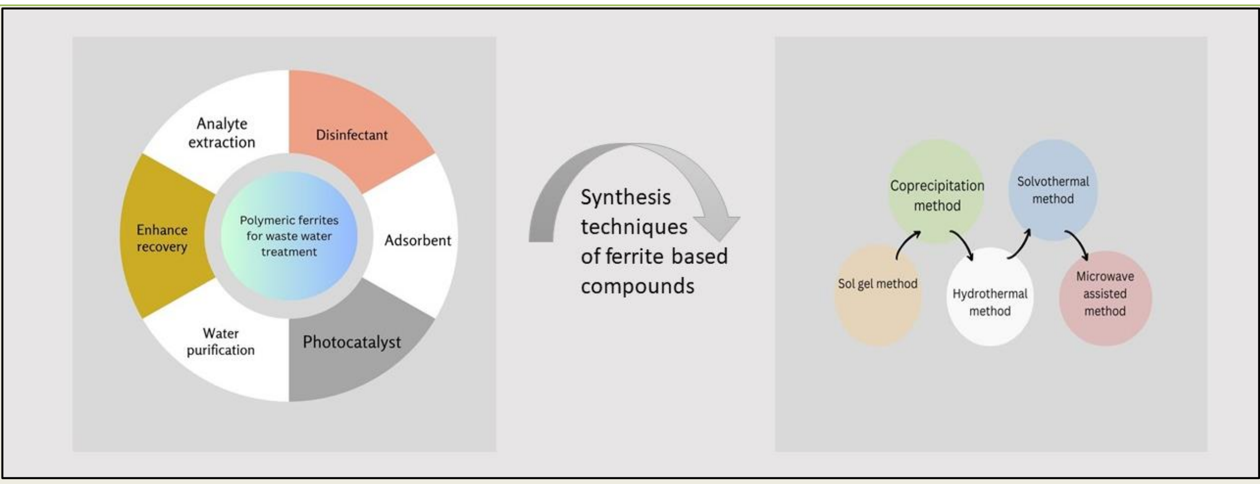
***Corresponding author:** Zobia Liaqat
Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan

Abstract

Review Article



Graphical Abstract

Ferrite polymer composites are progressively taking the place of traditional ceramic magnetic materials due to their superiority and lower cost. They are utilized to treat hard water, have incredible stability, can be recycled efficiently, and may be used multiple times without losing their qualities. Additionally, they might make good materials for sensors, microwave absorbers, and other aeronautical uses. The creation of ferrite polymer nano-composite and their uses are the primary topics of this review. A brief discussion of the various types of ferrite nanoparticles, their synthesis processes, properties, and applications has also been provided. Due to the vast size of the area, every effort has been made to integrate the original sources that provide greater detail about each specific application. Ferrites are typically known for their porosity in its physical and chemical absorbance qualities, all of which are readily adjusted by selecting the suitable synthesis pathways and parameter such as the morphology pH of a solution temperature during sintering, amount of doping and co-doping particles, or composites of nanoparticles. The research on ferrites' evolution as a gas sensing component over the last 20 years is compiled in this publication.

Keywords: Polymeric ferrites, Pollutants, Nanocomposites, Photodegradation, Nanoparticles.

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1. INTRODUCTION

Water supplies are extremely vulnerable to pollution. The stability of the natural environment, aquatic ecosystems, community health, and the social and economic well-being of society are all greatly impacted by contaminated water. For example, it has been reported that over 30,000 people globally die each day from a combination of poor sanitation and insufficient water sources, both in terms of quantity and quality (Abdel Maksoud *et al.*, 2022). Water contamination induced by increased industrialization and overpopulation constitutes one of the most serious environmental issues confronting the entire world. Numerous polymeric ferrite materials synthesized are used to eliminate the synthetic chemically reactive dye from wastewater (Mustafa *et al.*, 2025).

To accomplish clean wastewater treatment, oily wastewater treatment now aims to minimize the application of chemicals while simultaneously pursuing operational simplicity and floor space reduction (Gao *et al.*, 2018; Wang *et al.*, 2020). Nanostructured spinel ferrites are particularly intriguing in this context, as they differ from the bulk materials in two significant aspects with respect to their chemical and physical characteristics. A significant portion of a nanomaterial's atoms live on its surface, which causes a change in its properties. The single factor is associated with the effect on the surface. The second component is the outcome of quantum confinement claims that if electrons are spatially confined, it affects their electronic energy levels (Huang *et al.*, 2014). The spinel ferrite single cell consists of 32 oxygen atoms combined in a cubic tight packing, eight of which are oriented in a tetrahedral orientation. Sixteen atoms are combining octahedral (B) sites and (A) sites. The magnetic behavior of ferrites is known by the difference in the cations' magnetization moments among B and A intervening sites, that is, via oxygen atoms, linked to the super-exchange connections.

The primary cause of the ferrimagnetism of this material is the most prevalent kind, JAB. Among many ferrites, nanoscale $MnFe_2O_4$, Co Fe_2O_4, Zn Fe_2O_4, Cu Fe_2O_4, and Mg Fe_2O_4 have garnered the most interest because of their exceptional thermal, chemical, and structural resilience (El-Masry *et al.*, 2023). Among these, spinel ferrite nanoparticles (SFNPs) have received particular attention. This is mostly because of their excellent magnetic capabilities, straightforward chemical makeup, and numerous uses in a variety of contexts, such as wastewater and water therapeutic, biological, catalytic, and electrical apparatus. The standard chemical formula of spinel ferrites is AB_2O_4, wherein Fe(III) is one of the main structural components and A and B are metallic cations that are uniformly distributed into two unique crystallographic sites, either tetrahedral (A sites) or octahedral (B sites). Tetrahedral as well as octahedral coordinated with oxygen atoms, respectively, are the cations of both orientations. Within the formula MFe_2O_4, there are three different spinel ferrite structures known: normal, inverse, and mixed. These structures depend on the location of the M(II) and Fe(III) sites of preference. M(II) and Fe(III) are positioned at tetrahedral and octahedral positions, respectively, in the typical spinel structure of ferrite. Fe(III) has equal distribution at both sites in the opposite spinel framework of ferrite, whereas M(II) only occupies octahedral sites (El-Masry *et al.*, 2023).

The tetrahedral and octahedral positions in the combined spinel arrangement of ferrite are occupied at random by both ions. Normal spinel ferrite is represented by Zn Fe_2O_4, inverse spinel ferrite is often represented by Fe_3O_4 and Fe_2O_4 and mixed spinel ferrite is typically represented by Mn Fe_2O_4. In particular, water supplies are extremely vulnerable to pollution. The sustainability in the natural environment, aquatic ecosystems, community health, and the social and economic well-being of society are all greatly impacted by contaminated water. For instance, it has been stated that around 30,000 people worldwide pass away every day as a result of insufficient water resources both in, quantity and quality, combined with inadequate sanitation. Eighty percent of these occurrences take place in rural regions, with newborns accounting for the largest share (Ochieng *et al.*, 2010). The need for safe and clean water is currently growing quickly on a global scale but the widely used purification techniques are insufficient to supply the necessary volume of water of the highest grade. It is therefore necessary to search for innovative and affordable methods of purifying water.

Using nanoparticles specifically offers a lot of potential to improve water filtration. However, some nanoparticles (NPs) are poisonous, and if the right attention isn't given to them, they might develop into a new class of pollutants that are dangerous to the environment and public health (Brame *et al.*, 2011). However, resonance absorption is low and only occurs in a small frequency range because ferrites with weaker magnetic permeabilities are found in the higher GHz range. Alternatively, ferrites can be engineered to display elevated dielectric losses over a wide frequency range by carefully choosing their composition and implementing the appropriate heat treatment. It is anticipated that electrons hopping among Fe^{+3} and Fe^{+2} ions will increase the dielectric losses. In the current work, we produced ferrite into polyurethane (PU) substrate at various ratios to create ferrite-polymer composites. We next investigated the X-band (8.2-12.4 GHz) complicated permeability and permeability. In addition, the reflection loss within the combined samples was computed at different X-band frequencies or sampling densities using an electrical simulation that used a representation of a single-layer plane wave absorbent that included a perfect conductor. A slight peak in experiments using Nano-crystalline nickel ferrite, either field-cooled (FC) or zero field-cooled (ZFC) magnetization, was seen in the block temperature (TB = 16 K). At the spin-glass temperature of about 40 K,a difference between ZFC and FC plots was also observed (Kale *et al.*, 2004). High field irreversibility was used to characterize the ZFCFC plot separation, which was linked to a disordered glass state that had multiple spin configurations.

Interparticle interactions are stated to affect the surface spin orientations; these interactions rely on the arrangement of the particles, the surface structure, and the type of interactions (exchange, dipole–dipole, or dipole–dipole) (Zysler *et al.*, 2003). This work investigated the magnetic properties of a nano-crystalline form of nickel ferrites in a diluted (<10 weight percent) distribution of a non-magnetic polymer using two distinct approaches: dispersion in Nano-crystalline during in situ polymerization, frictional grinding to produce nano-crystalline nickel ferrites, and polyethylene, nickel ferrites were present in polystyrene. This research work used two different methods to examine the magnetic characteristics of nano-crystalline nickel ferrites within a dilute (<10 weight percent) arrangement of non-magnetic polymer dispersion inside Nano-crystalline. During in situ polymerization, the grinding of the Nano-crystalline nickel ferrites, and polyethylene, nickel ferrites were present in Polystyrene. The results of diluted dispersion of a Nano-crystalline form of nickel ferrites within the matrix of polymers are contrasted with powdered fragments of Nano-crystalline ferrites in order to further clarify the impact of surface or magnetic characteristics of nano-crystalline ferrites. The work based on the idea that, in a dilute dispersion, the magnetic behavior is going to be characteristic of independent mono-domain particles, and the dipole–dipole interaction will be very weak. To make sure that the goal of surface impact is not restricted to just one system or a single procedure, two distinct matrices and methods were chosen. Because of their superior magnetic characteristics, ferrites are better at suppressing electromagnetic interference (EMI) than their dielectric equivalents.

Ferrite materials have a variety of magnetic and electrical characteristics, including complicated permeability and complex permittivity. Permittivity is crucial for figuring out their high-frequency properties. The primary challenge in the development of polymeric/ferrite composites is managing the complicated permeability and permissiveness of these materials' frequency dispersion. By adjusting the composite filler type, inclusion size, concentration, and mixture shape through inclusion particle alignment, this issue can be resolved. Moreover, efforts have been undertaken to manipulate the magnetic characteristics using microstructure composites. Because of their possible applications in the areas of electromagnetic absorption materials, self-regulating heaters, antistatic materials, and preventing the accumulation of static electricity, ferrites and the conducting polymer composites are becoming increasingly significant in this field (Elimat, 2006; Elimat *et al.*, 2008). Nanoparticles, nanorods, nanowires, and nanotubes are all part of the nanofiller. Even when their chemical makeup is the same, the physical characteristics of nanoparticles in the 1-100 nm range differ from the characteristics of non-nanoscale particles.

The crucial question is whether the nanoparticles have distinctive qualities that influence either exposure or danger that, in essence, differ from those with larger particles of a comparable composition. Thus, the question remains unrestricted. Nanotechnology encompasses both completely new approaches based on molecular self-assembly and traditional device mechanics(Farokhzad and Langer, 2009). It gives researchers the chance to create new materials with nanoscale dimensions and to better regulate atomic-scale issues. The convergence of scientific advancements, such as the development of scanning tunneling microscopy (STM) in 1981 with the discovery of fullerenes in 1985, contributed to the advent of nanotechnology in the 1980s. Drexler then modified Taniguchi's 1974 coined term "nanotechnology" in his work (Engines of Creation, 1986). We have recently concentrated mostly on inorganic metals and metal oxide-based particles because of their significance for commercial advancement and the worry about their potential hazards or toxicological effects (Chen *et al.*, 2014).

2. CLASSIFICATION OF FERRITES

Iron (III) oxides (Fe_2O_3, rust) is combined in small amounts with a few additional metallic elements to create ferrites, which are ceramic materials. The general formula for ferrite is typically M–(Fe_xO_y), where M denotes a divalent ion of minerals such as Ba, Co, Ni (Birajdar *et al.*, 2012). Ferrites are a popular **choice due to** their enhanced saturation magnetism, raised resistivity (0.1–105 Ω-m), and adjustable contrast range, making them a great choice in a variety of applications. The magnetic moments associated with single electrons produce the magnetic characteristics of ferrite materials, while the number of single electrons surrounding the nucleus determines the magnetic behavior due to their spin around the nucleus and around itself. An atom's electron provides a magnetic moment. The magnetic coercivity of ferrites allows for the division of these particles into two categories.

2.1 SPINEL FERRITE

The general equation Q–(Fe_2O_4), where Q represents the divalent ions that are part of minerals such as zinc, nickel, cobalt, manganese, and iron, usually provides this information is used to estimate the tetrahedral or octahedral interstitial locations, respectively. Because spinel alloys are useful in the microwaves domain and have large magnetic losses and low conductivity (particularly for semiconductors), they can be used as MAMs. Unfortunately, the low frequency of resonance of spinel ferrites limits their applicability in microwave absorption (Pubby *et al.*, 2020; Tekle Abegaz, 2021).

2.2 Garnet ferrite

Usually, this is provided by a general formula Re3 Fe_2O_{12} that alludes to a trivalent ion, such as gadolinium neoymium. This type of ferrite that have a structure similar to that of spinel ferrite, but with few more places. With its substantial Ms and low Hc content, garnet is a softer ferrite with excellent chemical stability for EMI repression (Akhtar *et al.*, 2018).

2.3. Hexagonal ferrite

This type of ferrite is more resonant in the upper GHz range due to its flat contrast and enhanced crystalline magnetic contrast field. Its applicability in a variety of applications is increased by its hexagonal ferrite characteristic. This ferrite forms a hexagonal crystal shape. Apart from spinel ferrites, these ferrites' strong essential magnetic variance allows the trait to function throughout the gigahertz range due to their magnetic structure (Kumar *et al.*, 2019). Almost six types of hexagonal ferrites.

2.4 M-Kind

The usual classification for M-kind ferrites is Q- ($Fe_{12}O_{19}$), where Q denotes mineral ions, namely lead, barium, and strontium. These ferrites are good microwave materials because to their large magnetic crystal properties, affordability, high temperature Curier (TC), or unique MS qualities.

2.5 Y-Kind

The formula T2Q2-($Fe_{11}O_{22}$) represents Y-kind ferrites. Here, T denotes mineral ions like lead, barium, and strontium, and Q denotes ions like copper, zinc, cobalt, etc. These ferrites are composed of ferromagnetic materials. In order to achieve the best microwave absorption, adding mineral ions to these hexa-ferrites will therefore dominate their magnetic characteristics (Song *et al.*, 2016).

2.6 W-kind

W-kind ferrites made with the formula T_2Q_2-($Fe_{16}O_{27}$) These ferrites are associated with the M-kind. The ferrites in characteristics depended on the crystal body's cation content and arrangement as well as the form of the particles (Farhadizadeh *et al.*, 2016; Gordani *et al.*, 2016).

2.7 X-Kind

X-kind ferrites can be made using this formula T_2Q_2-($Fe_{28}O_{46}$) (Sadiq *et al.*, 2020). One way to Imagine hexaferrites of the X type are a mixture of M or W-kind hexagonal ferrites. These ferrites function as the best MAMs because they have larger Tc and Ms than M and W-kind hexaferrites.

2.8 Z-Kind

Ferrites of the Z-kind are represented by the formula T_3Q_2-($Fe_{14}O_{41}$). When These ferrites have larger resonance frequency and total permeability compared to spinel ferrites. Ferrites of this kind are only used in microwave systems as a result, which include inductors, antennas, and permanent magnetic applications (Guo *et al.*, 2018)

2.9 U-Kind

It is possible to obtain U-kind hexaferrites using a combination of T_4Q_2- ($Fe_{36}O_{60}$). These ferrites have higher MS and more thermal stability among the hexaferrites (Kumar *et al.*, 2019). Because of this, this type of ferritin has been used extensively in studies pertaining to electromagnetic interference.

3. Ferrite Polymer Nanocomposite

Ferrite-doped polymer nanocomposite synthesis has garnered significant attention in fundamental studies and engineering applications lately. Since the discovery of inherent conductivity in organic polymers, there have been significant advancements in the field of hybrid variety materials, such as ferrite dispersed polymer nanocomposite, which combine the ferrites with the beneficial qualities and advantageous magnetic properties of ICPs, such as high conductivity, higher dielectric strength, light weight, etc., in a single material. The synthetic pathways that have been established to generate these polymer composites consist of either adsorption onto the particle or polymerization on the particle surface. Prior to 1994, Hofman-Caris thoroughly examined the methods utilized to create particles with an inorganic core, such as ferrites, or a polymer shell using chemical coupling and polymerization processes (Ormrod *et al.*, 1965).

Particles having solid cores covered in a polymeric shell have been created using a variety of polymerization-based techniques. These include the adsorption of monomers onto the particles, which is followed by polymerization (Chen *et al.*, 2003), hetero-coagulation polymerization (Shimano and MacDiarmid, 2001) and emulsion polymerization (Genies *et al.*, 1990).

The polymerization reaction is able to be aided either by particles with colloidal structure that help themselves or through an initiator to proceed the process in the first method, which is one of the most commonly used to produce coatings of polymers on solid particles. The coating of silica particles modified by aluminum hydrous oxide by Matijevic *et al*., layers of poly (divinylbenzene) (PDVB) were reported. This was accomplished by adding divenylbenzene and a radical initiator after prior to treating inorganic cores with coupling agents such as 4-venylpyridine or 1-venyl-2-pyrrolidone (Chen *et al.*, 2003). Using a similar method, the polymer shells of PVBC and PDVB, copolymers of PVBC and PDVB, and polymer layers of PVBC were also produced around inorganic particles (Cao *et al.*, 1989). Electrophoresis measurements showed significant alterations in the surface properties of silica cores. By using catalytically active core to cause the polymerization of monomers adsorption on the particle surface, the need for soluble or electrochemical creators can be avoided.

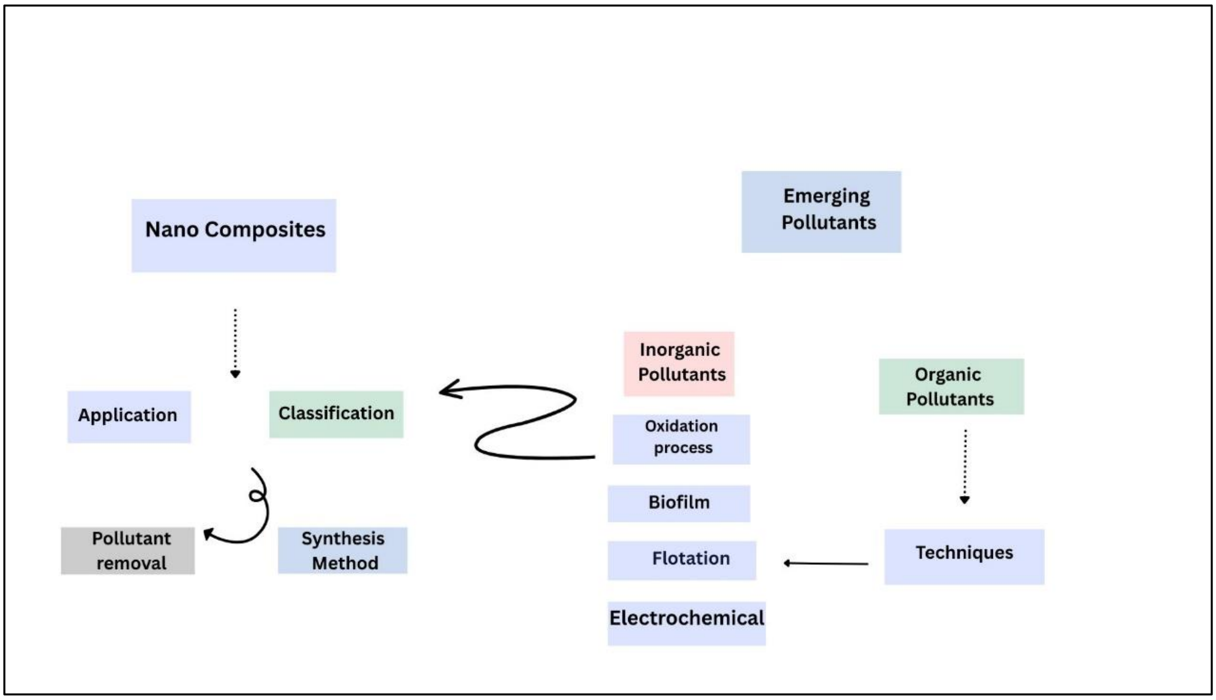


Fig 3.1 Techniques to synthesize polymeric ferrite composites

By utilizing the active sites on metal oxide surfaces like hematite (Fe_2O_3), silica-modified hematite, or cerium (iv) oxide (CeO_2) to start the polymerization of pyrrole, this method was used to create poly (pyrrole) coats on a variety of inorganic cores (Chiang and MacDiarmid, 1986). The polymer layer thickness in both scenarios depends on the kind of cores utilized and whether any additional polymers are present. The thickness of the coating of polymers can be adjusted by changing the length of time the cores are in contact with the polymerization solution. Hetero-coagulation of small and bigger particles, followed by heating, is an alternative method for creating core-shell particles, which are composed of a solid core enclosed in a polymer layer. For instance, negatively charged polystyrene nanoparticles (600 nm in diameter) are hetero-coagulated onto cationic polymeric (butyl methacrylate) (PBMA) particles, which had a diameter of 167 nm. A non-ionic polymeric layer was grafted onto the surface of the PBMA particles, stabilizing the ensuing cluster.

The sample spread after being heated to a temperature that was about 45 degrees Celsius over the PBMA glass transition temperature, and the non-ionic polymer moved to the surface to function as a steric stabilizer layer. The final particles were composed of a PBMA with a polystyrene core that was comparatively evenly covered. Although this is an intriguing technique, there are challenges in achieving the appropriate covering of tiny particles, obtaining uneven coatings may also jeopardize colloidal stability. Emulsion polymerization is a frequently employed alternative method for producing core-shell particles (Ormrod *et al.*, 1965). Polymer films have been utilized in this manner to encapsulate inorganic and organic particles of sizes between sub-micrometers and micrometers (Cao *et al.*, 1989). By adjusting the concentration of monomers, the coating thickness in the range of 2–10 nm can be easily regulated. It was discovered that On the other hand, the polymer-encapsulated cores may be routinely centrifuged and distributed to the uncoated particles.

4. Morphology of ferrites

In general, the structure of spinel either 32 octahedral (Oh) or 64 tetrahedral (Td) domains arranged in a cubic crystal structure. Ferrite becomes electrically charged when divalent (M^{2+}) ions occupied 8 Td sites and trivalent (Fe^{3+}) ions takes up 16 Oh sites neutral (Tatarchuk *et al.*, 2017). Around A-site, there are four oxygen atoms, while around B-site, there are six nearest oxygen atoms. The ferrite structure might be normal, inverted, or mixed, depending on the site occupancy. Ferrite is referred to be normal spinel when trivalent ions occupied Oh sites and divalent ions occupied Td sites (e.g. Zn Fe_2O_4) Ferrite is considered to be opposite if all of the trivalent compounds are divalent and half of the cations of a trivalent element (such as Fe_3O_4) occupy Td sites and other half for the compounds are trivalent and occupy Oh sites. An arbitrary occupation of sites by cations results in mixed ferrite. Lattice energy, crystal fields impact, cationic charge, cation parameters, and electrostatic charge are factors that influence the amount of space of the cation in the lattice (Potakova *et al.*, 1972; Rath *et al.*, 2002).

5.Synthesis methods

It has been shown that there is a notable influence of the applied synthesized process on the crystallinity, size of particles, and area of surface of materials. Therefore, a variety of factors, including crystal chemistry, phase a state of making high photocatalytic material active requires consideration of equilibrium kinetics of reactions, or calcination temperature. The two types of synthesis approaches that these methods fall into are "bottom-up" and "top-down."

Microwave assistance, hydrothermal, solvothermal, sol-gel, co-precipitation, and heating methods are among the former; other, less prevalent procedures are associated with "top-down" synthesis processes. However, while each of these preparation techniques has advantages and disadvantages of its own, there is no known, standardized way for synthesizing highly active ferrite nanoparticles. In the subsections that follow, the most popular techniques for synthesizing ferrite will be covered in depth.

5.1 Sol-gel/citrate method

The well-known sol-gel method of colloidal chemistry has the potential to create a variety of materials with novel, predetermined features in an easy-to-follow procedure at a fair price. It cannot be categorized as a single method because there are many different ways to do it: (a) Molecular precursors that have been dissolved are transformed into Activated molecular precursor are poly-condensed into tiny clusters in a reactive state; this results in the production of a colloidal liquid or sol; subsequent steps include gel formation, aging, washing, drying, and stabilization. Sol-gel numerous factors, including as catalysts, as well temperature, solvents that are additives, and solutions pH, can affect the chemistry of gels. This method was combining the metal using iron salts, mostly nitrate, and agitating the mixture with a magnetic tool. Then, in order to make a sol (in this instance of the sol-gel/citrate approach), the solution of the precursor was mixed with citric acid, which serves as a complexities agent, and left to combine at room temperature. The mixture including citric acid or precursors underwent hydrolysis or condensation polymerization processes at low temperatures to generate the gel.

An oxide (ferrite) byproduct is produced when the gel is heated to a temperature ranging from 450 and 800°C, dried, and then calcined the proper pace (Rao *et al.*, 2017). This work shows how changing the calcination temperature and the ratio of the agent that interacts with the metal ion can have an impact on the properties of the end-product cobalt ferrite nanoparticles. In a similar vein (Zahi *et al.*, 2006) synthesized Ni 0.3 Zn 0.1 Fe_2O_4 composition efficiently at low temperatures by applying a basicsol-gel technique.

5.2 Co-precipitation method

Co-precipitation is another widely used process for producing ferrites with consistent nanoparticle size (Mostafa *et al.*, 2012). Co-precipitation processes happen when agglomeration, coarsening, growth, and nucleation all happen simultaneously. Nucleation is an important step that produces a large number of minuscule particles. The shape, morphology, and other features of the products are significantly impacted by secondary processes such aggregation and Ostwald ripening, which causes a large particle to grow at the expense of a small one. Lastly, the super-saturation levels required for precipitation to occur.

This procedure involved stirring and gently heating the water-based solutions of Fe (III) or the metal salts in a basic media. Using an ammonium as well as sodium hydroxide solution, the pH should be adjusted to between 7 and 10 in in order to create the nanoparticle of ferrite. After collecting the precipitate using centrifugation or filtering, it is repeatedly washed in ethanol or Using DI water, dry at 80–100 °C. The nanoparticles can be calcined at different temperatures after drying. This synthesis process has several advantages over other ones, such as large-scale product synthesis, low temperature or controlled morphology and excellent consistency in the final product (Amiri and Shokrollahi, 2013) used the chemical co-precipitation approach to Co0.9RE0.1Fe2O4 nanoparticles containing three different rare-earth ions are produced. The best magnetic output of the Gd–Co ferrite makes it perfect for treating hyperthermia. In an additional study (Vinosha *et al.*, 2016) produced Co-precipitation of cobalt ferrite (Co Fe_2O_4) nanomaterials method to determine their optical and magnetic characteristics.

5.3 Hydrothermal route

One of the most effective and safest methods for producing ferrites nanoparticles on a large scale without harming the environment is the hydrothermal approach (Coppola *et al.*, 2016). This method uses an aqueous solution under high pressure and temperature to crystallize a substance. Another method known as the solvothermal method uses hydrothermal synthesis as a solvent instead of water. This container produces extremely high pressure when heated, and the process known as a hydrothermal reaction takes place at such high pressure. The following ideas are often used to define hydrothermal processes: Reactants in the forms of suspensions, gels, and/or solutions are precursors. Mineralizers: high-concentration inorganic or organic additions used to control a solution's pH additionally Additives are relatively modest amounts of organic or inorganic chemicals used to aid in particle dispersion or crystal morphology.

The hydrothermal method of material synthesis involves direct crystallization from solutions, often in two stages: the creation of crystals and their subsequent development. Controlling processing variables including temperature, pH, concentrations of reactants, and surfactants can result in the production of final products with suitable particle sizes and morphologies Soluble salts utilized in the hydrothermal synthesis process are often iron salts and salts of other metals, which are typically employed in nitrate, sulfate, and chloride forms. Separately dissolved salts are combined with water or a different solvent while being stirred, then the pH is modified to a range of 7 to 10. After that, the solution is cooked for between 12 and 24 hours at high pressure in an autoclave, and it then naturally cools to room temperature. The solution is then cooked for 12 hours at high pressure in an autoclave, and then it cools naturally to ambient temperature (Peng *et al.*, 2012) examined the hydrogen generation activity of magnetic Ni Fe_2O_4 nanoparticles produced by a combined hydrodynamic and calcination technique with and without CTAB. When compared with Ni Fe_2O_4 without CTAB, the generated CTAB-Ni Fe_2O_4 with reduced particle size and a substantial specific surface area demonstrated higher activity (Wu *et al.*, 2018)

5.4 Solid-state reaction

Solid-state reaction also referred to as the traditional mixed oxide process, are the most widely used and straightforward way for creating nanoparticles. This process iinvolves combining powdered metal salts or iron in stoichiometric quantities, then grinding the mixture well to create a homogenous slurry. Solid-state reactions, also referred to as the traditional mixed oxide process, are the most widely used and straightforward way for creating nanoparticles. This process involves combining stoichiometric proportions of metal salts or iron powder, and then thoroughly grinding the combination to get a uniform slurry. The powdered powder is annealed for a longer period of time at an extremely high temperature in a furnace. Ideally, oxides ought to be thoroughly combined with crucible alumina and heated to elevated temperatures.

Despite the fact that this strategy has a number of advantages, including an easy synthesis process and well-formed nanoparticles, it nevertheless has certain drawbacks, such as a short surface area, a big particle size and an extensive particle size dispersion, and an extra undesired phase. Furthermore, wet milling that is, Wet or alcoholic grinding is preferable to dry milling, which has a negative impact on particle size (Kulkarni and Mathad, 2018)

5.5 Other methods

The literature has reported on a variety of regularly used techniques for the manufacture of ferrites nanoparticles. Through the combustion pathway (Angadi *et al.*, 2016) demonstrated the significant impact of the Nano-scale Sm3+ Gd3+ co-doping Wet or alcoholic grinding is preferable to dry milling, because this approach is straightforward, inexpensive, and produces a homogenous fine product, the authors suggested utilizing it to synthesize Mn–Zn ferrites. Several options for producing porous materials that could be helpful for catalyst support or thermal insulation are provided by spray pyrolysis. In this particular situation (Kotsikau *et al.*, 2015) created single-phase ferrite Zn0.5Mn0.5 Fe_2O_4 by low-temperature spray pyrolysis using metal nitrate precursors, determining the structural and magnetic characteristics of the resulting spinel form Mn–Zn. The structural analyses show that Mn or Zn atoms having equal distribution over the ferrite lattice, while the magnetic tests showed that the formation of unique iron oxide layer ferrite doesn't take place.

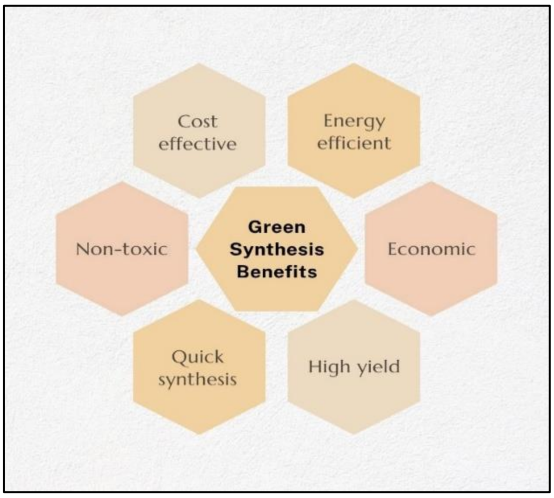


Fig 5.5.1 Advantages of green synthesis of polymeric ferrite composites

Given that there is a substantial correlation between the ferromagnetic characteristics of ferrites and their chemical makeup, (Cortés *et al.*, 2015) using an electro-spinning method to create $CoFe_2O_4$, Co1-x(Cu, Ni, and Zn)x Fe_2O_4, and Co1-x Gdx $Fe_2O_4+\delta$ nanostructures using methods for electro-spinning PVP and metal nitrates were employed as polymeric carriers and precursors, respectively. Their research revealed a considerable correlation between the applied thermal temperature and the replacement ions and the magnetic characteristics of the magnetic fibers.

It is well known that the self-propagating combustion at high temperatures (SHS) process can be used to manufacture refractory materials. For instance (Cross *et al.*, 1999) employed this method to convert the precursors of several spinal ferrites, such as MFe_2O_4 and Rhombohedral $BaFe_2O_4$, into oxides or peroxides. Paradoxically, the composition and magnetic characteristics of spinel ferrites may be affected by the usage of a magnet outside throughout SHS production. The ratio of Cu Fe_2O_4's tetragonal to cubic phase rose as the applied field was increased, according to the results. Owing to its superior heat conductivity, manganese-doped ferrite (MnxFe1x) Fe_2O_4 was composited using magnetic nanoparticle Graphene oxide via a straightforward micro emulsion/solvent evaporation method, as described by (Peng *et al.*, 2014). The produced Nano-composites' content-dependent magnetic Hyper-thermic response was examined, and the results showed that when the concentration of the Nano-composite dropped by a factor of three, the Nano-composite's field-dependent specific absorption rate increased twice. Because of their use as molecular imaging contrast agents, functionalized manganese nanoparticles made of ferrite were created by (Leal *et al.*, 2015) using a facile liquid exchange method.

6. Electrical Conductivity of Ferrites

Even though hexagonal ferrites make excellent electrical resistors, when a bivalent ferro (Fe^{2+}) ion is coupled to a ferrous (Fe^{3+}) ion, even though the resistance is still quite high, when there are trace amounts. This is because electrons can exchange places relatively easily, or "hop," which results in a current (Acharya and Choudhary, 2015). Magnetite is a great electrical conductivity for oxides because of this. The two possible N-type electron conduction and p-type hole conductivity are the two conduction methods. When a cation in materials with high resistance is swapped out with one that aims to reduce the valency level. This is known as p-type conduction; n-type conduction happens when the ation tries to reach a higher valency. Ferrites exhibit n-type conduction when there is an excess of iron present (or a low oxygen content from high-temperature sintering), and extremely poor p-type conductivity when there is a deficit of iron.

Therefore, if the material to be used in every electrical applications, a high level of iron should be avoided. The quantity of Fe^{2+} within ferrite is unfortunately increased by the extremely high sintered temperatures required to produce a dense product; however, the resistance can be significantly reduced by adding manganese and cobalt, even within little amounts (as little as 0.02%) (Pullar, 2014). Additionally, in polymorphic ceramic ferrites, highly resistant grain boundaries separate low resistance grains, resulting in an interfacial polarization that can contribute to conductivity; with bigger grained ferrites, this will be lessened. It has been suggested that the reaction of Fe^{2+} + Co^{3+} Fe^{3+} + Co^{2+} will decrease the propensity of Fe^{2+} + Fe^{3+} in cobalt-containing ferrites, as well as that other stability multivalent electrons like Mn will have an analogous impact. Due to its ability to form a localized stable pair with Fe^{2+} and Mn^{3+} is hypothesized to increase resistivity more than Co^{3+} because it keeps electrons from exiting the Fe^{2+} in favour of other ferric ions (Parker *et al.*, 1966). Because of their electrical applications, W ferrites' conduction mechanisms have been studied more than most. According to recent modeling, Fe^2W is more conducting due to the fact that it consist of blended valence-type ions (Fe^{3+} and Fe^{2+}) in 6 grams locations at the interface among two S layers, creating an electrical conducting layer.

Additionally anisotropic, this conduction has a significantly higher resistance perpendicular to the conductive layer along the c-axis (Kalyane and Pathan, 2021). For RT AC as well as DC conductivity values have been measured to be 3106 X1 cm1 and 5106 X1 cm1 , respectively, at low frequencies (1 kHz), and they increase with increasing frequency or temperature (El Ata *et al.*, 1999). One can boost conductivity by multiple orders of magnitude by substituting Ni^{2+} or Cu^{2+} for Co. BaM's RT conductivity is comparatively high at 2104 X1, but this can be reducedgreatly as (Co^{2+} /Ti4+) is substituted for Fe^{3+}, decreasing by five orders of magnitude to 7 109 X1 cm1 for BaCo 0.5 Ti 0.5 $Fe_{11}O_{19}$ (Ravinder *et al.*, 2004). The efficiency of charge transfer and separation has been evaluated on both doped and undoped photo-catalysts using electrochemical impendence spectroscopy (EIS). The doped sample's EIS spectra show a smaller arc radius, which is indicative of a higher charge transfer effectiveness, as demonstrated by the Nyquist plots of the two samples. This demonstrates the fact that Ag-doped copper nanoparticles made of ferrite have a reduced barrier to charge transfer, indicating that they may facilitate charger transfer at the interface (Kamble *et al.*, 2015). Additionally, it was confirmed that electrochemical impedance spectroscopy could be used to investigate the charge immigration at the interface. A smaller arc radius, as the Nyquist plot of the charge indicates immigration at the interface. A lower arc radius, as the Nyquist diagram illustrates, indicated a lower rate of charge recombination and a greater degree of charge carrier separation (Dixit *et al.*, 2012).

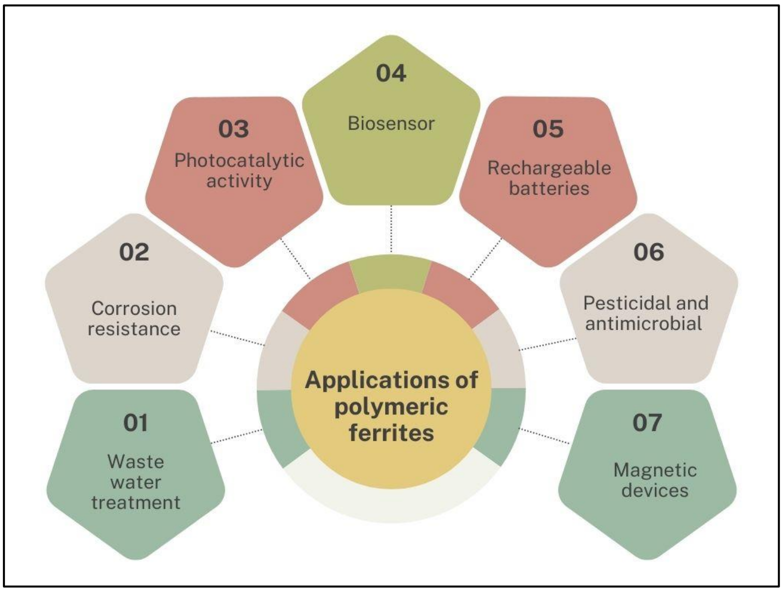
7. Applications of Polymeric ferrites Nanocomposites

New, exciting and tunable physical properties shown by nano-materials are due to their size and microstructures and make them exotic materials in a number of important technologies e.g. Electronic and Photonic Devices (Caruso, 2000). Size effects cause magnetic nanoparticles to exhibit unique behaviors (Kodama, 1999). Ferrite nanoparticles have been claimed to have several new potential uses, particularly in the fields of health and information storage.

Applications in biomedicine include cellular imaging, targeted drug administration, MRI, and hyperthermia (Sun *et al.*, 2008; Gao *et al.*, 2009). However, in order to administer medications, drug-containing particles are injected into the body. For the aim of medication distribution, it is therefore essential to understand the biological suitability of the parts and potential coating materials (Lu *et al.*, 2007).

So, conclusively we can say that preparation of ferrites nanoparticles with desirable dimension and biocompatibility is an essential area of research in the field of nanotechnology. Due to special microstructures of nanomaterials, the materials are becoming of increasing importance for applications such as
(a) Catalysis
(b) Selective Membranes (Gas Liquid)
(c) Ion Selective Surface
(d) Hydrogen Storage, etc.

Further, interesting mechanical features of metallic nanomaterials have led to their use as high strength materials and biological activity in some nanostructural organic nano-composites for some diverse applications such as bioanalysis, molecular electronic devices, biocatalysis, molecular recognition and energy transduction. More specifically, the therapy of cancer using hyperthermia (HT) is one of the exciting potential uses for ferrite nanocomposites. To do this, the temperature must be raised to about 42 and 46 °C in order to kill the malignant cells. The tissue undergoes coagulative necrosis when heated to temperatures higher than 56 °C. The goal of enhanced therapy and thermometry systems in therapeutic hyperthermia is to optimize the tumor tissue's temperature uniformity between 42 and 46 degrees Celsius. Ferro-fluids containing ferrimagnetic and super-paramagnetic Fe_3O_4 or Fe_3O_4 particles have been widely used for applications related to hyperthermia. Nonetheless, the most promising options for successful treatment possess sufficient biocompatibility and Curie temperatures (Tc) between 42 and 60 °C for magnetic materials.This allows them to function as an in vivo temperature control switch during therapy, preventing overheating (Junior *et al.*, 2007).



7.1 Applications of Polymeric ferrites nanocomposites in various fields

Polymer-based nanocomposites have recently emerged as a new type of material with applications in versatile electronic equipment and modern energy storage systems. Polymer-based nanoarchitectures are particularly useful for energy storage applications because of their features such as strong mechanical properties, non-corrosive nature, lightweight, cost-effectiveness, flexibility, thermal and electrical insulation (Hussain *et al.*, 2020). Similarly ferrite-based composite materials are widely recognised for their interesting magnetic properties, diverse redox chemistry, high stability, and strong catalytic characteristics, all of which make them valuable for a growing number of applications related to energy (Abdulwahab *et al.*, 2024).

The benefits of ferrites synthesis methods include a lack of selectivity with organic and inorganic compounds, a quick breakdown rate, mineralization, a wide range of applications, a lack of mass transfer limitations, a short reaction time, simple equipment and mild operating conditions .On top of that, hydrogen peroxide is completely safe to use, doesn't do any long-term harm to the environment, and breaks down quickly into oxygen and water. As an analogy, iron is cheap, harmless, and less toxic to the environment (Chen *et al.*, 2011; Takkar *et al.*, 2022). Co-precipitation, thermal breakdown , micelle manufacturing, and hydrothermal synthesis have all contributed significantly to the size and morphology control of magnetic nanoparticles. A major difficulty remains corrosion prevention, hence appropriate protection measures will be emphasised, such as surfactant/polymer coating, silica coating, and carbon coated with magnetic nanoparticles or incorporating them in a support. Properly shielded magnetic nanoparticles can be utilised as building blocks for the creation of diverse functional systems, with applications in catalysis and biotechnology (Lu *et al.*, 2007).

PVC/ Fe_3O_4 nanocomposites made through electrospinning are used for electromagnetic radiation protection and high-frequency electronics (Chiscan *et al.*, 2012). An innovative $SnFe_2O_4$/polypyrrole composite photo-Fenton catalysts were created and characterised by various techniques.The effect of varying ferrite and polymer proportions in the composite on tartrazine dye degradation efficiency was examined as a function of pH and H_2O_2 dose. The 10 wt% $SnFe_2O_4$ composite materials shown strong activity, discolouring entirely the tartrazine coloured solution in 60 min using the photo-Fenton technique. Furthermore, the composite has a high physicochemical stability and may be recycled eight times. In general, because the composite exhibited inherent properties, substantial catalytic activity, ease of preparation, and excellent reuse, its supporting catalyst demonstrated the potential to be an extremely efficient and ecologically conscious catalyst to assist in the treatment of organic pollutant containing wastewater (Leichtweis *et al.*, 2021).

Polymer nanocomposites (PNC) have not only exceptional properties, but they can also be engineered to have a combination of qualities for multifunctional applications. Electromagnetic interference shielding protects electronic devices from disturbances and prevents irreversible damage to the gadgets. Traditionally, this can be accomplished by absorbing it through a metal screen. Because metals are prone to deterioration, low environmental resistance, dense structure, and polymer nanocomposites including magnetic nanofillers present a radical alternative. Ferrite particles are extremely relevant materials, and their characteristics improve when the size is reduced to less than 30 nm. The superparamagnetic property of ferrite particles and nanocomposites of polymer is thus primarily determined by particle size and distribution within the polymer matrix (Sambhudevan, 2021).

A new glassy carbon electrode (GCE) developed with chitosan-coated manganese nanoparticles composed of ferrite (MnFe2O4@CTS) was used for the electrochemical measurement of bifenox, a nitrodiphenylether herbicide. The core-shell nanoparticles were manufactured through ionic gelation. Initially the synthesised material was examined in the electroanalysis of environmental contaminants. The unique modified $MnFe_2O_4$@CTS/GCE offered a considerable increase in peak currents when bifenox was present. Bifenox concentrations were electrochemically determined in stream and tap water samples. The recovery values ranged from 82 to 97%. The innovative analytical platform shown promising features for bifenox environmental investigation (de Matos Morawski *et al.*, 2021).

This study focusses on the synthesis and evaluation of different kinds of nanocomposites. These composites are composed of ferrite core and polypyrrole polymer. To generate ferrite filler, the co-precipitation approach was used, while polypyrrole was obtained using the renowned in-situ polymerization process. The incorporation of Nd0.04 Fe_2O_4 ferrites into the polypyrrole matrix of polymer resulted in nanocomposites. The structural and magnetic characteristics of the manufactured samples were investigated. The manufactured composites' ferromagnetic behavior was observed using a hysteresis loop. When the amount of ferrite filler in the matrix was raised, the magnetic properties was changed. The high dielectric constant results indicate that these samples could be appropriate for microwave electronics (Qindeel *et al.*, 2020).

Nano-ferrites constitute as one of the most well studied sensing materials for detecting and quantifying the evolution of harmful gases from industry, automobile exhaust, and biological waste. It can be used to monitor and regulate environmental pollutants. According to the literature on ferrite with single metallic ion dopant, doping with a single ion, specifically Mg or Zn, which falls under the category of soft ferrites, significantly improves sensitivity, selectivity, and decreases the operating temperature. The doping of rare earth elements exhibits similar behavior (Ranga *et al.*, 2021). Despite all of the improvements, photo catalysts still have several drawbacks, therefore further development is required. Pollutant photo degradation can be simply accomplished using an LED lamp or natural sunshine. The decomposition of two organic colored compounds was carried out simultaneously in order to examine their photocatalytic characteristics under real-world conditions. However, because their spectra overlapped, it was impossible to observe the process and measure species concentrations using UV-Vis spectrophotometry. To tackle this difficulty, a novel and rapid method, known as EXRSM, was employed. The CCD-RSM was also utilized to optimize, predict, and further analyses the impact of key factor interactions on the deterioration process. Researchers investigated the recycling capabilities of Ag@PCMSQ@Co Fe_2O_4, finding that the photocatalytic effectiveness of the retrieved catalyst was lowered by less than 10% after five cycles for each dye. Simultaneous degradation in a binary mixture of dyes was carried out to evaluate the photocatalytic activity of the synthesized compound (Musabeygi *et al.*, 2022).

This work presents comprehensive results of the fabrication (i.e., production and characterization using standard methodologies) of self-standing, portable, extensible polymer-cobalt ferrite (Co Fe_2O_4) hybrid thin films. This distinct field sensing property shows that the discovered material has potential use in multifunctional equipment, specifically as field sensor (Behera *et al.*, 2022). In recent years, researchers have examined a wide range of nanomaterials for a variety of applications. Magnetic nanoparticles (MNPs) are among the materials under study. Magnetic nanoparticles are widely used in biomedical applications, both in vivo and in vitro. They perform better in diagnosis, particularly as MIR, since MNPs are utilized as contrast agents. Furthermore, they are often employed in drug delivery. When these nanoparticles are functionalized with polymer compounds, they may collaborate with biologically active molecules that recognize and act on specific targets (Bustamante-Torres *et al.*, 2022)

Water challenges have a global impact on societies and industries. Organic dyes, which are used in the textile, plastic, paper, nutrition, and printing industries, are a major source of water contamination. Dye is harmful to the welfare of humans as well as animals and penetrates into the food chain via water bodies. Researchers investigated the environmental application of polymeric ferrite composites as well as the usage of adsorbents to remove dyes. This research emphasizes on the production of polymeric ferrite composites Ni-$CoFe_2O_4$/Chitosan, Co-$NiZnFe_2O_4$/Polyaniline, Zn-$NiFe_2O_4$/Starch, and Cr doped $ZnCoFe_2O_4$/PVA for removing of Golden Yellow-160 dye (Mustafa *et al.*, 2024). Ferrite nanoparticles offer a wide range of applications in treating wastewater, and there is an increasing interest in using these particles specifically for waste treatment. However, the knowledge of how ferrite qualities that can be controlled by synthesis processes affect wastewater treatment effectiveness requires further explanation. For an extended period, ferrite nanoparticles were thought to be adsorbents capable of physically removing pollutants, however current research indicates that these nanostructures may be capable of UV visible light-induced photocatalytic degradation of contaminants (Sukovienė *et al.*, 2025).

8. Recovery and reuse

One of the essential elements that makes the method appealing and economical is the regaining and repurposing of spinal ferrite nanoparticles after they have been utilized as an adsorbent. The recovery and reprocessing of silver nanoparticles (SFNPs) in hardwater purification methods is possible. Due to its simplicity, selectivity, and speed, the external magnetic field method of SFNP separation is preferable to the often-employed filtration and centrifugation procedure (Vader, 2015). As stated earlier, this approach is suitable for wastewater treatment because spinel ferrites may be regenerated and reused after being employed in wastewater treatment, and they retain their degrading efficiency. Both the operational cost and the environmental effect are decreased as a result of this. Because it is quick, easy, and selective, the separation of catalysts by means of an external magnetic field outperforms the conventional methods of filtration and centrifugation. After each reaction, the catalysts were cleaned using alcohols or bases, low-centration acids, or distilled water (Venturini, 2019).

The catalysts were then dried in an oven at 80 to 100°C and used for another oxidation cycle, according to this literature review. Nanoparticles may prove to be an effective way to eliminate contaminants from water, but it's yet unclear how they will directly affect people's health. It is difficult to efficiently extract these nanoparticles from liquid media due to their minuscule size. On the other hand, magnetic separation is an efficient method for obtaining SF-based magnetic nanoparticles from the liquid medium (Vestal and Zhang, 2003).

9. Challenges and future prospects

Dyes are widely employed in a variety of sectors and are introduced into the aquatic environment via wastewater. Their chemical composition is relatively robust and impermeable to natural breakdown. As a result, they might stay in the surroundings for an extended period of time. As a result, the treatment of wastewater is becoming an increasingly significant subject in chemistry and engineering sciences, with numerous studies lately conducted in this area. As a result of these studies, a variety of approaches and tactics have been proposed to address this issue, including oxidation, adsorption, biological therapy, electrodialysis, and floating precipitation. However, the emphasis has been on advanced oxidative processes (AOPs) and absorption. In absorption techniques, absorbent materials are capable of eliminating contaminants through a variety of chemical relationships between their active regions and pollutants. In simple terms, they can only be concentrated in adsorbents rather than being degraded, resulting in secondary contamination. AOPs, including Fenton, photo-Fenton, ozone formation, and photo-catalysis, can degrade the chemical constituents of pollutants through reactive oxygen compounds (Patial *et al.*, 2021). As a result, advanced oxidation processes (AOPs) are extremely effective due to their capacity to degrade pollutants. When they are used, no traces of contaminants remain in the environment. However, AOPs have major flaws. For example, the majority of the methods described require a UV source or unique devices and facilities, which raises the process cost. The short half-life of ozone makes it difficult to employ. Photo catalysis is possibly the most promising of these techniques since solar power is accessible as an everlasting, abundant, and free resource, so harnessing sunlight is more affordable than other sources of energy (Sharma *et al.*, 2019).

Developing biodegradable materials and polymer composites from renewable resources with superior material properties is a crucial task for the polymer industry. The adverse ecological effect of unused polymers is a growing global concern.

Innovative strategies are needed to create biodegradable polymers and composites. Bio-nanocomposites are a biodegradable alternative to conventional materials. Although nanofillers with polymer composites play a vital role, they also have significant downsides. Although magnetic nanoparticles, such as ferrites and mixed iron oxides, have numerous applications, they also have certain drawbacks. Due to poor thermal characteristics, limited magnetization, and poor dispersibility, this material falls behind other high-performing smart materials. Incorporating magnetic nanoparticles into polymeric matrix is hard due to their agglomerative nature. Future efforts should focus on improving the dispersibility and stability of nanofillers. Polymer inorganic nanocomposites are increasingly being used for electromagnetic wave absorption and shielding due to their magnetic properties. Polymer-inorganic nanocomposites can serve as a dynamic component in optical and magneto-optic applications. Important considerations for PINC include dispersibility, nanofiller size range, thermal stability, and composite performance under various conditions. Therefore, when working on PINC, it's important to consider these considerations. Few studies have focused on conducting polymer-based magnetic nanocomposites. Future research will focus on the magneto-electric characteristics of composites and the development of novel superconducting materials using conducting polymers. Magnetic nanoparticles and composites continue to pose obstacles for development. To progress, we must address these issues and make necessary changes (Bajpai *et al.*, 2014).

The future possibilities of green spinel ferrite-based nanomaterials are promising, particularly in terms of medical applications. In this era, the unique properties have allowed the development of green routed spinel ferrites-based nanomaterials converting into a nano framework for specific drug delivery and hyperthermia-based treatment of cancer, with future prospects emphasizing on improving biocompatibility, and reducing toxicity (Ali *et al.*, 2024). To completely remove hazardous contaminants and ferrites from water and wastewater following treatment, appropriate quality control must be implemented before applying FNPs. Quality control offers two main benefits: first, it can collect and reuse FNPs after they are used, which reduces their relatively expensive cost; second, it can lessen any potential negative health effects on the ultimate consumer of the treated water. Furthermore, proficiency is needed to ensure that every process is well controlled (Yadav *et al.*, 2020). Effective adsorbents are important because water shortages are getting worse and water treatment is required. Now, treated water is being treated with magnetic nanoparticles and their composites that have been specifically engineered for size, content, magnetic properties, and structure. Although spinel ferrites such as MFe_2O_4 (M = Mn, Cu, Co, Ni, Zn, Mg, Ca, etc.) are increasingly being employed, Fe_3O_4 has historically been used for hard water purification techniques (Yasar, 2024).

Regardless of the pollutant that is intended to be eliminated, the increased concentration of pollutants in the wastewater must always be accounted for when assessing the photocatalytic materials' ability to degrade. This is so that the pollutant can occupy its intended function and cover the photocatalyst's active surface. Pre-determining the pollutant concentration and optimizing the catalyst dosage must therefore be taken into account; in fact, the literature hardly ever mentions these experiments (Zohrabi, 2024).

CONCLUSION

According to the above description, magnetic nanoparticles (Fe3O4) are superior fillers for a variety of polymer matrices, and the electrical conductivity, magnetic attraction, optical, endurance to fatigue, thermal stability, sensing ability, and mechanical characteristics of the hybrid composites they create are noticeably improved. Initially, further research is required to create a cost-effective technique for producing large-scale magnetic ferrites using materials based on magnetic ferrite. For instance, the conventional techniques for synthesizing meso-porous ferrites are labor-intensive and need costly materials like polymer templates. This argument is significant because the synthesis process greatly influences other factors that affect the overall photocatalysis process, including surface area, size of particles, and crystallinity. However, the sol-gel method was demonstrated to be less successful in the decolorizing iron oxide and nickel ferrite oxide nanoparticles and removing metal ions than the co-precipitation method. Secondly, as ferrite stability will be the primary obstacle to the development of photocatalysts, future research should concentrate on it. The mechanical and chemical resistant properties of ferrite-based materials is a topic that has received less attention.

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