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Nanomaterials and Ferrite Nanoparticles: A Comprehensive Review

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Abstract

Nanomaterials have emerged as a revolutionary class of materials with unique properties and extensive applications across various fields. This review article provides a comprehensive overview of nanomaterials, covering their fundamental properties, classification, and diverse applications. Special emphasis is placed on ferrite nanoparticles, highlighting their types and multifaceted applications in fields such as medicine, electronics, environmental remediation, and energy. The article also delves into the future scope of ferrite nanoparticles, exploring potential advancements and innovations. By examining the current state of research and technological developments, this review aims to elucidate the significance of nanomaterials, particularly ferrite nanoparticles, and their promising role in shaping future scientific and industrial landscapes.

Keywords: Nanomaterials; ferrite nanoparticles; doping; composite; biomedical applications.

1. Introduction to Nanomaterials

Overview of Nanomaterials: Materials that have been reduced in size to between 1 and 100 nm (nm = 10-9 meters) are called nanomaterials [1]. In physics, a "nano" is one in a billion, although its Greek (or Latin) etymology is "nanos," which means "dwarf." The spectrum of nanomaterials in relation to human hair, etc., is shown in Figure 1.

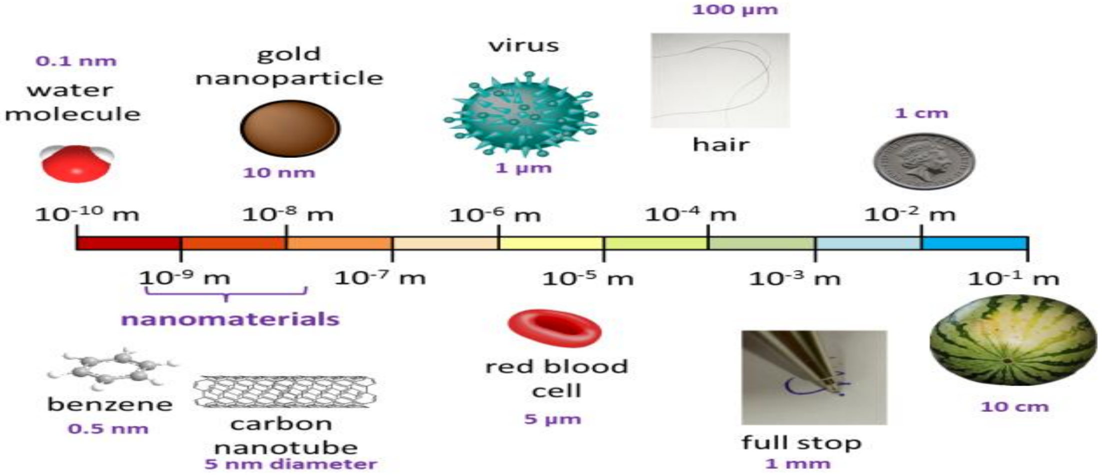

Fig.1: The nanomaterials scale [1]

The size of nanomaterials Nanotechnology, the study of nanoparticles and their applications, is a rapidly growing field. At this particle size, the properties of materials can vary greatly. Materials with larger particle sizes have unique characteristics, including reactivity, solubility, and electrical and magnetic transport across membranes. The utilization of nanoscale materials has grown and is currently gaining popularity over the last fifteen years or more. There are many applications for this approach in consumer goods, information technology, energy, water, performance materials, and health.

1.1. Properties of Nanomaterials

The remarkable physical, chemical, optical, thermal, electrical, structural, and mechanical features of nanomaterials increase their catalytic activity. In short,

a) Physical properties

Nanomaterials can be categorized into four groups based on their size and dimension: zero dimensional materials, which include clusters and particles; one dimensional materials, which include nanotubes and nanowires; two dimensional

materials, which include nanoplates and layers; and three dimensional materials, which include bundles of nanowires and nanotubes along with multinanolayers [7]. They can have spherical, tubular, ellipsoidal, or irregular shapes and can exist in solitary, fused, aggregated, or agglomerated forms. Materials classified as zero-dimensional (0D) nanomaterials have all three dimensions (x, y, and z) measured inside the nanoscale range of 1–100 nm. Spherical nanoparticles are the most widely used illustration of 0D nanomaterials [8]. Nonetheless, this class also includes nanoscale polygonal and cubic structures. They may be polycrystalline, single-crystalline, or amorphous. This class includes uniform materials with nanodimensions, including molecules, grains, rings, clusters, fullerenes, particles, and particles.
Common examples of this class are metallic nanoparticles, which include hollow spheres, nanolenses, core-shell quantum dots, heterogeneous and uniform particle arrays, and silver and gold nanoparticles [9]. They can also have different forms and shapes and be made of ceramic or polymeric materials. One-dimensional (1D) nanomaterials are needle-shaped because they have a longer length (>100 nm) in the third direction than they do in the other two, where they are nanometer-sized. The most popular examples of 1D nanomaterials include carbon nanotubes (CNT), metals or metal oxides nanowires, polymer nanowires or nanofibers, and hybrid materials [10]. Because of their excellent mechanical, electrical, and optical capabilities, as well as their intrinsic high aspect ratio structural feature, one-dimensional nanomaterials offer special beneficial properties. Two-dimensional (2D) nanomaterials are atomically thin sheets of a material that have two dimensions: one that is at the nanoscale and the other two that are not. Common examples of 2D nanomaterials with plate-like structures are Nanofilms, nanolayers, and nanocoatings. The most recent member of this class is graphene, which is a single carbon layer with a graphite honeycomb structure [11]. Properties of nanomaterials II. Nanotechnology: Materials that are not limited to the nanoscale in any dimension are known as three-dimensional (3D) nanomaterials. Above 100 nm, they have three arbitrary dimensions. On the other hand, three-dimensional nanomaterials possess features at the nanoscale or a nanocrystalline structure. Bulk nanomaterials can consist of many configurations of nanosize crystals oriented differently, based on their nanocrystalline structure. In terms of nanoscale characteristics, 3D nanomaterials can include multinanolayers, dispersions of nanoparticles, and bundles of nanowires and nanotubes. Figure 2 provides a good illustration of all these nanomaterials in four different sizes and forms. Surface effects: The fraction of surface atoms per unit volume is high in nanomaterials. The sharp rise in the surface to inner atom ratio in nanomaterials is what causes significant

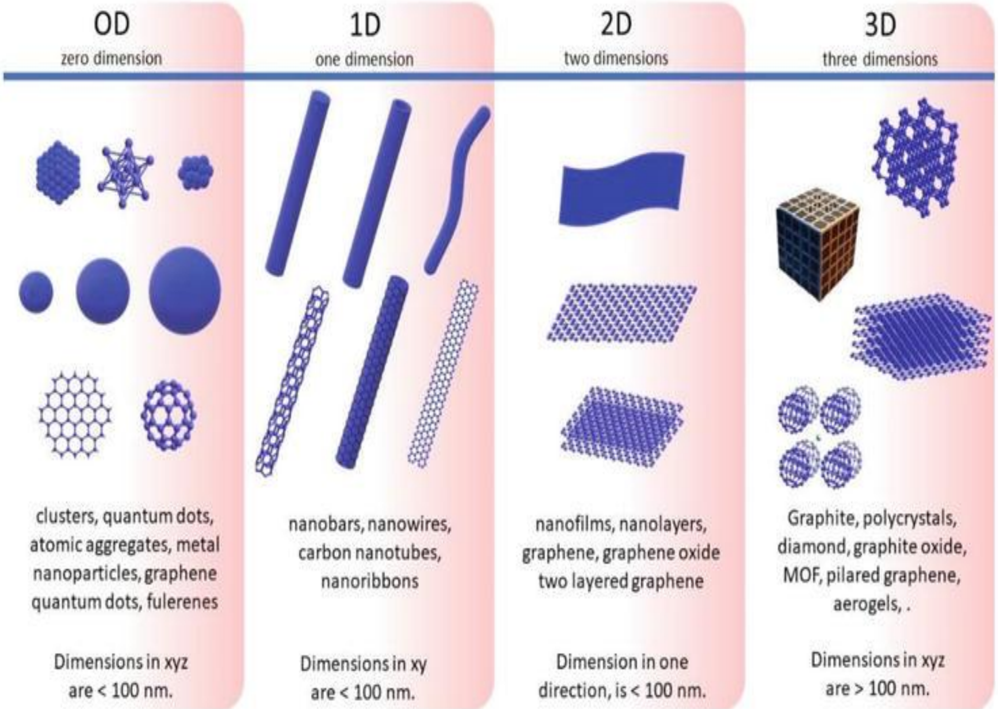

Fig.2: The classification of nanomaterials with suitable example [66]

b. Chemical properties

Chemical structure and composition of nanomaterials: Multilayers and/or multiphases comprising several components make up the surface and interior structures of nanomaterials, each of which is essential to achieving the intended functionalities. Atoms can organize themselves in lattice structures in a variety of ways, leading to distinct crystal forms for some materials with the same amounts of contained elements, depending on external factors like temperature or pressure. Therefore, one nanomaterial can have many crystal structures with various physiochemical properties, such as reactivity or photocatalytic activity, depending on the environmental conditions. The unit cell of a crystal lattice is typically used to describe the spatial arrangement of its atoms. The smallest volume that exhibits the complete symmetry of the crystal is called a unit cell. Certain materials might have several unit cells with various structural configurations. For instance, diverse crystal structures of nanomaterials, such as carbon, silicon dioxide, or iron oxide, are shown in Figure 2. Diamonds and graphite, a stack of several graphene layers, are two forms of carbon. A number of carbon nanostructures, including graphene, fullerene, and CNTs, have garnered significant interest due to their notable chemical, mechanical, and electrical characteristics. The valence of carbon atoms is the only factor that makes these many forms of carbon feasible. Different allotropes are created when carbon atoms make covalent connections with one another [26]. Allotropes typically have the same chemical makeup but very different physical characteristics. Different allotropes are created when carbon atoms join forces with one another to form covalent bonds and are arranged differently. Fig. displays the various diameters of distinct carbon structure types. 2. Since fullerenes were initially identified in the mid-1980s, carbon nanostructures have been the subject of extensive interest and investigation [28]. Before then, covalently linked networks made of diamond and graphite were the only two known allotropic forms of solid carbon [29]. Fullerenes, which are molecules made up of 60 carbon atoms (C60), are based on an icosahedral symmetry closed cage structure with 20 hexagonal and 12 pentagonal rings. Every carbon atom in this structure is bound to three other atoms.

Two bond lengths are present in the C60 molecule, such as the 6:6 ring bonds, which are shorter than the 6:5 bonds and can be thought of as "double bonds." These sphere-shaped molecules attach themselves to one another in the solid state to create a face-centered cubic crystal lattice. Weak Vander Waals forces hold the C60 molecules together in the lattice, where each molecule is separated from its nearest neighbor by 1 nm (the distance between their centers is 1 nm). Due to its propensity to avoid double bonds in the pentagonal rings, which leads to poor electron delocalization, C60 is not considered to be "super aromatic." Because of this, C60 interacts with electron-rich species more easily and functions as an electron-deficient alkene. Subsequently, researchers discovered that graphite sheets (sp2 carbon) could be rolled into tiny, concentric cylindrical tubes, which they called, respectively, single-walled and multi-walled carbon nanotubes [30, 31]. The diameter and length of the CNTs are typically measured in tenths to tens of nanometers and centimeters, respectively. Normally, CNT ends are covered in a structure resembling a fullerene. CNTs can have many distinct structures, including chiral, zigzag, and arm chair architectures. Each of these configurations has unique characteristics.

c. Magnetic properties

Nanomaterials exhibit a wide range of peculiar magnetic behavior when compared to bulk materials because to surface or interface phenomena, such as charge transfer, symmetry breaking, electronic environments, and magnetic interaction. Additionally, compared to bulk materials, the constituent atoms of nanostructures have a distinct magnetic interaction with surrounding atoms because to the increased surface-area to-volume ratio [39]. The magnetic domain structure of ferromagnetic materials is also the foundation of fine particle magnetism. Larger ferromagnetic particles with several domains exhibit non-uniform magnetism, whereas single-domain particles, smaller than critical size, exhibit uniform magnetism [42]. The degree of the magnetic saturation, the strength of the crystal anisotropy and exchange forces, the surface or domain-wall energy, and the particle shape are some of the variables that influence the critical size of the single domain. The two primary characteristics of ferromagnetic materials' reactivity to an applied field are coercivity and remanence.

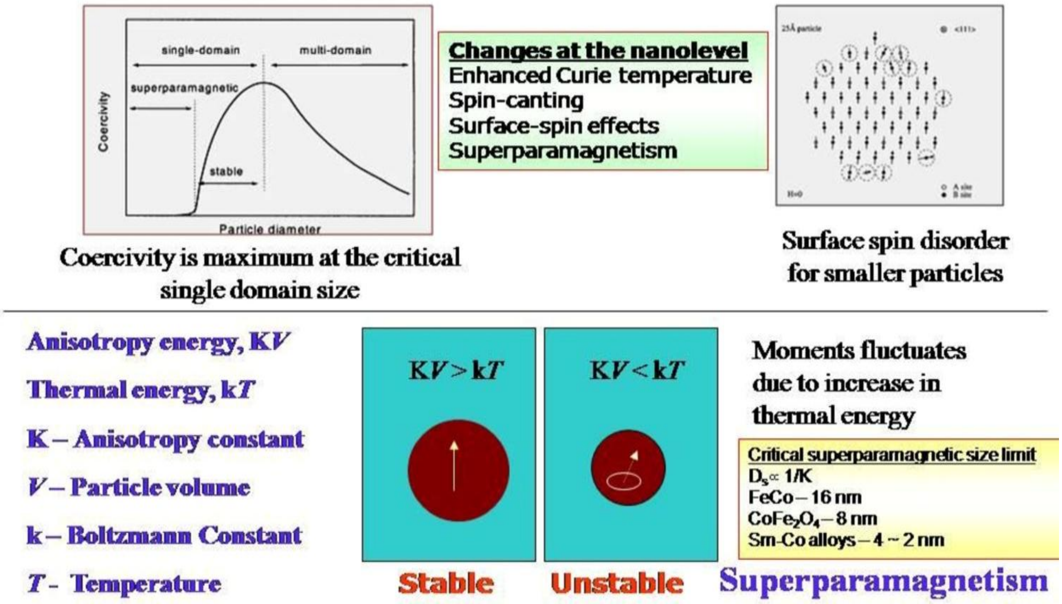

Fig.3: shows Coercivity, Surface spin, Anisotropy energy KV, Thermal energy kT, Superparamagnetism

Among these, the particle size has a notable effect on the coercivity of magnetic materials. The coercivity rises to a maximum at the single domain size as the particle size is lowered. Due to thermal factors, it subsequently falls for extremely small particles and eventually zeros at the superparamagnetic particle size (Fig. 3). As a result, even though the bulk materials that correspond to the nanoparticles are not magnetic, the nanomaterials may become superparamagnetic. For instance, despite the ferromagnetic nature of bulk iron oxide (Fe3O4), Fe3O4 nanoparticles exhibited superparamagnetic-like behavior. This effect is caused by the Fe3O4 nanoparticles' exceptional surface energy and their spin electrons' flipped orientation [38]. When placed in a zero magnetic field, superparamagnetic nanoparticles are not magnetic; yet, when an external magnetic field is introduced, they rapidly become magnetized. The nanoparticles can rapidly return to a nonmagnetized condition when an external magnet is removed when they are below the superparamagnetic diameter.

d. Optical properties

Since the electronic structure of the nanomaterials is heavily dependent on surface atoms, the optical properties of the materials—such as reflection, transmission, absorption, and light emission—are entirely dependent on their electronic structure, which varies significantly for different morphologies. The size-dependent optical characteristics of nanomaterials are largely influenced by two factors: surface plasmon resonance and increased energy level spacing (quantum effect) [37]. When the particle size is down to 10 nm, size effects on optical characteristics are seen [38]. Because nanoparticles are so small, their electrons are not as free to travel as they would be in a bulk material. Because of this electron quantum confinement, the way that nanoparticles react to light is different from that of the bulk material.

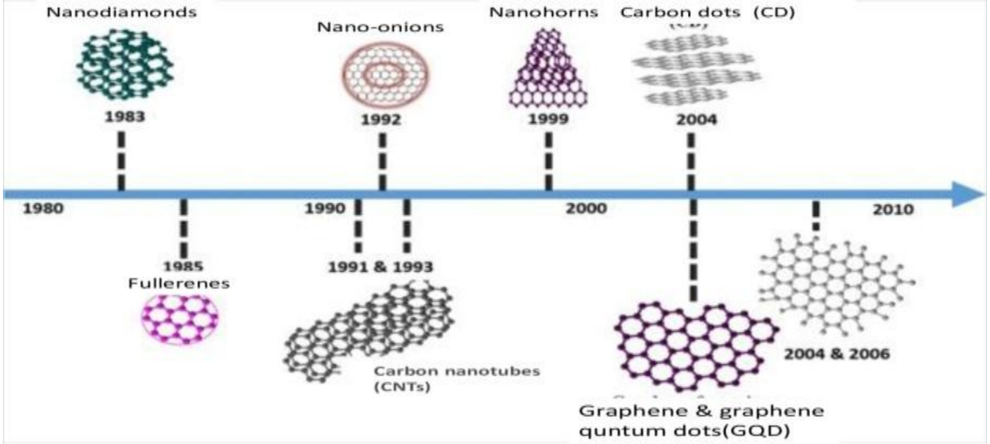

Fig.4: Shows the year wise data about nanoparticles [164]

The energy of the lowest vacant molecule orbital, which is basically the conduction band, and the highest occupied molecular orbital, which is a valence band, are most significantly affected by reduced dimensionality in the electronic structure of the nanomaterials [39]. When an electron moves from these two bands, optical characteristics including emission and absorption take place. When particle size decreases, this optical band gap widens, particularly for semiconductor nanomaterials. A photon with wavelength λ¼hc/ΔE is released when an electron transitions from a higher energy state to a lower energy state. The Plank's constant, light speed, and energy differential between permitted electron energy levels are represented by h, c, and ΔE, respectively. The wavelength (blue shifted) decreases with increasing ΔE. Because of these quantum confinement phenomena, semiconductor nanomaterials absorb and emit light at specific wavelengths that are highly dependent on both particle size and form. The emission wavelengths of the nanomaterials can be controlled from the ultraviolet through the visible to the near-infrared parts of the spectrum by varying their size and composition. For instance, the emission wavelength of colloidal CdSe-CdS core-shell nanoparticles can be adjusted from 2 to 6 nm in diameter, with the larger particles generating red light and the smaller particles emitting blue light (Fig. 4) [13].

e. Electrical properties

qualities that fall under the heading of electrical qualities include resistivity and conductivity. These qualities, like optical or magnetic ones, are also found to vary at the nanoscale. The mobility of the charge carriers is the primary concern of nanomaterials' electrical characteristics. There is no way around the quantum-size effect and quantum confinement effect when a material's dimensions are down to the nanoscale range. Certain conductive metal nanoparticles can become nonconductive when exposed to a specific voltage due to the quantization of electron energy. For instance, if a metal, like copper, is reduced in size to a few nanometers, it can lose its conductivity; on the other hand, insulating materials, like silicon dioxide, would lose their insulating qualities and turn conductive [2]. The dielectric characteristics, resistivity, and electrical transports of nanomaterials are primarily controlled by increased interfacial atoms or ions, sinking a significant amount of defects along the grain boundaries, grain size, and doping impurities [44]. Because the band gap energy of nanomaterials increases with decreasing particle size, especially in the case of semiconductor nanoparticles, their electrical conductivity is often lower than that of bulk materials [45].

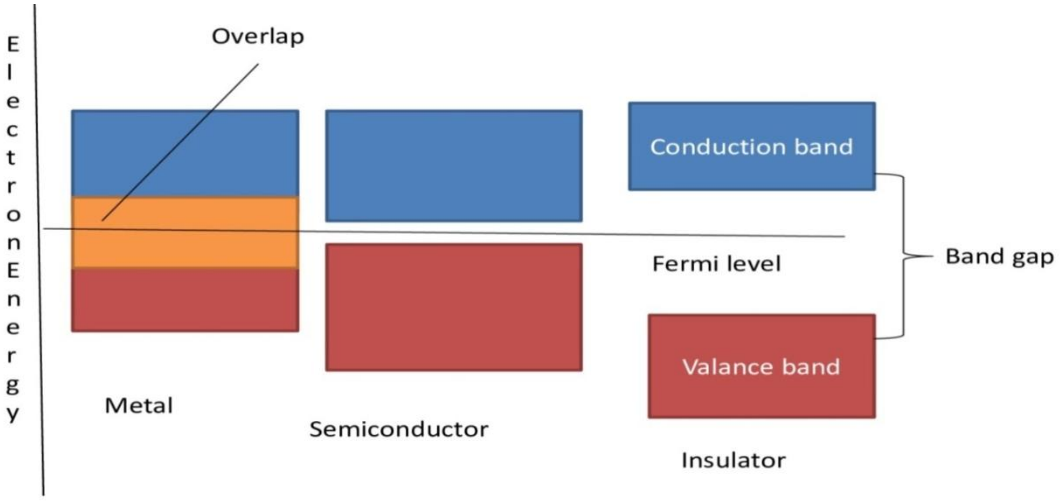

Fig.5: Indicates to electron energy from metal, semiconductor, and insulator [163]

For instance, even though gold nanoparticles are metallic, they become insulators as the energy bands stop overlapping in the 2-4 nm range [46]. An energy range in a solid where no electron states are permitted is called a band gap. In momentum space, the minimum (lowest energy state) of the conduction band and the maximum (highest energy state) of the valence band are directly above each other when a direct band gap is present. The difference between the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO) at the bottom of the conduction band is known as the electrical band gap [47]. The fundamental factor influencing electrical conductivity is the distance between neighboring energy levels. Particle size has a major impact on the electrical structure of the nanoparticles [38]. The number of energy states in discrete nanoclusters made up of relatively few atoms reduces with decreasing size. As a result, the nanoclusters conductive qualities change from metallic to semiconducting and insulating, depending on how much space there is between neighboring energy levels. Fig. illustrates how the conductive characteristics in isolated nanoclusters change from metallic to semiconducting/insulating. 5. This is only true for 0D nanoparticles; in contrast, the electrical conductivity of 1D or 2D nanomaterials, like nanowire or nanotube, may even rise in relation to the aspect ratio and ordering of the nanomaterials' structure. By mechanically reducing the nanowires diameter at a steady applied voltage, the number of electron wave modes that contribute to electrical conductivity is reduced in well-defined quantized stages. The conductivity of nanowires rises sharply in comparison to bulk materials as their diameter falls below 20 nm because of enhanced surface scattering for electrons and phonons, larger surface areas, and a very high density of electronic states [49]. Depending on their size, crystal structure, and chemical makeup, carbon nanotubes can exhibit a broad spectrum of electrical properties, from metallic, insulating, and semiconducting to superconducting [50]. In conclusion, decreasing the size of the material will lead to a reduction in defects or crystal perfection, which will decrease defect dispersion and, ultimately, decrease resistivity and increase conductivity. We provided a thorough introduction of nanomaterials, their kinds, and their physiochemical properties in this chapter. Nanomaterials, depending on their size, form, and chemical compounds, offer a wide range of unique properties because of their nanoscale size. Nanoscience is based on these size-dependent features, which are used to explore potential applications. Even though nanoparticles have a wide range of applications, their uncontrolled use and release into the environment pose some health risks. These issues should be taken into account while developing more environmentally friendly and convenient ways to employ nanomaterials.

1.2 Applications of nanomaterials

Nanomaterials, also known as nanocrystalline materials, are materials whose grains are as small as a billionth of a meter. They have a variety of structural and non-structural uses because to their highly appealing and practical qualities. Because of their unique, beneficial physical, chemical, and mechanical qualities, nanoparticles can be used in a wide range of applications, such as the ones that follow.

I. Future-Stage Computer Chips

Miniaturization is the process of making circuit components like transistors, capacitors, and resistors smaller. The microelectronics industry has focused particularly on this process. These components' size has been significantly reduced, which makes microprocessors made with them work much faster and perform computations at much faster rates. Unfortunately, a number of technical challenges stand in the way of these advancements. These include inadequate heat dissipation due to the large amounts of heat generated by these microprocessors because of their faster speeds, poor mean time to failures (poor reliability), and a lack of ultrafine precursors to make these parts. By providing producers with materials with improved thermal conductivity, nanocrystalline starting materials, ultra-high purity materials, and more robust, long-lasting interconnections (connections between various parts in the microprocessors), nanomaterials assist the industry in overcoming these challenges.

ii. Enhancement of Lethality in Kinetic Energy Penetrators

Depleted uranium (DU) projectiles, also known as penetrators, are used by the Department of Defense (DoD) to combat enemy armored vehicles and fortified targets. However, DU retains residual radiation, making it dangerous (carcinogenic), explosive, and potentially fatal for individuals who utilize them. However, the fact that DU penetrators have a unique self-sharpening mechanism upon impact with a target and that there isn't a suitable non-explosive, non-toxic substitute for DU are some of the main factors contributing to their continued employment. Such self-sharpening mechanisms can be realized in nanocrystalline tungsten heavy alloys because of their unique deformation features, such as grain-boundary sliding. Consequently, the potential of nanocrystalline tungsten heavy alloys and composites as substitute DU penetrators is being evaluated.

III. Improved Materials for Insulation

The sol-gel process produces nanocrystalline materials that resemble foam and are referred to as "aerogels." Despite being incredibly light and porous, these aerogels have the capacity to support weights 100 times greater than their own weight. Aerogels consist of a continuous three-dimensional network of particles with air or any other type of fluid trapped in the spaces between them, like a gas. Aerogels are utilized as insulation in houses, workplaces, and other spaces because they are porous and contain air trapped at the interstices. This results in significant energy savings and a decrease in the related environmental pollutants by lowering the heating and cooling expenditures. Additionally, they are being used as the building blocks for "smart" windows, which illuminate in low light and darken in high light (much like prescription glasses and sunglasses with interchangeable lenses).

IV. High-Definition TV Phrases

The size of a pixel affects a monitor or television's resolution. The basic building blocks of these pixels are substances called "phosphors," which light up when an electron stream passes through them within the cathode ray tube (CRT). A decrease in the phosphors or pixel size improves the resolution. Potential materials for improving monitor resolution include lead telluride, zinc sulfide, cadmium sulfide, and nanocrystalline zinc selenide made using the sol-gel process. The goal of using nanophosphors in displays is to reduce their cost so that the ordinary American household may buy high-definition televisions (HDTVs) and personal computers.

v. Affordable Flat-Panel Screens

The market for laptops, or portable computers, has a strong need for flat-panel displays. Japan is in the lead in this field, mostly as a result of its research and development work on the display materials. Synthesizing nanocrystalline phosphors can greatly reduce the manufacturing costs of these display systems while also improving their resolution. Furthermore, because of their enhanced magnetic and electrical capabilities, flat-panel displays made with nanomaterials have significantly higher contrast and brightness than standard ones.

vi. Harder and Tougher Cutting Instruments

Compared to their conventional (large-grained) counterparts, cutting tools constructed of nanocrystalline materials, such as carbides of tantalum, tungsten, and titanium, are significantly tougher, much more wear- and erosion-resistant, and have a longer lifespan. Additionally, they enable the maker to machine many materials at a faster rate, increasing productivity and reducing manufacturing costs significantly. In addition, the process of shrinking microelectronic circuits calls for the use of microdrills, which are drill bits with diameters smaller than the average human hair (100 µm). These drill bits also need to have far greater wear resistance and edge retention. These micro drills use nanocrystalline carbides because they are significantly stronger, tougher, and wear-resistant.

VII. Removal of Pollutants

Grain boundaries in nanocrystalline materials are extremely large in relation to their grain size. They are therefore highly active in terms of their mechanical, chemical, and physical characteristics. Because of their enhanced chemical activity, nanomaterials can be used in power generating equipment and car catalytic converters as catalysts to react with harmful and noxious gases like carbon monoxide and nitrogen oxide, preventing the pollution that comes from burning coal and gasoline.

viii. Elevated Power Density Batteries

Almost all devices that require electricity utilize batteries, both conventional and rechargeable ones. These applications include next-generation electric vehicles (NGEVs), which lessen pollution in the environment, watches, laptop computers, cars, toys, electric vehicles, and portable stereos. These batteries require regular recharging because of their extremely low energy density (storage capacity). Both conventional and rechargeable batteries have a short lifespan. The foam-like (aerogel) structure of nanocrystalline materials made by sol-gel processes allows them to store a substantial amount more energy than their conventional counterparts. They are therefore ideal for battery separator plates. Furthermore, because of their large grain boundary (surface) area and improved chemical, physical, and mechanical properties, nickel-metal hydride (Ni-MH) batteries made of nanocrystalline nickel and metal hydrides are expected to require much less recharging and to last considerably longer.

ix. Strong Magnets

Coercivity readings and saturation magnetization are used to quantify a magnet's strength. When the specific surface area (surface area per unit volume of the grains) of the grains increases and the grain size decreases, these numbers will rise. It has been shown that the incredibly enormous surface area of magnets built of nanocrystalline yttrium-samarium-cobalt grains results in exceptionally rare magnetic characteristics. These high-power rare-earth magnets are frequently used in automotive alternators, quieter submarines, ultra-sensitive analytical instruments, land-based power generators, ship motors, and magnetic resonance imaging (MRI) for medical diagnostics.

x. Extremely Sensitive Sensors

Sensors employ their sensitivity to identify changes in the various characteristics that they are designed to assess. Chemical activity, thermal conductivity, electrical resistivity, magnetic permeability, and capacitance are some of the factors. The microstructure, or grain size, of the materials used to make the sensors has a significant impact on all of these factors. The physical, chemical, or mechanical properties of the sensor material, which is used for detection, show variations in the environment of the sensor. For instance, the chemical stability of zirconium oxide, or zirconia, is used by a carbon monoxide sensor to determine the presence of carbon monoxide. The carbon in carbon monoxide and the oxygen atoms in zirconium oxide combine to partially decrease zirconium oxide when carbon monoxide is present. A decrease in particle size greatly increases the rate and degree of this reaction, which initiates an alteration in the sensor's properties such as capacitance and conductivity (or resistivity). As a result, nanocrystalline material sensors are extremely sensitive to changes in their surroundings. Common uses for sensors created with nanocrystalline materials include smoke detectors, ice detectors on airplane wings, and sensors that measure engine performance in cars, among other things.

xi. Vehicles with Higher Fuel Economy

Due to incomplete fuel combustion, modern car engines waste a significant amount of gasoline, contributing to environmental pollution. An old-fashioned spark plug isn't designed to burn fuel completely and effectively. Faulty or worn-out spark plug electrodes exacerbate this issue. Nanomaterials are currently being suggested for use as spark plugs because they are stronger, tougher, and far more resistant to wear and erosion. These electrodes assist burn fuel much more thoroughly and efficiently while also extending the spark plugs' lifespan. The "railplug," a completely new spark plug design, is likewise at the prototype stage. The technology used in this railplug was taken from the "railgun," a renegade of the well-known Star Wars defense program. But these railplugs (with an energy density of over 1 kJ/mm2) generate far stronger sparks. As a result, conventional materials corrode and deteriorate quickly and are frequently useless for use in cars. Railplugs composed of nanomaterials, on the other hand, endure far longer than even regular spark plugs. Moreover, the loss of engine thermal energy results in significant energy waste in autos. This is especially valid for engines that run on diesel. Therefore, it has been suggested that the engine cylinders (liners) be coated with nanocrystalline ceramics, including zirconia and alumina, to improve heat preservation and guarantee complete and effective fuel combustion.

xii. Components for Aerospace with Improved Performance attributes

The goal of aircraft makers is to make aerospace components more durable, resilient, and long-lasting due to the risks associated with flight. Fatigue strength is one of the most important characteristics that airplane components must have, and it decreases with component age. The aircraft can have a much longer lifespan if the components are made of stronger materials. As the material's grain size decreases, the fatigue strength rises. When compared to standard materials, nanomaterials provide such a significant reduction in grain size that fatigue life is typically enhanced by 200%–300%. Additionally, components made of nanomaterials are stronger and can operate at higher temperatures, allowing aircraft to travel farther and faster on the same amount of aviation fuel. In spacecraft, the ability of a material to withstand higher temperatures is crucial because components like thrusters, rocket engines, and vectoring nozzles operate faster and at much higher temperatures than those found in aircraft. Additionally, nanomaterials make excellent candidates for spacecraft uses.

xiii. Upgraded and Upcoming Weapons Platforms

Conventional weaponry, such cannons, 155 mm howitzers, and multiple-launch rocket systems (MLRS), burn a charge of chemicals to produce chemical energy. The highest speed at which the penetrator can be propelled is between 1.5 and 2.0 km/second. On the other hand, electromagnetic launchers, sometimes known as railguns, use both electrical energy and the resulting magnetic field to accelerate their penetrators, or projectiles, to speeds of up to 10 km/s. Greater kinetic energy results from this increase in velocity for the same penetrator mass. The energy output is directly correlated with the target's level of injury. As a result, the DoD has conducted extensive research into railguns, especially with the U.S. Army. The rails of a railgun must be exceptional electrical conductors because they operate on electrical energy. Moreover, they must be so rigid and powerful that the railgun does not sag and collapse under its own weight during firing. The obvious choice for high electrical conductivity is copper. However, due to the hypervelocity projectiles' corrosion of the rails, copper railguns deteriorate far more quickly. They also lack strength at high temperatures. Copper rail deterioration and wear necessitate barrel replacements on a regular basis. A nanocrystalline composite material consisting of titanium diboride, tungsten, and copper is being evaluated as a possible contender to meet these requirements. This nanocomposite demonstrates very high strength, hardness, high stiffness, wear/erosion resistance, and the required electrical and thermal conductivity. As a result, railguns made of this material can withstand erosion and wear better than their conventional counterparts, lasting longer and firing more frequently.

xiv. Extended-Duration Satellites

Applications for satellites are used in both defense and civilian sectors. Due to the influence of the earth's gravitational pull, among other reasons, these satellites require thruster rockets to maintain or change their orbits. Thus, in order to move the satellites, thrusters are required. The amount of fuel that these satellites can carry on board largely determines how long they can survive. In actuality, partial and inefficient combustion of fuel, like hydrazine, results in the repositioning thrusters wasting more than one-third of the fuel brought aboard by the satellites. The onboard ignitors wear down quickly and stop working properly, which leads to partial and inefficient combustion. Nanomaterials such as nanocrystalline copper-tungsten diboride-copper composite show promise in enhancing the characteristics and longevity of these ignitors.

xv. Extended-Duration Medical Implants

Titanium alloys and stainless steel are typically used in the construction of orthopedic and heart valve implants, among other medical devices. Because these alloys are biocompatible—that is, they do not negatively react with human tissue—they are mostly used in human applications. When it comes to orthopedic implants (artificial hip bones, etc.), these materials are rather non-porous. In order for an implant to effectively resemble a normal human bone, the surrounding tissue must pierce the implant, providing the implant with the strength it needs. The efficiency of the implants is decreased since human tissue cannot pass through them due to the relative impermeability of these materials. Furthermore, these metal alloys deteriorate quickly, necessitating costly, repeated procedures. However, because biological fluids are corrosive, nanocrystalline zirconia (zirconium oxide) ceramic is robust, resistant to wear, and biocompatible. By employing sol-gel techniques, nanoceramics can also be made as porous as aerogels, which can withstand up to 100 times their own weight. This would result in a significant decrease in the number of implant replacements and, consequently, in surgery costs. SiC, or nanocrystalline silicon carbide, has several advantages over other materials for prospective application in prosthetic heart valves, including low weight, extreme hardness, high strength, resistance to wear and corrosion, and inertness (SiC does not react with biological fluids).

xvi. Machinable and Ductile Ceramics

Because of this, ceramics are very brittle, rigid, and difficult to machine. Because of these characteristics, potential customers have been discouraged from taking advantage of ceramics' benefits. Nonetheless, the use of these ceramics with smaller grains has increased. It has even been possible to turn the hard, brittle ceramic zirconia into a superplastic, one that can flex to larger lengths (up to 300% of its initial length). But in order for these ceramics to be superplastic, they need to have nanocrystalline grains. Actually, automotive applications including ball bearings, high-strength springs, and valve lifters have made use of nanocrystalline ceramics like silicon carbide (SiC) and silicon nitride (Si3N4). This is due to their exceptional physical, mechanical, and chemical qualities, as well as their good machinability and formability. They are also utilized as parts of furnaces with high temperatures. At much lower temperatures, nanocrystalline ceramics can be pressed and sintered into a variety of shapes. In contrast, even at high temperatures, pressing and sintering traditional ceramics would be extremely difficult, if not impossible.

xvii. Enormous Electrochromic Displays

Materials that allow for the addition of an optical absorption band or the modification of a current band by providing an electric field or flowing current through the materials make up an electrochromic device. Large electrochromic display devices use nanocrystalline materials such as tungstic oxide (WO3·xH2O) gel. By interacting with the nanocrystalline tungstic acid to make tungsten bronze, the double-injection of ions (or protons, H+) and electrons is the reaction that controls electrochromism, a reversible coloration process that is affected by an electric field. These gadgets are mostly used to transmit information on public billboards and ticker boards. Comparable to the liquid-crystal displays (LCD) seen in most watches and calculators are electrochromic devices. However, electrochromic devices use color changes in reaction to applied voltage to display information. When the polarity is reversed, the color becomes bleached. The grain size of the tungstic acid gel has a significant impact on these devices' resolution, contrast, and brightness. Consequently, research is being done on nanomaterials for this reason.

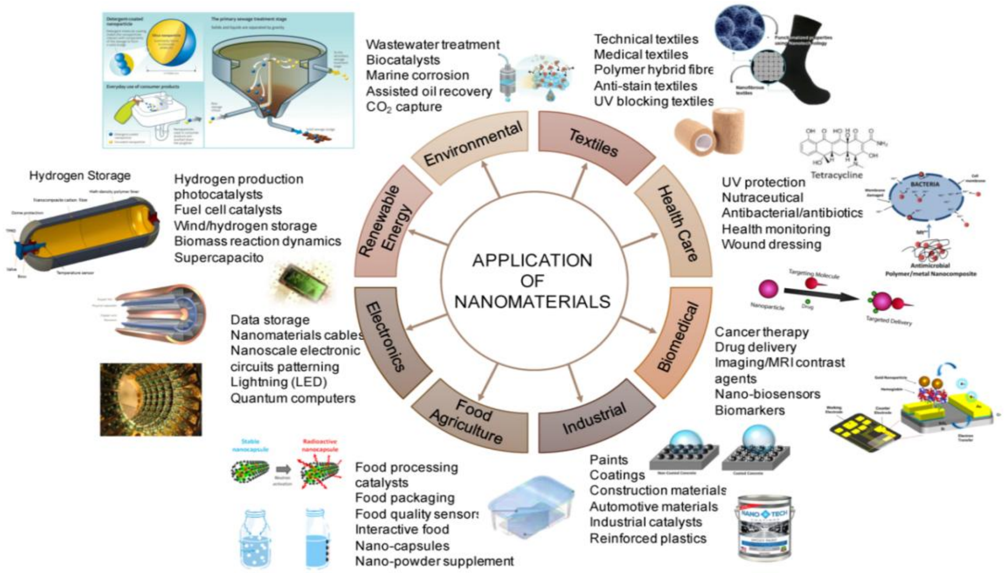

Fig.6: Shows a Nanomaterials: Current Practices, Challenges, and Future Prospects [52]

1.3 Metal oxide nanoparticles

Photocatalytic activities are exhibited by metal oxide compounds. Metal oxides such as TiO2, ZnO, WOx, SnO2, Fe2O3, CuO, ZrO2, and MoO3 are among those that are utilized in the production of nanoparticles [159]. In order to increase photocatalytic activity and produce more reactive oxygen species, photocatalytic substances interact with light energy [160]. The surface of metal oxide nanoparticles can be changed by non-metal insertion or metal ion doping [161]. Generally speaking, the photocatalytic degradation process utilizing nanoparticles speeds up the degradation process, which is mostly beneficial for waste treatment. After waste is treated, these effluents in agriculture can be utilized to prepare herbicides since they help avoid soil pollution [51] and are deemed safe in low amounts [160].

Metal oxides are used in redox and acid-base processes and are regarded as heterogeneous catalysts. Due to their outer electron arrangement, some groupings of metals, especially transition metals, have garnered a lot of interest. Ferromagnetism is a property of several different crystalline materials, including Fe, Co, and Ni. The most popular of them is ferrite oxide-magnetite (Fe3O4), which is utilized in a variety of biological applications as superparamagnetic nanoparticles [43]. Their breadth of applications is astounding and includes everything from power handling, simple permanent magnets, magnetic recording, inductors, high frequency, power, suppression of electromagnetic interference (EMI), and biosciences to millimeter wave integrated circuitry [44].

2. FERRITES INTRODUCTION

Ferrites are composed of many tiny crystals and are hard, brittle, iron-containing, and typically gray or black in color. They are made up of a chemical mixture of iron oxide and one or more additional metals [66]. We have advanced to a new level of understanding thanks to several years of globally significant advancements in nanoscience, which combine physics, chemistry, material science, theory, and even biosciences. Nanotechnology emerges as a crucial

Ferrites, or magnetic oxides, have a long history, and their uses date back several centuries. The first documented descriptions of the loadstone (magnetite, Fe3O4), a naturally occurring non-metallic mineral that may attract iron, date back to approximately 800 B.C. Magnetite was first utilized as "Lodestones," which were used by early navigators to find magnetic North, a long time ago. Because it was the first technical magnetic substance to build a compass, it was the first scientific significance to be recognized (Crangle, 1977). William Gilbert published De Magnete, the earliest scientific study on magnetism, in 1600. Hans Christian Oersted later noted in 1819 that a magnetic compass needle was impacted by an electric current flowing through a wire.

Magnetite that occurs naturally is a weak 'hard' ferrite. "Hard" ferrites are magnetized in a nearly permanent way. produced initially in a limited range of sizes and forms, mostly for use as antennas and inductors. "Soft" ferrite is available in an endless variety of forms and sizes for a wide range of applications. Additionally, ferrites are widely utilized in three fields of electronics:

I. Low-level programs
ii. Power-related uses
III. Reduction of electromagnetic interference (EMI)

Ferrites are being increasingly widely used in electrical circuitry. Ferrite components are the preferred option for both traditional and cutting-edge applications due to their broad variety of potential geometries, ongoing advances in material properties, and relative cost-effectiveness. A kind of ceramic substance called ferrite is made of iron oxide (Fe2O4) mixed with one or more other metallic elements. It is a member of the ferrimagnetic material class, which includes materials with distinct underlying processes but similar magnetic characteristics to ferromagnetic materials. High-temperature techniques can be used to manufacture the ferrites in powder or thin film form. These are

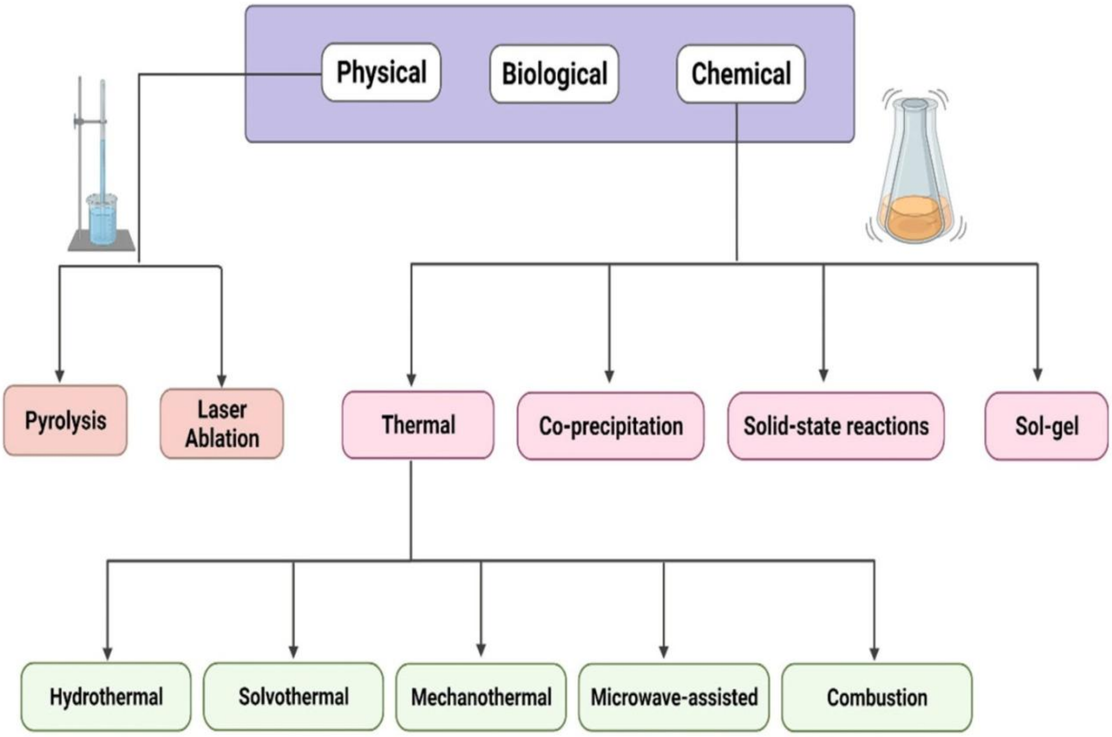

Fig.7: Synthesis methods for ferrite nanoparticles[67]

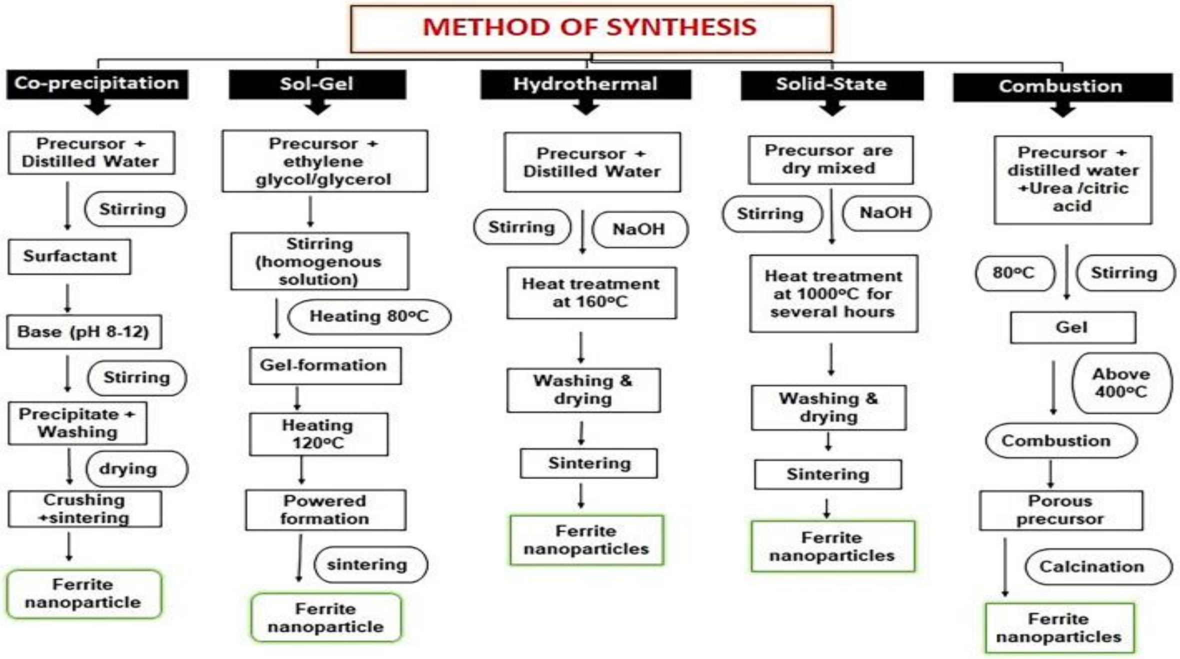

Fig.8: Process of synthesis methods for ferrite nanoparticles[162]

In order to create a ferrite core, a combination of powders containing the component raw materials is pressed into the desired shape before being sintered into a ceramic component. The interactions between metallic ions that occupy specific places in relation to the oxygen ions in the oxide's crystal structure give rise to the magnetic characteristics. Three major classes may be distinguished among the commercial ferrites, each of which has a distinct crystal structure:

- Microwave ferrites, or soft ferrite with a garnet structure (e.g., YIG—Yttrium Iron Garnet)
- Soft ferrites like MnZn-, NiZn-, and MgMnZn ferrites have a cubic spinel structure.
- Ba and Sr hexaferrites are examples of hard ferrites with the magnetoplumbite (hexagonal) structure.

Ferrites are commonly utilized in interface suppression, power conversion, transformers, and telecommunications.

2.1 Classification and Types of ferrite

Iron oxide and metal oxides make up ferrites' primary component. Ferrites can be classified into the following categories based on their crystal structure (Table 1).

I. Ferrite Spine
II. Garnet
III. Ferritin
IV. Ferrites that are hexagonal.

I. Ferrite Spine

The chemical formula for spinel ferrites is MFe2O4, where M denotes divalent metal ions. Tetrahedral (A) and octahedral (B) are the two interstitial sites found in the crystal structure of spinel ferrite. The tetrahedral A site and the octahedral B site may tolerate a wide range of cations, allowing for significant diversity in the characteristics of ferrites. We can have a number of spinel ferrites and substitute M with various divalent metal ions. Al3+, Cr3+, Ga3+, and other trivalent ions can be used in place of Fe3+ ions. Divalent and tetravalent ions can also be used in place of Fe3+ ions.

II. Ferrite garnet

Ferrimagnetic garnet has the chemical formula Me3Fe5O12, where Me is a trivalent ion like yttrium or rare earth. Me3Fe5O12, or eight molecules, make up the cubic unit cell (160 atoms). Three different kinds of sites are covered by the metal ions. Eight oxygen ions surround the Me ions at the dodecahedral sites (also known as c sites), whereas the Fe3+ ions are dispersed in a 3:2 ratio throughout the tetrahedral and octahedral sites. Consequently, Me3cFe2aFe3dO12 can be used to represent the cation distribution of Me3Fe5O12. Similar to spinels, the super exchange contact between the intervening oxygen ions causes the magnetic alignment. This interaction is anticipated to be stronger the closer the Me-O-Me angle is to 1800 and the shorter the Me-O distance. This leads to the conclusion that there is a rather significant (both negative) interaction between the d and a cations. The solid's magnetic alignments are governed by these interactions, which produce the subsequent spin arrangement. Me3cFe2aFe3dO12 for magnetic Me3cFe2aFe3dO12 for non-magnetic Me ion The whole magnetic moments of the "a" and "d" ions are antiparallel, and the moments of the c-ions are antiparallel to those of the d-ion. Therefore, the arrangement is 6Fed, 4Fed, 6Mc for the formula (3M2O3) c (2Fe2O3) a (2Fe2O3) d. Assuming a magnetic moment of 5µB per Fe ion, the net magnetic moment m (in terms of the Bohr magneton per unit formula) is m = 6mc - (6md-4ma) = 6mc -10 µB 1. This is equivalent to m = (3mC - 5µB) in terms of the unit formula M3Fe5O12 equation 1, where mc is the magnetic moment per Me ion.

III. orthodox-ferrites

The usual formula for ortho-ferrites is MeFeO3, where Me is a massive trivalent metal ion, like Y or a rare-earth ion. With an orthorhombic unit cell, they crystallize in a deformed pervoskite structure. The slight canting in the alignment of two anti-ferromagnetically connected lattices has been identified as the cause of the mild ferromagnetism observed in these ortho-ferrites. It is possible to introduce a tiny net ferromagnetic moment perpendicular to the antiferromagnetic axis with a canting angle of around 10-2 radians. Experimental research [61] has determined the direction of the Fe ion's spin orientation in HOFeO3 and ErFeO3. At room temperature, the direction is parallel to the (100) axis; as the temperature is lowered, the spin axis rotates; at 1.25K, the direction is (001) for HOFeO3 and (110) for ErFeO3. At a significantly lower Neel temperature [4.3 K for ErFeO3 and 6.5 K for HO FeO3], the spin moment on the rare earth ion becomes organized.

4. Hexagonal iron oxides

Many ferrites have a hexagonal crystal structure, and some of these have become quite important in recent years from a technological standpoint. These ferrites are divided into compounds that are M, W, Y, Z, and U. These all have various crystal structures that are connected to one other. The simplest structures are found in the M compounds. This class includes the well-known hard ferrites, such as barium ferrite. These substances have the general formula MeFe12O19, where Me is one of the divalent ions—Ba2+, Sr2+, or Pb2+—with a large ionic radius. There are several known compounds containing trivalent Me, such as La3+, Al, Ga, Cr, and Fe. To enable the charge adjustment in these, one iron is present as Fe2+ per formula unit. Barium ferrite has a hexagonal crystal structure, with two unit formulas making up the unit cell. The arrangement is comparable to the spinel structure, where the oxygen lattice, f, is located. c.c., are made up of many oxygen layers arranged hexagonally and oriented perpendicular to the (111) direction.

Method	Composition	Calcinating Temp. (^{0}C)	Duration (h)	Refs.
Sol gel	$BaFe_{12-x}Ti_xO_{19}$	850	1	[3]
		1000		
	$Cu_{0.5}Ni_{0.5}Fe_2O_4$	800	2	[42]
	$Ni_xZn_{1-x}AlFeO_4$	600	5	[69]
	$SrFe_{12-x}Co_xO_{19}$	1000	2	[94]
	$SrLa_xFe_{12-x}O_{19}$	650	2	[95]
		1050		
	$Sr_{1-x}Nd_xFe_{12-x}Co_xO_{19}$	1200	3	[97]
	$Sr_{1-x}La_xFe_{12}O_{19}$	1000	1.5	[98]
	$Sr(MnTi)_xFe_{12-2x}O_{19}$	900	2	[100]
	$SrMn_{x/2}(TiSn)_{x/4}Fe_{12-x}O_{19}$	1000	1	[106]
	$Ni_{1-x}Zn_xFe_2O_4$	1000	1	[112]
	$Co_{1-x}Zn_xFe_2O_4$	800	2	[68]
		400	6	[113]
		600	12	[114]
	$BaFe_{12}O_{19}$ nanorods	850	1	[115]
	$SrFe_{12}O_{19}$	900	4	[116]
	$SrFe_{12}O_{19}/ZnFe_2O_4$	850	1.5	[117]
	$BaCe_{0.05}Fe_{11.95}O_{19}$	800	0.5	[118]
Hydrothermal	$NiFe_2O_4$	45-150	18	[73]
	$NiFe_2O_4$	180	3-15	[77]
	$ZnFe_2O_4$	160		
	$Co_xZn_{1-x}Fe_2O_4$	150	12	[78]
	$SrFe_{12}O_{19}$	220	5	[93]
	$Mg_{1-x}Zn_xFe_2O_4$	200	2	[121]
	$Co_{0.5}Zn_{0.5}Fe_2O_4$	170	30	[122]
	$Mn_{1-x}Cd_xFe_2O_4$	180	20	[123]
	$Mn_xCo_{1-x}Fe_2O_4$	180	24	[124]
	$Mn_{1-2x}Ti_xFe_2O_4$	180	20	[125]
	$CuFe_2O_4$	100-200	12-36	[126]
Co-precipitation	$Co_{1-x}Zn_xFe_2O_4$	85	1	[11]
	$Ni_{0.5}Zn_{0.3}Co_{0.2}Fe_2O_4$	800	3	[79]
	$Sr_2Cu_{2-x}Co_xFe_{12}O_{22}$	950	4	[83]
	$BaFe_{12}O_{19}$	800	3	[102]
	$SrFe_{12}O_{19}/ZnFe_2O_4$	850-1150	4	[104]
	$SrFe_{11.2}Ni_{0.8}O_{19}$	1200	4	[127]
	$Ni_{0.4}Cu_{0.2}Zn_{0.4}Fe_2O_4$	100	24	[130]
	$Cu_{1-x}Ni_xFe_2O_4$	900	5	[132]
	$Co_{1-x}Zn_xFe_2O_4$	95	1	[135]

Method	Composition	Calcinating Temp. (^0C)	Duration (h)	Refs.
Ceramic Calcination temperature for pellets	$SrFe_{12-2x}(Mg, Co)_{x/2}Ti_xO_{19}$	900	1	[136]
	$SrFe_{12-x}Ti_{x/2}Zn_{x/2}O_{19}$	900	1	[137]
	$Ni_{0.65}Zn_{0.35}Al_xFe_{2-x}O_4$	1200	4	[64]
	$MgFe_2O_4$	1200	24	[67]
	$CoFe_2O_4$			
	$ZnFe_2O_4$			
	$Mg_{1-x}Zn_xFe_{2-y}Sm_yO_4$	1100	18	[74]
	$NiFe_2O_4$	1100	4	[76]
	$BaSrCo_{2-x}Ni_xFe_{12}O_{22}$	1250	12	[82]
	$BaMg_{2-x}Co_xFe_{16}O_{27}$	1100-1300	2	[84]
	$BaFe_{12}O_{19}$	1100	2	[89]
	$BaFe_{12-2x}Co_xZn_xO_{19}$	1100	3	[101]
	$Ba(ZnSn)_xFe_{12-2x}O_{19}$	1200	4	[103]
	$Ba_{1-y}La_yZn_{0.5}Mg_{0.5}Co\ Fe_{16}O_{27}$	1300	5	[108]
	$Ni_{0.5}Zn_{0.5}Fe_2O_4$	950	12	[138]
	$Ba_3Co_{2-x}Fe_{24+x}O_4$	1100-1300	16	[141]
	$BaFe_{12-2x}Zn_xTi_xO_{19}$	1050	1.5	[143]
	$Ba_{1-x}Sm_xFe_{12}O_{19}$	1250	5	[145]
	$Co_{0.65}Zn_{0.35}Fe_{2-x}Mo_xO_4$	1200	36	[146]

Table 1: Types of ferrites [53]

Type	Structure	General Formula	Examples
Spinel Ferrites	Cubic	$A\ \Pi\ Fe_2O_4$	A Π =Cd, Co,Mg, Zn etc.
Garnet	Cubic	$Ln3\ IIIFe_5O_{12}$	LnIII=Y,Sm,Eu, Gd,Tb,Dy,Ho,Er,Tm and Lu,
Magneto plumbite	Hexagonal	$A\ \Pi\ Fe_{12}O_{19}$	A Π $=BaF_{12}O_{19}$

2.2 The composites of ferrites

They are made of a chemical mixture of iron oxide and one or more additional metals. Ferric oxide, often known as iron oxide or rust, reacts with a variety of other metals, such as magnesium, aluminum, barium, manganese, copper, nickel, cobalt, or even iron itself, to generate ferrites.

Table 2: composites of ferrites [55]

Composite matrix	Examples	Applications
Cement	Concrete (cement, sand and gravel) Carbon fiber reinforced concrete	Structural, Price reduction
Carbon	Carbon fiber reinforced graphite, carbon-metal nanocomposites	Structural, Thermal, Electronic, Biomedical, Environmental
Metal	Carbon fiber metal-matrix composites	Structural, Thermal, Electronic
Ceramic	Carbide, Nitride of Silicon, Alumina composites	Structural, Thermal
Polymer	Polymer-clay, Polymer-metal, Polymer-carbon composites, polymer glass	Structural, Thermal, Electronic, Biomedical, Environmental

Table 3: Synthesis methods of ferrites in review reported [65]

2.3 Advancements

CoFe2O4's composition can be slightly doped with an external ion to modify its physicochemical characteristics without causing an unwanted phase transition [3]. Because they are dependent on the synthesis technique, composition, doping ions, and particle size distribution, the characteristics of CoFe2O4 are easily tunable [4,10,11]. While the doping with monovalent ions attracted less interest, the characteristics of CoFe2O4 doped with divalent (Mg2+, Cu2+, Ni2+, Zn2+, Mn2+) and trivalent (La3+, Ru3+, Gd3+, Al3+) ions were thoroughly investigated [12–18]. With the SiO2 functioning as a physical barrier that regulates the attraction between the magnetic nanoparticles, the formation of an inactive SiO2 coating on the surface of oxide systems may help to avoid their agglomeration and enhance their chemical stability [21–23,29, 30]. Furthermore, because it is possible to regulate particle size and reduce surface roughness and spin disorder, as well as improve the magnetic characteristics of the resulting nanocomposites, embedding magnetic ferrites into the SiO2 matrix has drawn a lot of attention [22, 23].Furthermore, because of its lower dielectric constant, the non-magnetic SiO2 matrix has a large surface area and has no effect on the electric or magnetic characteristics of the CoFe2O4 nanoparticles [29].

3. MONO DOPED

which, for the Na- and Ag-doped ferrites, is accompanied by cristobalite (JCPDS #89-3434), and, for the Ca-, La-, and Cd-doped ferrites, by cristobalite and quartz (JCPDS #85-0457). Higher crystallite sizes, minor changes in peak width, and a modest shift in the 2θ peak position were also seen during calcination [22, 23]. In comparison to the other gels, the Cd0.1Co0.9Fe2O4 gel exhibits the lowest intensity diffraction peaks, indicating the lowest crystallization. The degree of crystallinity and crystallite size increase with increasing calcination temperature, as indicated by the intensities of the diffraction peaks [22, 23]. The spinel crystal structure of the CoFe2O4 was preserved in the presence of La3+ ions, and no secondary impurity-related reflections were produced [6]. On the other hand, Mansour et al. observed that LaFeO3 appeared as a secondary phase as a result of some La3+ ions diffusing to the grain boundaries and reacting with Fe to produce LaFeO3 [8]. The calcination temperature, doping ions, crystallite size, lattice strain, and defects all affect the XRD patterns [22]. The structural characteristics of gels calcined at 400, 700, and 1000 °C were assessed using XRD and the M/Co/Fe molar ratio.

Table 4: Structural parameters determined via XRD and M/Co/Fe molar ratio of gels calcined at 400, 700 and 1000 °C.

Parameter	Temp (°C)	$CoFe_2O_4$	$Ag_{0.1}Co_{0.95}Fe_2O_4$	$Na_{0.1}Co_{0.95}Fe_2O_4$	$Ca_{0.1}Co_{0.9}Fe_2O_4$	$Cd_{0.1}Co_{0.9}Fe_2O_4$	$La_{0.1}CoFe_{1.9}O_4$
D_{XRD} (nm)	400	13.2	14.0	13.6	14.6	12.3	15.5
	700	23.4	24.7	23.7	25.2	22.5	26.1
	1000	37.2	65.1	47.6	73.7	35.0	81.8
DC (%)	400	58.8	62.7	64.2	63.7	64.8	60.2
	700	71.7	65.2	69.6	67.8	72.9	75.4
	1000	85.7	86.9	87.8	92.5	88.9	90.6
a (Å)	400	8.391	8.380	8.377	8.374	8.400	8.408
	700	8.395	8.400	8.390	8.388	8.412	8.411
	1000	8.403	8.410	8.400	8.397	8.422	8.423
V (Å^3)	400	590.8	588.5	587.8	587.2	592.7	594.4
	700	591.6	592.7	590.6	590.2	595.2	595.0
	1000	593.3	594.8	592.7	592.1	597.4	597.6
d_A (Å)	400	3.633	3.629	3.627	3.626	3.637	3.641
	700	3.635	3.637	3.633	3.632	3.643	3.642
	1000	3.639	3.642	3.637	3.636	3.647	3.647

Parameter	**Temp (°C)**	**$CoFe_2O_4$**	**$Ag_{0.1}Co_{0.95}Fe_2O_4$**	**$Na_{0.1}Co_{0.95}Fe_2O_4$**	**$Ca_{0.1}Co_{0.9}Fe_2O_4$**	**$Cd_{0.1}Co_{0.9}Fe_2O_4$**	**$La_{0.1}CoFe_{1.9}O_4$**
d_B (Å)	400	2.967	2.963	2.962	2.961	2.970	

Table 5: Magnetic parameters of gels calcined at 700 and 1000 °C.

Parameter	**Temp (°C)**	**$CoFe_2O_4$**	**$Ag_{0.1}Co_{0.95}Fe_2O_4$**	**$Na_{0.1}Co_{0.95}Fe_2O_4$**	**$Ca_{0.1}Co_{0.9}Fe_2O_4$**	**$Cd_{0.1}Co_{0.9}Fe_2O_4$**	**$La_{0.1}CoFe_{1.9}O_4$**
M_S (emu/g)	700	30.0	25.4	27.7	26.7	26.2	26.5
	1000	31.5	29.0	31.2	39.4	36.3	36.6
M_R (emu/g)	700	3.5	7.7	7.9	2.7	3.0	1.8
	1000	13.4	13.8	11.3	14.5	17.0	15.1
H_c (Oe)	700	600	530	360	410	440	385
	1000	1750	1850	1760	840	1070	1300
n_B	700	0.935	0.815	0.857	0.821	0.831	0.821
	1000	0.977	0.814	0.965	0.917	1.151	1.175
$K \cdot 10^3$ (erg/cm^3)	700	1.13	0.84	0.63	0.68	0.72	0.64
	1000	3.46	2.90	3.45	2.08	2.44	2

3.1 Applications of Ferrite Nanoparticles

Because of their special magnetic, electrical, and optical qualities, ferrite nanoparticles have many uses. The uses of ferrite nanoparticles are depicted in Fig. 7, with a few noteworthy uses being

a. Applications in Medicine

✓ MRI image contrast is improved by Ferritin nanoparticles, leading to more accurate diagnosis.

✓ They can be made functional to distribute medications to specific parts of the body, reducing adverse effects and enhancing the effectiveness of treatment.

✓ Ferrite nanoparticles can be utilized in cancer therapy to selectively kill cancer cells by producing localized heat when they come into contact with an alternating magnetic field.

b. Applications in the Environment

✓ By using adsorption and magnetic separation, ferritin nanoparticles can be utilized to extract heavy metals, organic contaminants, and pathogens from water.

✓ Because of their catalytic properties, they can help remove air contaminants.

C. Magnetic devices and electronics

✓ Because of ferrites' exceptional magnetic characteristics, high-density data storage systems use them.

✓ They are used in magnetic sensors, which are helpful in a variety of industrial and medical applications, to detect changes in magnetic fields.

✓ By strengthening their magnetic characteristics, ferrite nanoparticles help inductors and transformers operate better in electrical circuits.

d. Activation

✓ Ferritin nanoparticles function as catalysts in a range of chemical reactions, such as the production of fine compounds and the breakdown of contaminants.

✓ They are employed in fuel cells to improve the energy conversion processes' efficiency.

e. Power Retention

✓ Lithium-ion battery electrodes employ ferrite nanoparticles to increase capacity and charge-discharge rates.

✓ By improving the energy density and cycle stability of supercapacitors, they improve their overall performance.

f. Imaging in Biomedicine

✓ Ferrite nanoparticles can be utilized for bioimaging to monitor cellular activities and identify illnesses when paired with fluorescent molecules.

g. Magnetized Liquids

✓ These are steady colloidal mixtures of ferrite nanoparticles in a liquid carrier, utilized in damping agents, lubricants, and seals.

h. Theranostics

✓ Ferrite nanoparticles are particularly helpful in customized medicine because they may be engineered to concurrently carry out therapeutic and diagnostic tasks, a process known as theranostics.

I. Shielding against Electromagnetic Interference (EMI)

✓ Ferrite nanoparticles are utilized in coatings and materials that provide electromagnetic interference shielding for delicate electronic equipment.

j. Astute Materials

✓ Ferrite nanoparticles can be added to smart materials to make them react to pressure, temperature, or magnetic fields, for example.

These uses highlight the adaptability and potential of ferrite nanoparticles in promoting technological advancements and enhancing a range of industrial, medicinal, and environmental procedures.

Although ferrite nanoparticles have many advantages, they also have several disadvantages that may reduce their usefulness in some situations. Doping or the creation of composites with other materials are frequently effective ways to reduce these disadvantages. The following are some typical disadvantages and how to overcome them:

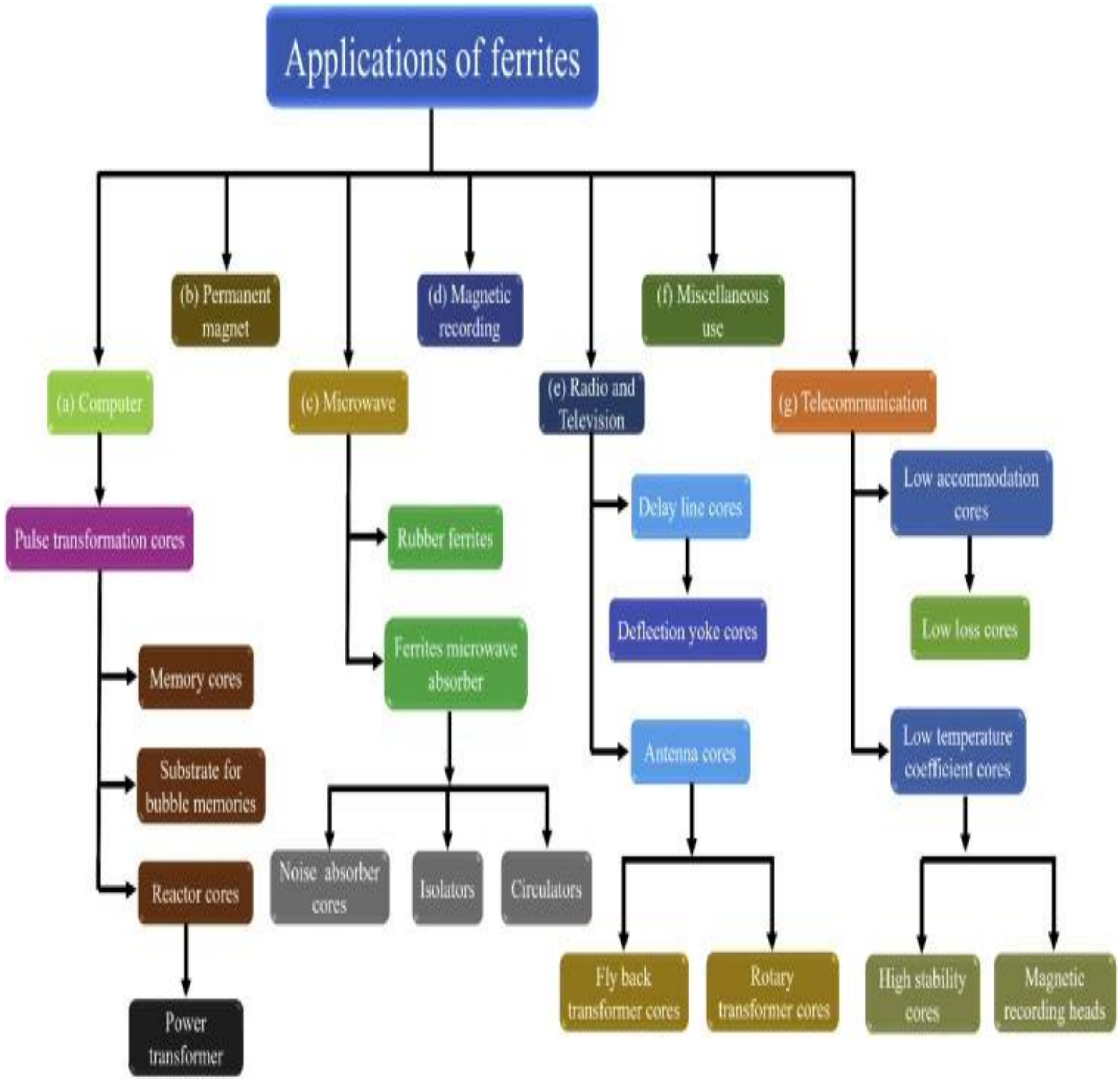

Fig.9: The various applications of nano ferrites [64]

Many of the intrinsic shortcomings of ferrite nanoparticles can be reduced by carefully choosing the right doping components or composite materials, increasing their usefulness and enhancing their performance in a variety of applications.

3.2 Ferrite Nanoparticles with Solution Drawbacks

a. Minimal Magnetization

- Drawback: In contrast to other magnetic materials like iron or cobalt, some ferrite nanoparticles, such manganese ferrite, may show lower saturation magnetization.

One possible solution is to increase the magnetic characteristics by doping with elements like as Zn, Co, or Ni. Cobalt doping, for example, can raise the saturation magnetization in ferrites (Co-doped MnFe2O4).

b. Combination and Consistency

- Drawback: Because of van der Waals forces and magnetic dipole interactions, ferrite nanoparticles have a tendency to agglomerate, which reduces their surface area and reactivity.

The dispersion and stability of the nanoparticles in solutions can be enhanced by coating them with polymers or surfactants, or by forming composites out of silica or carbon.

C. Insufficient Electrical Conductivity

- Drawback: The weak electrical conductivity of ferrite nanoparticles often prevents them from being used in electronic applications.

The solution is to increase electrical conductivity by doping with metals like Cu and Ag or by making composites with conductive materials like graphene or carbon nanotubes.

d. Chemical Resistance and Oxidation

- Drawback: Ferrite nanoparticles may oxidize or corrode in specific conditions, which will lessen their usefulness.

Solution: The nanoparticles can be shielded from abrasive chemical conditions by surface coating with inert materials as polymers, silica, or gold.

e. Insufficient Heat Stability

- Drawback: The magnetic characteristics of ferrite nanoparticles may be lost at high temperatures due to instability.
- Fix: Adding elements such as Cr or Al to the doping mixture can improve thermal stability. Moreover, using thermally stable materials to create composites can aid in preserving performance at high temperatures.

f. cytotoxicity

- Drawback: The cytotoxicity of certain ferrite nanoparticles restricts their employment in biological contexts.
- Reduction of cytotoxicity and enhancement of biocompatibility can be achieved by surface functionalization using biocompatible molecules, such as proteins, PEG (polyethylene glycol), or other biocompatible polymers.

Many of the intrinsic shortcomings of ferrite nanoparticles can be reduced by carefully choosing the right doping components or composite materials, increasing their usefulness and enhancing their performance in a variety of applications.

4. Doping

Doping is the deliberate addition of impurities to a material in order to change some of its characteristics. Doping ferrite nanoparticles with elements like Co, Ni, or Zn can improve their thermal, electrical, and magnetic characteristics, making them more appropriate for particular uses including higher thermal stability, enhanced data storage, and improved catalysis.

Table 6: Metal Doping in Ferrite Nanoparticles

Ferrite Nanoparticles	Doping Element	Observed Effects	Reference
Fe_3O_4 (Magnetite)	Co (Cobalt)	Enhanced magnetization and coercivity	[162]
Fe_3O_4 (Magnetite)	Ni (Nickel)	Improved electrical conductivity and stability	[163]
$MnFe_2O_4$ (Manganese Ferrite)	Zn (Zinc)	Reduced particle size, enhanced magnetization	[164]
$NiFe_2O_4$ (Nickel Ferrite)	Cu (Copper)	Increased electrical conductivity	[165
$CoFe_2O_4$ (Cobalt Ferrite)	Cr (Chromium)	Improved thermal stability and magnetization	[166]
$ZnFe_2O_4$ (Zinc Ferrite)	Al (Aluminum)	Enhanced magnetic and electrical properties	[167]
$MgFe_2O_4$ (Magnesium Ferrite)	Ti (Titanium)	Enhanced photocatalytic activity	[168]

Table 7: Key Studies on Composites with Ferrite Nanoparticles

Composite Material	Ferrite Nanoparticles	Application	Improvement	Reference
Polymer Matrix	Fe_2O_4	EMI Shielding	Enhanced EMI shielding	[169]
Graphene	$CoFe_2O_4$	Energy Storage	Increased capacitance	[170]
Silica Matrix	$MnFe_2O_4$	Catalysis	Improved catalytic efficiency	[171]
Carbon Nanotubes	$NiFe_2O_4$	Sensors	Enhanced sensitivity	[172]
Polyethylene Glycol	$ZnFe_2O_4$	Drug Delivery	Better biocompatibility	[173]

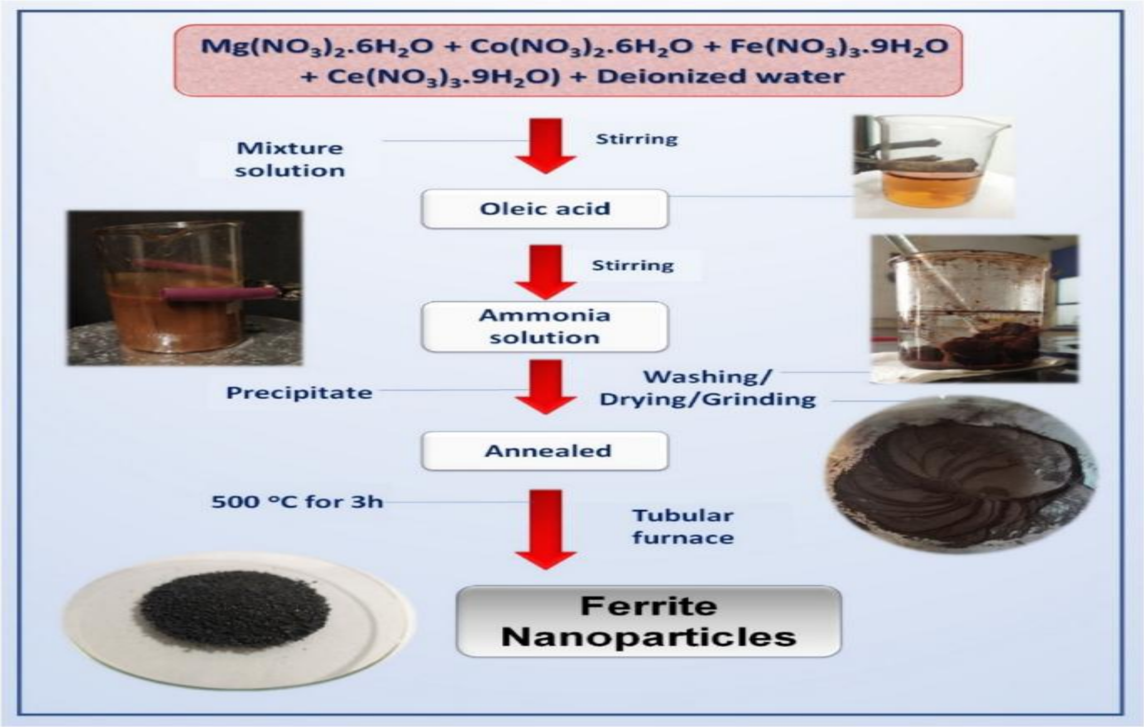

Fig.10: synthesis process of Ferrite Nanoparticles[161]

They are made of a chemical mixture of iron oxide and one or more additional metals. Ferric oxide, often known as iron oxide or rust, reacts with a variety of other metals, such as magnesium, aluminum, barium, manganese, copper, nickel, cobalt, or even iron itself, to generate ferrites.

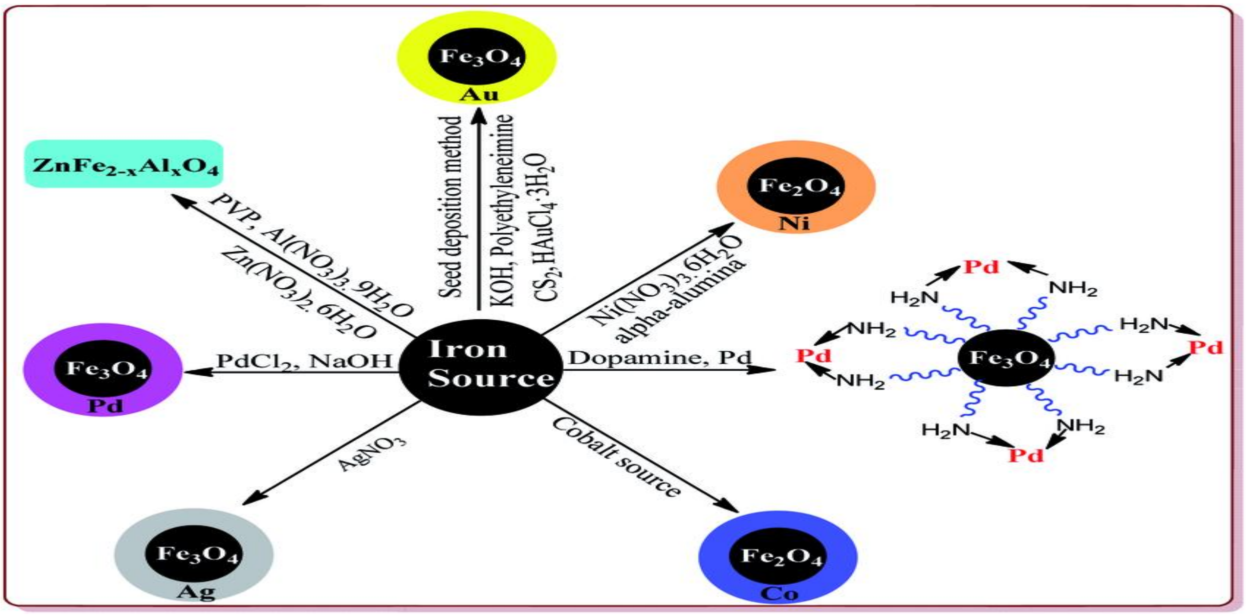

Fig .11: Metal doped ferrite nanoparticle[140]

4.1 Polymer-ferrite nanoparticle composites

The beneficial qualities of ferrite nanoparticles and polymers are combined in polymer-ferrite nanoparticle composites. These composites have important uses in environmental science, healthcare, electronics, and other domains. An extensive summary of polymer-ferrite nanoparticle composites (Fig.12), along with advantages, disadvantages, and examples from the literature, is provided below.

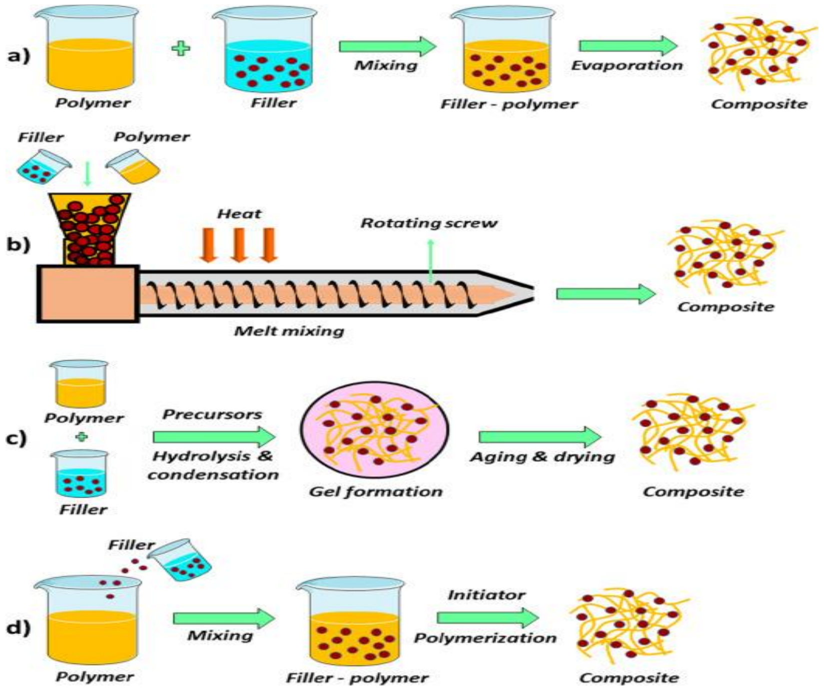

Fig.12: synthesis of composites polymer-ferrite nanoparticle [139]

a. Advantages

- Ferrite nanoparticles enhance the polymer matrix's magnetic characteristics, which qualifies these composites for uses such as magnetic sensors and electromagnetic interference (EMI) shielding.
- The mechanical strength, durability, and flexibility of the polymer matrix can be improved by adding nanoparticles.
- Composites are advantageous in high-temperature applications because they frequently show superior thermal stability than pure polymers.
- Ferrite nanoparticles' surfaces can be functionalized to modify the composite's characteristics for particular uses, such catalytic activity or targeted drug administration.
- Since polymers are often simple to work with and form, intricate structures and forms can be created for a wide range of industrial uses.

b. Negative aspects

- Ferrite nanoparticles have a propensity to congregate because of van der Waals and magnetic forces, which can be detrimental to the qualities of the composite.
- Incompatibilities between the polymer and the nanoparticles could result in inadequate interfacial adhesion and dispersion.
- It can be costly to produce superior ferrite nanoparticles and incorporate them into polymers.

C. Overcoming Obstacles

- The dispersion of ferrite nanoparticles inside the polymer matrix can be enhanced by functionalizing their surface with coupling agents or surfactants.
- The distribution and interaction of nanoparticles within the polymer can be improved by employing methods including melt blending, sol-gel procedures, and in-situ polymerization.
- Creating hybrid composites by combining various nanoparticle kinds or employing copolymers helps tackle compatibility and performance issues.

4.2 Future scope

❖ Future applications of ferrite nanoparticles, including polymer-ferrite nanoparticle composites and doping, are numerous and bright, with potential breakthroughs in a number of crucial fields, including

❖ Enhanced drug delivery methods, tailored cancer therapies, biocompatible polymer-ferrite composites for theranostics, and advanced imaging techniques are examples of advanced biomedical applications.

❖ Next-Generation Electronics: Using optimized composites, high-performance, flexible, and wearable electronic devices with enhanced data storage capabilities, sensor technologies, and EMI shielding are developed.

❖ Environmental Remediation: Utilizing the enhanced characteristics of doped ferrite nanoparticles in polymer matrices, more effective and selective catalytic processes and pollutant removal systems are developed.

❖ Energy Conversion and Storage: Advancements in battery and supercapacitor technologies that result in increased energy densities, quicker cycles of charge and discharge, and improved thermal control using sophisticated composite materials.

❖ Smart Materials: Using the special qualities of doped ferrite nanoparticles in polymers, materials that are responsive to environmental stimuli are created for robotics, aerospace, and smart infrastructure applications.

Significant technical breakthroughs and novel applications from this research could inspire interdisciplinary study and industrial advances in the future.

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