UMYU Scientifica, Vol. 3 NO. 4, December 2024, Pp 063 – 087
https://doi.org/10.56919/usci.2434.007
ISSN: 2955 – 1145 (print); 2955 – 1153 (online)
*A periodical of the Faculty of Natural and Applied Sciences, UMYU, Katsina*

**REVIEW ARTICLE**

# Review of Magnetic Nanoparticles: From Synthesis and Design to Applications

Nnaji Precious Chinyere[1], Nnaji Joshua Nnaemeka[3,4], Suleiman Zakari[1,2,5], Doris Nnenna Amuji[1,2] and Olubanke Olujoke Ogunlana[1,2]
[1]Department of Biochemistry, College of Science and Technology, Covenant University, Ogun State, Nigeria
[2]Covenant Applied Informatics and Communication - Africa Centre of Excellence (CApIC-ACE), Covenant University, Ogun State, Nigeria
[3]Department of Chemistry, Alex Ekwueme Federal University, Ndufu Alike Ikwo, Ebonyi State, Nigeria
[4]Department of Chemical and Minerals Engineering, North West University, South Africa
[5]Department of Biochemistry, College of Medicine, Federal University of Health Sciences Otukpo, Benue State, Nigeria

## ABSTRACT

It is believed that among others, magnetic nanoparticles possess the ability for stability, biocompatibility, and cost-effectiveness in biomedicine. Despite many types of magnetic materials, including non-noble metals like iron, cobalt, and nickel, the potential applications seem not to have been as explored as with noble metals like gold. This review aimed to give a broad overview of magnetic nanoparticles, more so their synthesis, characterization, and various applications in disease detection, such as cancer diagnostics. This was a literature review design; the data were sourced from peer-reviewed articles published within the last ten years. The criteria for selecting studies included that they had to directly address magnetic nanoparticle synthesis, design, and application. For this purpose, databases such as PubMed, Scopus, and Google scholar were tapped into to ensure the widest possible relevant coverage. Different approaches, such as chemical or mechanical ones, are used to create magnetic nanoparticles. The paper outlines the advantages of magnetic nanoparticles in the treatment of diseases. Furthermore, as most of the categorization techniques now in use are found to be inaccurate and unreliable, they have now shown certain flaws. Therefore, the use of magnetic nanoparticles in biomedical applications, especially in diagnosing and treating diseases, holds great promise. However, improvement in the methodology for the classification of nanoparticles is quite necessary. Such standard protocols for synthesizing and characterizing magnetic nanoparticles should be developed in the near future, with new therapeutic applications being explored in this domain.

## ARTICLE HISTORY

Received June 29, 2024
Accepted October 12, 2024
Published October 16, 2024

## KEYWORDS

nanoparticles; synthesis methods, biomedicine, magnetic nanoparticles, disease detection

## INTRODUCTION

Nanotechnology is a broad science that encompasses chemistry, physics, biology, and engineering disciplines. These conventional disciplines inspire magnetic nanoparticles in the physics of their magnetic capabilities, the surface functionality of chemistry, and their application in various biomedical applications (Clemons *et al.*, 2019). The current trends in nanoparticles play a pivotal role in pharmacokinetic properties enhancement of therapies, increased blood flow time and targeting, and incorporating imaging agents within the nanoconstruct suitable for imaging in healthcare. MNPs, or nanoparticles with magnetic properties, play a major role in the illness diagnostic and therapeutic field, especially in cancer, via modification using a variety of substances. MNPs present a category of noninvasive nanomaterials with many useful characteristics, such as Being stable, biological compatibility, and pharmacological payload capacity (Mehta & Pardeshi, 2023). The specific characteristics of MNPs depend on the synthesis circumstances. As a result, Analyzing nanoparticles in the context of the physical and chemical properties they have gained is essential during the manufacturing process (Lu et al., 2004).

Significant progress has been made in how we create and design MNPs in recent years (Stiufiuc & Stiufiuc, 2024). These tiny particles can now be engineered to serve multiple functions at once. For instance, they can deliver drugs to specific body parts and enhance imaging techniques, making it easier to monitor and diagnose diseases in real-time. Innovations in how we coat and modify these particles have also improved their safety and effectiveness. Despite these advancements, some important challenges still need to be addressed (Schneider-Futschik & Reyes-Ortega, 2021). One major issue is that no standard method exists for creating MNPs with

**Correspondence:** Nnaji Precious Chinyere. Department of Biochemistry, College of Science and Technology, Covenant University, Ogun State, Nigeria. ✉ precious.nnajipgs@stu.cu.edu.ng. Phone Number: +234 705 833 9338

**How to cite**: Nnaji, P. C., Nnaji, J. N., Zakari, S., Amuji, D. N., & Ogunlana, O. O. (2024). Review of Magnetic Nanoparticles: From Synthesis and Design to Applications. *UMYU Scientifica*, 3(4), 63 – 87. https://doi.org/10.56919/usci.2434.007

consistent properties. Differences in the dimensions, form, and surface layer of these particles can affect their performance, which makes it harder to use them reliably in clinical settings. Additionally, while we have made strides in developing multifunctional MNPs, we still need more research to ensure that the particles are safe for long-term use and do not have harmful effects.

This review attempts to give a straightforward and comprehensive summary of the current condition of MNPs, focusing on the synthesis, design, and applications of multifunctional MNPs. It will critically assess recent advancements and highlight the challenges faced in the field.

## SYNTHESIS OF MAGNETIC NANOPARTICLES

Materials with the necessary magnetic characteristics, primarily employed for biomedical applications, are represented by magnetic iron oxide nanoparticles. The three main benefits are affordability, stability, and compatibility (Tadic *et al.*, 2014). Low-cost, environmentally safe, biocompatible, and possessing sufficient chemical and physical stability are some of the qualities of nanostructures of attract iron oxide. Defining parameters for the various NP qualities is mandatory to manufacture quality assurance and attain the necessary results for various applications. Typical forms (Figure 1) of these nanoparticles (NPs) with modified surface chemistry include Fe3O4 (magnetite), textiles, ferrofluids, and magnetic iron oxide (Bossmann & Wang, 2017).

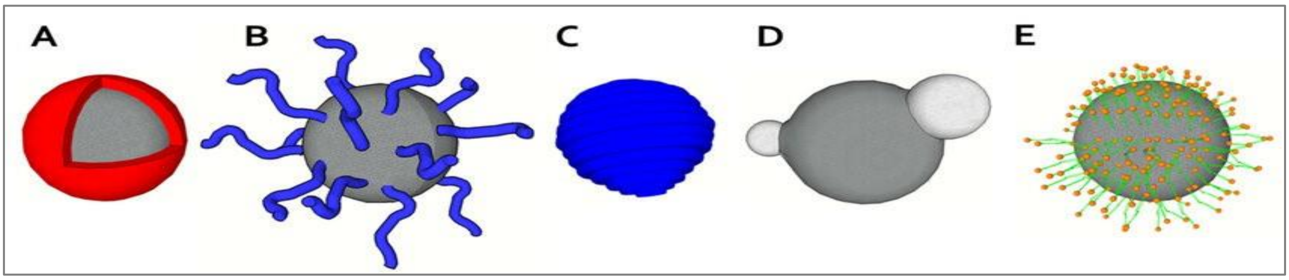

**Figure 1:** Magnetic coating techniques and particle architectures. The magnetic particles can be categorized as (A) end-grafted polymer coated, (B) heterodimer magnetic particles, (C) contained in a polymer coating, (D) hydrophilic magnetic particles within the lipid bilayer, (E) hydrophobic magnetic particles encased Inside the lipid monolayer (top section), inside the lipid monolayer (top segment), and core-shell.

These materials may find extensive industrial use in computer and sensing materials, Ferrofluids, textiles, remediation for the breakdown of emerging pollutants, and herbicides. It is believed that these materials possess intrinsic magnetic characteristics. Because of their chemical makeup and biocompatibility, the biological field of heat cauterization therapies, imaging, and diagnostics for deficiencies in iron anemia and medication delivery. The specific characteristics of MNPs depend on the synthesis circumstances. As a result, nanoparticles are analyzed in the context of physical and chemical characteristics acquired during manufacturing (Lu et al., 2004).

Compared to most other nanomaterials, MNPs have an elevated percentage of area covered relative to volume, indicating that they have special qualities not seen in bulk material, like a lower melting point, a reduced temperature during sintering, and special magnetic features. Several morphologies may emerge from the synthesis process and related factors, variables time to react, pressure equal to and temperatures, reagent the casting procedure, etc., which may change the magnetically charged, surface functionalized, and physicochemical properties of MNPs (Ramaswamy *et al.*, 2015). The magnitude of a ferromagnetic nanoparticle has a significant impact on its behavior. It changes from a multidomain particle to only one magnet subject nanoparticle and then to a superparamagnetic nanoparticle as the size is decreased. Functionalized materials can exhibit all latter properties through a range of synthetic processes that regulate the form and coating (Nurettin *et al.,* 2021). Differential synthesis processes (Table 1) have been developed employing parameters such as biologic support, temperatures, and atmospheric pressure to produce different MNP growing crystals, patterns, diameters, charges on the outside, and saturation in magnetic fields.

These methods use a range of apparatus, from basic ultrasonic baths to complex microwave devices. Certain MNP functionalities can be obtained via these channels for various applications.

### Making Magnetic Nanoparticles Synthesized under wet-chemical

#### *Co-precipitation synthesis*

Coprecipitation is the most effective method for simplifying synthesis (Figure 2). Adding basic-pH solution at room temperature or above can rapidly convert a basic molecular ratio of ferric to ferrous: 1:2 sodium chloride into MNPs ($Fe_3O_4$ and $\gamma$-$Fe_2O_3$). This procedure is well-known, simple, inexpensive, and straightforward (Kavre et al., 2014). Most processes could benefit from an inert gas environment to prevent further oxidation and preserve their magnetic qualities. The size, form, and composition of the magnetic particle are affected by the ferric/ferrous ratio, the salt used (which may consist of nitrates, sulfates, or chloride compounds), the degree of temperature at which the reaction takes place, the pH level, and the amount of ionization of the medium. The intrinsic value

**Table 1:** Various synthetic pathways for the production of MNPs

| S/N | Synthetic Pathway | Description | Reference(s) |
|---|---|---|---|
| 1 | Co-precipitation synthesis | A method where metal salts are mixed in a solution, leading to the simultaneous precipitation of nanoparticles. | Liu et al. (2016); Gupta et al. (2017) |
| 2 | Thermal decomposition | Involves the thermal breakdown of organometallic precursors to form nanoparticles at high temperatures. | Wang et al. (2015); |
| 3 | Sol-gel synthesis | A chemical process that transforms a solution (sol) into a solid (gel) to create nanoparticles through hydrolysis and condensation reactions. | Brinker & Scherer (1990); |
| 4 | Microemulsion synthesis | Involves using microemulsions as templates to create nanoparticles, allowing for controlled size and morphology. | Hyeon, T. (2003) |
| 5 | Flame spray synthesis | A technique that uses a flame to vaporize metal precursors, which then condense into nanoparticles upon cooling. | Sattler et al. (2007); Ghosh et al. (2021) |
| 6 | Biological derivatives | Involves using biological materials, such as plant extracts or microorganisms, to synthesize nanoparticles through green chemistry methods. | Green et al. (2016); Shankar et al. (2019) |

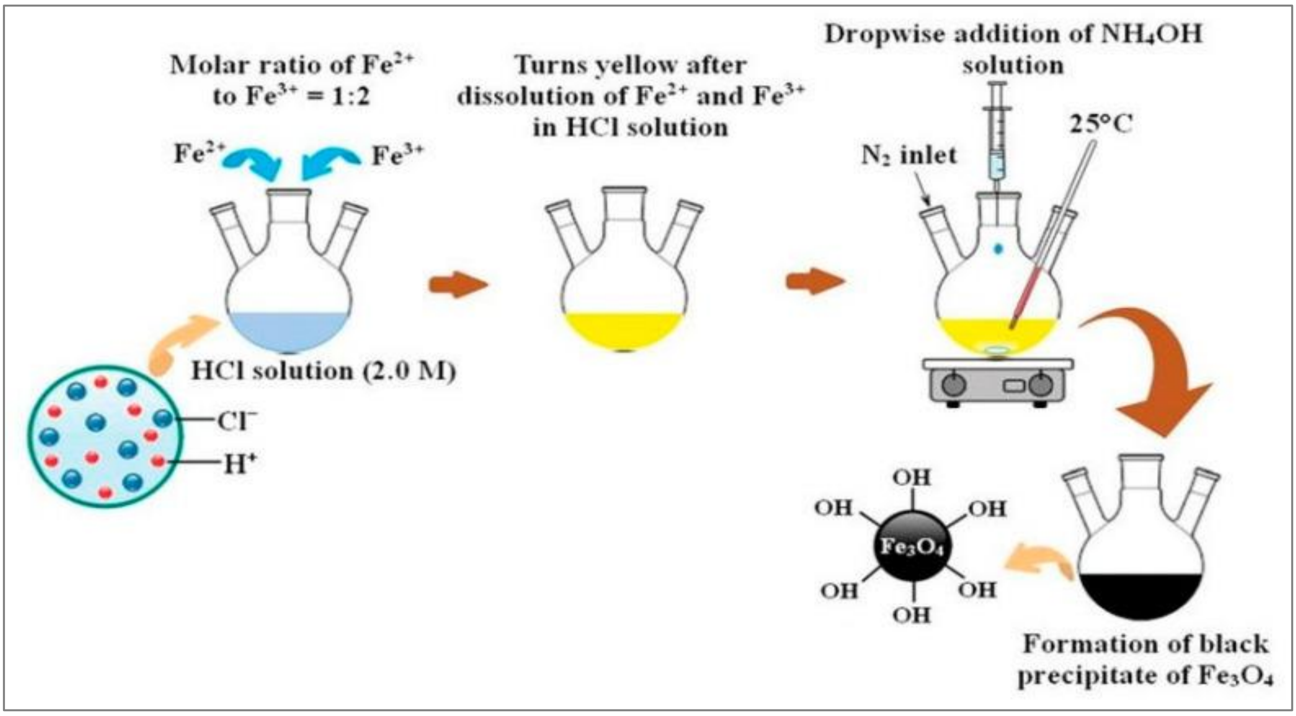

**Figure 2:** Diagram showing the co-precipitation method's production of magnetite (Hyeon, 2003)

of the magnetic particles is fully repeatable if the synthesis circumstances are regulated (Mornet et al., 2006). However, the ability to regulate The fast generation of particles reduces the particle's dimension properties. The coprecipitation process generates a higher output of MNPs with substantial magnetic characteristics (50 to 90 Am2kg−1) compared to alternate synthesis methods but with less control over form and size (Gleich & Weizenecker, 2005).

The following reactions were suggested as the magnetite production mechanism. Ferric and ferrous hydroxides precipitate in the water solution during the first stage:

$Fe(OH) = Fe_3^+ + 3OH_3^-$. (1)

$Fe(OH)_2 = Fe_2^+ + 2OH-$ (2)

In the subsequent phase, ferric hydroxide breaks down into FeOOH:

$Fe(OH)_3$ equals $H_2O + FeOOH$ (3)

Ultimately, magnetite is formed through a solid state interaction between $Fe(OH)_2$ and FeOOH amid them:

$Fe_3O4 + 2H_2O = 2FeOOH + Fe(OH)_2$, (4)

Here is the general response:

$Fe_3O_4 + 4H_2O = 2Fe(OH)_3Fe(OH)_2 \rightarrow 2Fe^{3+} + Fe^{2+} + 8OH-$, (5) (Elliott & Zhang, 2001)

Numerous parameters, such as the mole ratios and starting concentrations of ferric and ferrous salts, affect the quantity and shape of magnetite nanomaterials. The frequency and duration of mixing, the room temperature of the responses, the existence or lack of a magnetized environment and microwave irradiation, the type and concentrations of the base solution, etc. (Philip et al., 2008).

**Thermal decomposition**

One possible method for creating monodispersed tiny magnetite nanoparticles without particle aggregation is the thermal breakdown of precursors of organometallic substances in various solvents (water and organic) with high boiling temperatures and stabilising agents (Philip et al., 2008). The nucleation process has allowed the development of several synthesis variants that can synthesize MNPs with controlled dimensions. Furthermore, the formation of nanocrystals can be aided by encouraging the adsorption of compounds such as the ligand pair oleic acid–oleylamine. This technique is motivated by fabricating superior semiconductor oxides and nanocrystals via thermal breakdown in a wet-chemical medium (Chaudhary et al., 2017). As a consequence, It is possible to produce tiny superparamagnetic nanostructures.

In contrast to coprecipitation, the nucleation condition used in this approach permits particle separation from growth, averting a more complex reaction pathway that can lead to oxidation. Regarding proper morphological control and size, the thermal breakdown synthesis process is widely considered to be among the best. Powerful magnetic characteristics (40 to 90 Am2kg−1), high yield, and particle size control are all made possible by thermal breakdown, where oxygen concentration plays a major role in producing the necessary iron oxide structure (Mahendran & Philip, 2012).

**Hydrothermal synthesis**

Hydrothermal synthesis is the most widely used process for creating NMs. In short, hydrothermal synthesis is a technique for producing single-crystal nanoparticles that do not require the high temperatures and pressures of traditional crystal-making synthesis; rather, it is contingent upon the water's solubility as an aqueous solution. In essence, Solution-reaction chemistry is the foundation for this synthesis method (Chaudhary & Ramanujan, 2016). Hydrothermal synthesis allows NMs to be produced at room temperature or between 130 and 250 °C. The synthesized compounds' shape can be adjusted during the method by utilizing different vapor pressures, ranging from 0 to 3-5 MPa (Chaudhary et al., 2019). This can help the source material crystallize in a tight enclosure and significantly enhance the preferred development of specific MNP planes. But still, in contrast to other, more straightforward, and affordable synthesis methods, the high pressures and temperature destroy the MNPs' magnetic characteristics (Philip et al., 2013).

**Sol-gel synthesis**

Sol-gel synthesis is a well-known and often used wet-chemical method in the field of materials sciences and engineering that is mostly used to create NM (typically metal oxides). Usually, it starts as a suspension of colloidal particles that forms the foundation of a comprehensive isolated particle network. A gel gives the system structure, a continuous three-dimensional framework surrounding the colloidal liquid component and a sol phase, which is a constant dispersion of colloidal fragments in a solvent. The network is made up of a network of colloidal particles of a colloidal gel. Sub-colloidal aggregates agglomerate to form a polymeric sub-structure within the particles of a polymer gel. MNPs have various benefits over the previous hydro or wet-chemical syntheses methodology because they feature hydrophilic ligands on their outermost layers that are used for surface coating and to offer the sol-gel reaction excellent control over size and form (Guerrero et al., 2001).

However, compared to other techniques like coprecipitation, sol-gel synthesis yields less, is more expensive for reagent precursors (alkoxides), and does not adequately extract magnetite structure. Iron precursors are hydrolyzed and polycondensed in the Sol-gel technique, a wet chemical process that yields a colloidal solution of the particles (called a "sol") (Kralj et al., 2010). After that, the mixture is dried (called a "gel") to extract the solvent and create magnetite nanoparticles. Shaker et al. described magnetite nanoparticles annealed at 200, 300, and 400 °C using the sol-gel method. The characterization results demonstrated that varying the annealing temperature might alter the magnetite nanoparticle size. They claim that the synthesis method is inexpensive and ecologically safe and that Various annealing temperatures can produce size-controlled magnetite nanomaterials. These are the benefits of the sol-gel technique for producing magnetite nanoparticles. Takai et al. showed how to synthesize magnetite nanoparticles using sol-gel and then anneal them at various temperatures (200–400 °C) in a vacuum (Kralj et al., 2012). Altering the annealing temperature was sufficient to produce magnetite nanoparticles of various sizes. The particles that were obtained at 400°C have more spherical morphologies. The mean particle size of the nanoparticles produced increases with temperature. Sol-gel synthesis has several benefits, including monodispersed excellent regulation of microscopic structure and size of particles, the capacity to produce products with desired lengths and shapes, high purity, and good crystallinity. This method's drawbacks include the result becoming contaminated with the matrix component, its lengthy completion time, and the use of hazardous organic solvents (Grass et al., 2007).

### Sonochemical synthesis

Ultrasonic irradiation is applied to cause acoustic cavitation in the solution of water, which starts the chemical reaction through the sonochemical procedure. This type of cavitation forms bubbles that expand and burst, releasing a large amount of energy and increasing temperature and pressure. This technology may be used to synthesize magnetite nanoparticles (Johnson et al., 2010). When utilizing the homogenous co-precipitation technique with sonochemical assistance to create MNPs, De Freitasa et al. reported because of the size of the resultant nanostructures of approximately 35 nm. The scientists discovered that a higher power was necessary to produce the smaller diameter nanoparticles and that they could produce iron oxide nanoparticles at a pH lower than 6. It was found that ultrasonic energy speeds up the process. Wang et al. used a combination precipitation helped by an ultrasonography approach to control the size (~15 nm) as well as the distribution of magnetite nanoparticles. About 50 A/kg was the saturation magnetization of the resultant nanoparticles (Grass & Stark, 2006). However, because of the size difference, the scientists discovered that the generated nanoparticles' magnetic properties were inferior compared to those made without ultrasound's help. Fuentes-García and associates devised a rapid, one-step sonochemical approach for the environmentally friendly production of magnetite nanoparticles, employing iron sulfate serving as the sole source of iron and sodium hydroxide acting as a reducing component in an aqueous medium. They stated that the concentration of sodium hydroxide was adjusted to maximize the magnetite nanoparticles' ultimate size and magnetic characteristics and reduce the quantity of corrosive reaction byproducts. The generated MNPs can be uniformly sized and shaped within the ≈20−60 nm range according to the suggested approach, which bodes well for its prospective application in soon-to-be biological fields (Fang et al., 2011). The sonochemical process has the advantage of accelerating the rate of reaction while decreasing the formation of crystals. Saturation magnetization, High crystallinity, and narrow-size distribution nanoparticles could be obtained. Nevertheless, it is challenging to regulate the size and form of the resulting nanoparticles since the mechanism underlying this activity is still poorly understood (Zhang et al., 2013).

### Microemulsion synthesis

The production of micro- and nano-NMs via self-assembly has garnered interest in recent years because of their unique features resulting from alterations in physical and physical-chemical characteristics at the micro- and nanoscale compared to their bulk material counterparts. A surfactant stabilizes a dispersion of two immiscible liquids that are thermodynamically stable and isotropic, typically based on an oil substance and water (Reeves & Weaver, 2012). It comprises various arrangements and permutations that correspond to different capabilities of forming colloidal systems (Figure 3). Depending on the target material, the surfactant that regulates the produced domains is a key interaction to consider and should be chosen carefully. We have produced iron oxide nanoparticles using this technique. Iron ionic precursors, like chlorides, can be added to a basic pH medium, like ammonium, after being absorbed in liquid to provide an accessible environment that can lead to the necessary particle condensation. This method offers the ability to regulate the dimensions of the nanoparticles by controlling the proportion of water to surfactants via both the amount of precursors and the available space in the resulting solution. It involves a chemical reaction that transforms solubility precursors into insoluble ones in the aqueous phase. Microemulsion can produce monodispersed nanoparticles with reasonable control over size and form despite its low-efficiency output, low magnetic properties (20 to 60 Am2kg−1), and poor magnetite presence (Weizenecker et al., 2009).

### Flame spray synthesis

The coating techniques known as thermal spraying include the spraying of heated or melted materials onto a surface. Heat is applied to the "feedstock" (coating precursor) using either chemical (combustion flame) or electrical (plasma or arc) methods. Heat spraying can produce thick coatings (in comparison to other coating techniques like electroplating, mechanical vapor deposition, and chemical vapor deposition, about 20 microns to several mm, dependent on the method and material) over a broad region at a rapid rate of buildup. Heat spraying is an option to coat materials made of composite metals, alloys, ceramics, and polymers (Reeves & Weaver, 2014). In the form of wire or powder, micrometer-sized particles are added, heated to a molten or semi-molten state, and then guided toward surfaces. Thermal spraying typically uses one of two energy sources: combustion or electrical arc discharge (Figure 4). The aggregate formed by multiple sprayed particles creates the coatings. It's possible that insufficient warming of the surface will cause flammable materials to build up on it. The most common methods for assessing the quality of a coating are measurements of its Surface texture, permeability, oxide concentration, bonding capacity, and both macro- and small-scale hardness. Particle velocities frequently result in better coating quality (Reeves, 2017).

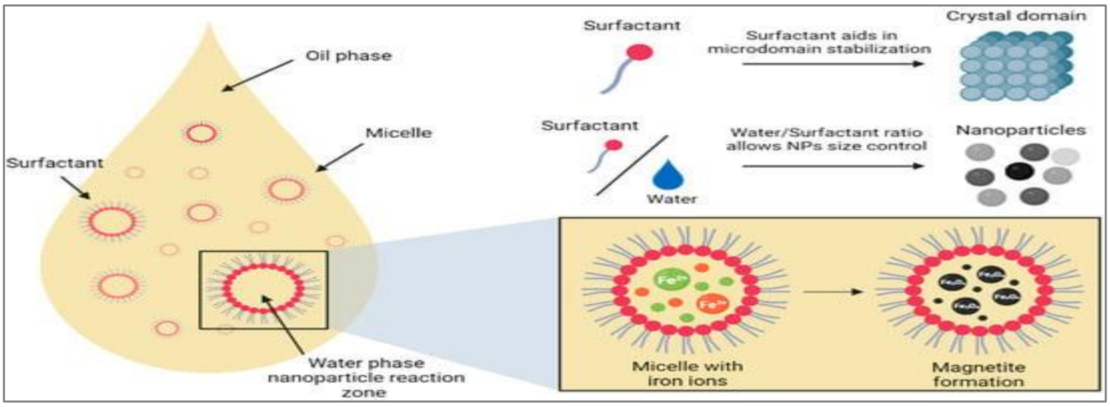

**Figure 3:** Sample micro-domains in microemulsions representing the two immersible phases(Carrey et al., 2011).

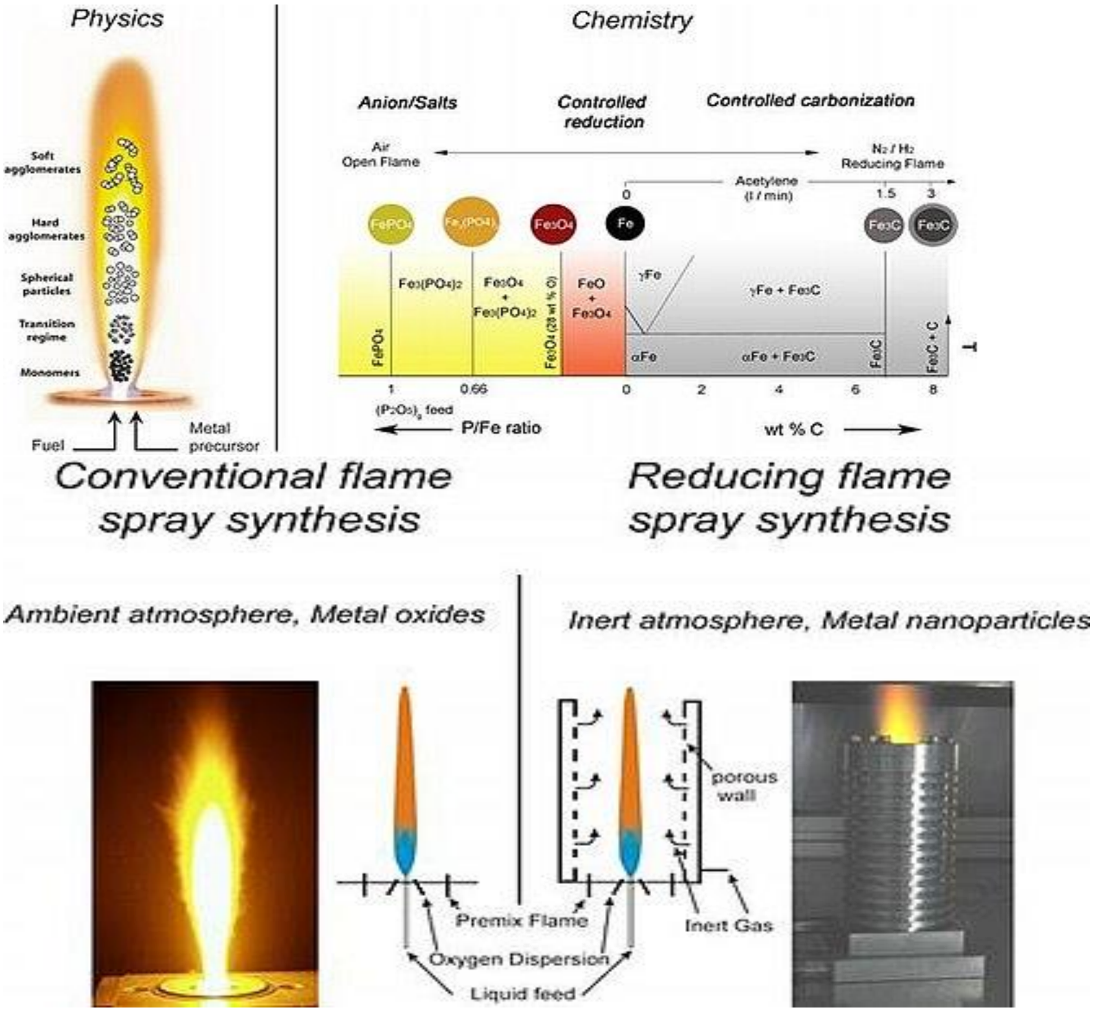

**Figure 4:** Different flame spray settings and how they affect the final nanoparticles(Elaissari et al., 2009)

**Production of magnetized nanoparticles via biological means**

Blakemore discovered magnetotactic bacteria in 1975, which might also be used to synthesize MNPs. The "biologically controlled mineralization" process produces iron oxide nanoparticles (NPs) encased in a lipid bilayer membrane known as a magnetosome. These days, MNP synthesis may be accomplished using certain cultivated strains of magnetotactic bacteria. MNPs are homogeneous in their chemical makeup, morphology, and crystal size across all strains. Within the magnetosomes of cultivated strains, magnetite crystals can take the shape of a combination of a cube, the prism of a cuboctahedron, or a round object and dodecahedron[36]. Chemically produced nanoparticles lack some characteristics of molecularly manufactured ones. Their morphology is homogeneous, their size distribution is narrow, and their magnetite crystallinity is high. Since these particles are usually singular magnetic domain nanoparticles, They have a thermally resistant magnetic field at physiological temperatures. The bacteria have a high rate of internalization within human cells because of how their magnetosome chains are arranged inside them, inhibiting aggregation[37].

Currently, a number of researchers are working to develop NP synthesis experimental protocols that are dependable, hygienic, and acceptable to the environment. One highly promising approach is the manufacture of NPs using different biological components, including plant derivatives. Controlling synthesis, size, magnetic properties, morphology, and other aspects sometimes requires sacrificing structure during oxidation and other thermic processes. Fe(III)--reducing bacteria are Thermoanaerobacter, SAR324, and Bdellovibrionota. Magnetosomes are domain-specific iron oxide nanoparticles that are produced biologically by magnetotactic bacteria through a process known as biomineralization. Proteobacteria (alpha, eta, zeta, and gamma), a species of Phoenix dactylifera, are generally grown at 65 °C from a ferric oxyhydroxide precursor. Afterward, a living membrane that controls the shape and size of the magnetosome encloses 5–140 nm-sized magnetite crystals(Heydari et al., 2015). An alternating high-frequency magnetic field is applied to sick tissue after nanoparticles have been introduced, a procedure known as heat exhaustion of magnetic fluids (MFH).

One important tool for killing the malignant cells might be the heat generated. It is believed that blood circulation within the tissue is a particularly complicated aspect of the MFH that needs to be considered when assessing the MFH. This work aimed to investigate the heat transfer of fluid-flowing agar gel experimentally. Fe3 O 4 was added as a nanoparticle to the gel's core. Furthermore, it was subjected to 3600 (s) of changing magnetic field at a frequency of 50 (kHz) and 7.3 (kA/m) while being embedded with extra cylindrical gels. The gel's temperature The measurements were taken thrice. Implementing the thermodynamic distributions was determined by the experimental data.

Furthermore, the time differential temperature function was used to calculate the specified absorption rate (SAR) at t = 0 based on research information. A model that was created using the finite element technique (FEM) was utilized for checking the SAR function. The findings illustrated the influence of fluid movement and the SAR function's precision for gel generation of heat. Bacteria include magnetosomes grouped in constrained down-size distribution chains throughout the crystal plane. One mechanism that might contribute to the environmentally friendly production of NMs is the capacity of living organisms to transform metals and oxides into certain structures during their metabolism.

Moreover, biological materials like fungi, plants, bacteria, etc., can be used to create MNPs. The process of biological synthesis is non-toxic, efficient, and environmentally benign. The result is greater agglomeration and decreased homogeneity and stability of the generated particles. For MNPs, this is the main green synthesis scheme. Magnetosomes were easily functionalized due to the lipid coating that gives their surface a negative charge. They are very biocompatible and do not harm living things in any way. Due to all of the benefits listed below, magnetotactic bacteria make an excellent substrate for creating magnetite nanoparticles (Heydari et al., 2015).

To make MNP, a green substrate comprising biological molecules is combined with precursor salts. Green substrates can settle particulates along the synthesis process by serving as limiting and decreasing agents. Variations in the amounts of the precursor salt and green substrate, in addition to changes in the temperature, time, and pH of the synthesis, may produce NPs with different properties. This method is not only easy to employ, but it's also affordable, waste-free, and good for the environment. Because the MNPs produced by this process are coated with the ecological components of the greener substrate that are biocompatible and harmless, they can be used in biomedical applications. (Sharifi et al., 2012). Furthermore, as several phytoremediation investigations have shown, certain plant species can either reduce metallic ions in various organs to build metal oxide structures or hyper-accumulate them in tissues to form nanoparticles. As a result, different plant extracts, such as those derived from fruits, seeds, roots, leaves, and stems, have been used to create nanoparticles (Figure 5).

Utilizing plant extracts in their natural state is a very economical and environmentally responsible method. (Meng et al., 2011). For this method, no intermediate base groups are required, such as mercaptoundecanoic acid (MUA), sodium cholate, cetyltrimethylammonium bromide (CTAB), oleic acid, or polyvinylpyrrolidone (PVP). Furthermore, costly equipment and precursors are superfluous. Plant extracts are rich in metabolites, including phenolic chemicals that can reduce ions. For this reason, most of the research on using these extracts to produce MNPs has focused on using the leaves as the extract source. A number of considerations must be made regarding the solvent, the vegetative source, the extraction techniques, the response time, and exogenous industrialized chemical substances used in the production of NMs by leaf extractions.

MNPs are more biocompatible and colloidally stable when compared to typically functionalized with a variety of materials, including silica, iron oxides, phosphate, chitosan, albumin, polyethylene glycol, and citrate. This is because, once exposed to physiological in-nature fluids, uncoated MNPs exhibit an adverse effect and a propensity to flocculate (Colombo et al., 2012). To gain an understanding of how MNPs respond in relevant cultural media, we will measure the volume and zeta potential of MNPs over time in a variety of media, including phosphate buffer, cultural medium, and media including or lacking FBS. Despite being a novel method of producing NPs, the primary issues with the manufacturing process are that it is energy-intensive, and reactions that occur take a lengthy period. Thus, it is difficult to obtain precise chemical reactions in order to identify the processes that underlie the biosynthesis process (Schätz, Grass, et al., 2010).

$Fe_3O_4$, or iron oxide magnetite, has an inverse spinel structure. Among the initial crystalline structures found by the X-ray diffraction method was presented in 1915 by W.H. Bragg, who also identified the intricacies of its structure. Magnetite is an iron oxide with mixed valences of $Fe^{3+}$ and $Fe^{2+}$, and its stoichiometry is $Fe^{2+}/Fe^{3+} = 0.5$. The lattice constant of its cubic unit cell is A = 0.839 nm. There are two crystallographic locations for iron ions in the spinel crystal lattice, which is its main characteristic. Four ions surround the tetrahedral sites, while six ions surround the $Fe^{2+}$ and half the $Fe^{3+}$ octahedral sites (Figure 6). Magnetite's non-stoichiometric nature often results in a cation-deficient $Fe^{3+}$ layer. To modify the lattice constant, substitute other divalent ions ($Mg^{2+}$, $Co^{2+}$, $Ni^{2+}$, etc.) for part or all of the $Fe^{2+}$(Schätz et al., 2008).

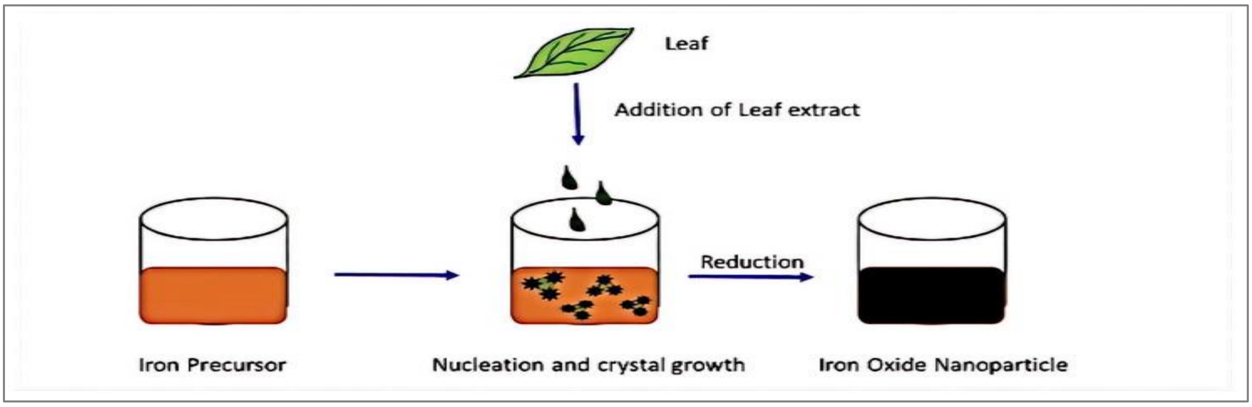

**Figure 5:** Synthesis of magnetite nanoparticles with plant extracts (Javidi et al., 2015)

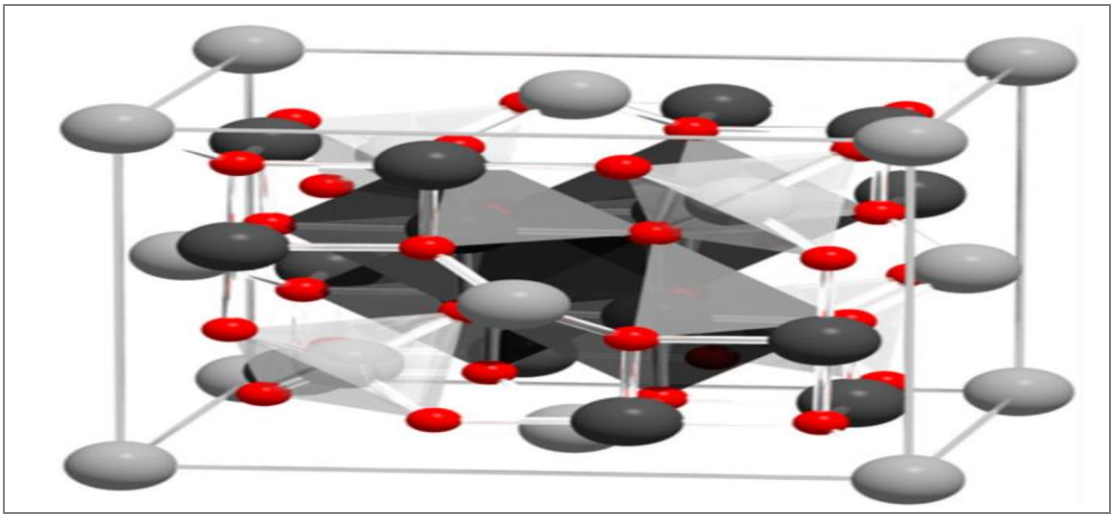

**Figure 6:** The magnetite unit cell was observed with oxygen (red), tetrahedral Fe2+ (light grey), and octahedral Fe2.5+ (dark grey). The unit cell's fully coordinated Fe sites' octahedral and tetrahedral geometries reveal the local site symmetries. A bulk ferrimagnetic state results from the tetrahedral and octahedral sites exhibiting dominant antiferromagnetic coupling due to the differing bond angles between the Fe sites (Yoon et al., 2003).

Magnetite's crystal structure dictates its magnetic characteristics. A unique relationship that exists between the electrons in the third-d shells of the surrounding cations is specifically responsible for the sorting of iron cation magnetic spin moments in the crystal lattice. The entire magnetic ordering in magnetite is determined by the sequential arrangement of magnetic spin moments. Magneto crystalline anisotropy is a particular type of magnetic anisotropy seen in magnetite that is associated with spin-orbit coupling (Panahi et al., 2017). Magneto crystalline anisotropy, a critical component of magnetite's magnetic ordering, is governed by the crystal's structure, morphology, and composition.

In contrast to ferrites, magnetite's distinct magnetic and structural characteristics are also linked to the existence of "hopping electrons". In short, $Fe^{2+}(3d6) \leftrightarrow Fe^{3+}(3d5)$ represents the 3d electron transfer that takes place in the $Fe^{2+}$–$Fe^{+3}$ octahedral cation pair. One of the main factors affecting magnetite's magnetic properties is a greater concentration of electron hopping compared to spinel ferrites, which possess comparable lattice configurations. In summary, magnetite exhibits ferrimagnetic properties at ambient temperature and has a relatively large saturation magnetic resonance value of 92 A·m2/kg, 580 °C is its Curie temperature.

**Steps involved in synthetic magnetic nanoparticles**

The process of generating nanoscale MNPs and then dispersing the final nanoparticles into liquid media (Figure 7). Two different kinds of magnetic liquids are produced, based on the colloid stabilizing procedure that is employed: fluids based on water and fluids based on organic surface. Additives, a carrier liquid, and a magnetic phase are the typical components of FFs. In Ferrofluids, one of the most common magnetic phases is nano-sized iron oxide. To create and examine superior magnetic iron oxide nanoparticles, several techniques were used. These nanoparticles exist in liquid, gas, and solid phases. Solid (Schätz, Reiser, et al., 2010).

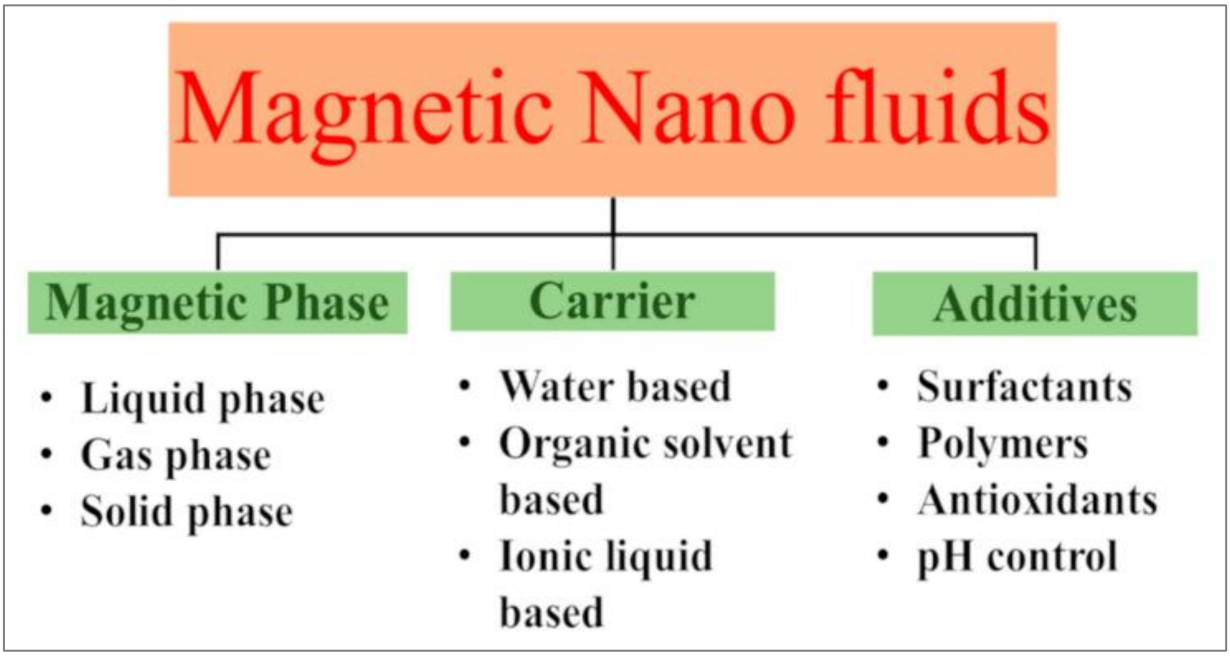

**Figure 7:** Diagram showing the steps involved in making magnetic Nanofluids (Wang et al., 2007).

Microemulsion, acoustic-chemical, thermal decomposition, microwave, and co-deposition methods can all be used to create MNPs in the liquid phase. They are obtained in the solid phase by annealing and burning; in the gas phase, they are generated by arc discharge, chemical gas-phase deposition, and laser pyrolysis. One alternative possibility is to put a magnetic powder that has been ground to micron size in a ball mill for a few weeks, along with a dispersion and solvent (Hou, Sun et al., 2007). One-step and two-step processes are commonly used to create nanofluids. The ferrofluid preparation and nanoparticle synthesis are combined in the one-step process. The second phase of the two-step process consists of producing the nanoparticles and then dispersing them in an appropriate carrier fluid (Figure 8). Magnetic granules are suspended in a carrier liquid with a moderate performance. Agglomeration and coagulation need to be avoided during the synthesis of FFs in order to protect the colloid nanoparticle from oxidation as well as throughout their transition entering the fluid carrier's colloidal stage. These fluids are made up of a variety of carrier liquids, including combinations of these and many other polar liquids, as well as kerosene, mineral oil, silicone oil, water, lubricating oil, and synthetic or semi-synthetic oil. The components of the device, as well as the carrier liquid, need to be magnetic phase resistant (Hou, Xu, et al., 2007). Other solvents, particularly ionic liquids, were looked into as potential replacements for the conventional alcohol- and water-based FFs. It appears from recent studies on FFs with ionic liquids that such an endeavor could be a worthwhile area of study. Rodriguez-Arco et al. claim to have produced magnetic fluids consisting of Ionic liquids with dispersed magnetite nanoparticles with various additives. The most direct way to provide steric repulsion, which was necessary for ionic liquid-based FFs to stay stable over time, was to use surfactants that were adsorbed on the particle surface and whose tails corresponded with the liquid carrier's (Chinnasamy et al., 2008).

Dispersants are needed during the synthesis of FFs in order to reduce particle agglomeration and improve colloidal stability two crucial FF application factors. The characteristics that nanofluids must have are stability, robustness, and a low tendency to clump together. Additionally, the dielectric properties of the carrier liquid must be taken into consideration while selecting additives. A common stabilizing agent for MNPs produced by the conventional co-precipitation technique is oleic acid (OA). Oleic acid is used with tartaric and citric acids to stabilize FFs throughout a broad pH range (pH 3–11). By keeping the particles from adhering to one another, polymers like ethylene glycol, polyvinyl alcohol (PVA), chitosan, and silica are capable of being added to nanoparticles to increase their dispersibility in aqueous solutions. It may be possible to stop oxidation by adding antioxidants. pHregulating additives are also necessary for FFs with a water base. Effective ways to lessen agglomeration and enhance the dispersion behavior of nanoparticles include the addition of surfactants and ultrasonication. (Seo et al., 2006).

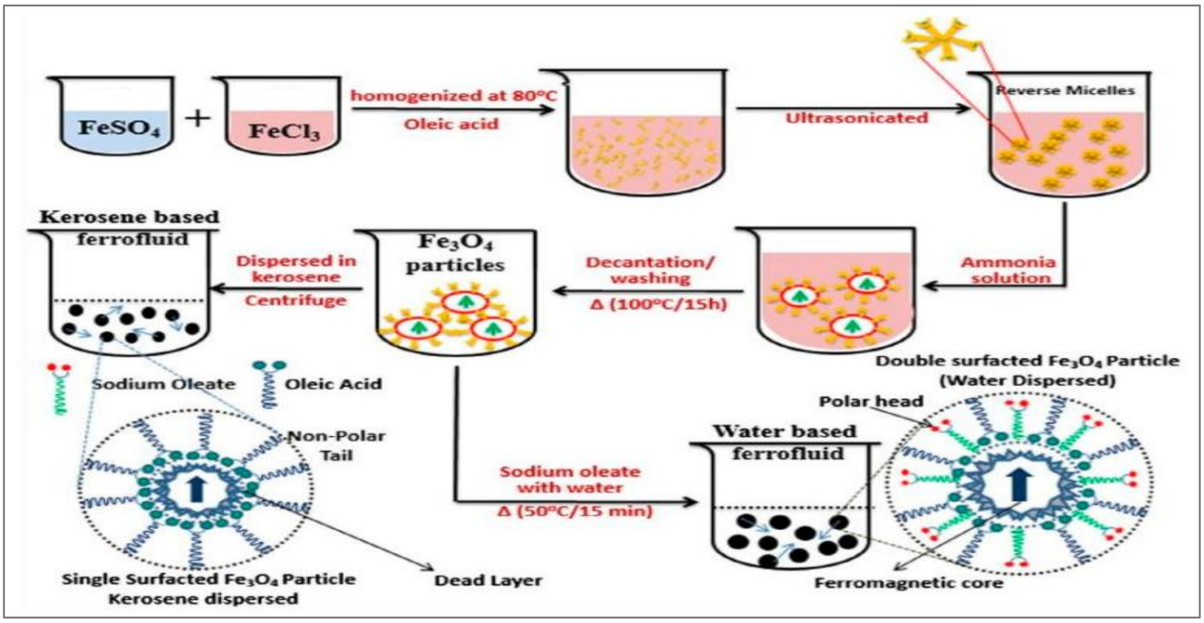

**Figure 8:** This figure illustrates the use of a two-step wet chemical manufacturing procedure using sodium oleate, green string, and double surfactants (oleic acid, blue thread) to disperse Fe3O4 MNPs in an aqueous and kerosene-based magnetic fluid (Van Dijk et al., 2015).

## Design of Magnetic nanoparticles

It is difficult to make magnetic nanoparticles for application in nanomedicine. Several factors must be taken into account at each step of the synthesis. These features can be optimized at the beginning of the design process despite the fact that they have the power to drastically change the intended outcome (Figure 9). Particles can have their chemical and physical characteristics altered to suit a range of uses. Magnetic nanoparticles are widely employed in the field of nanomedicine, especially in the medical treatment of cancer. The capacity of magnetic composites to react to stimuli from outside through a magnetic field makes them appealing for use in medicine delivery applications. This allows the drug distribution to be controlled in terms of dosage, timing, and location. Passive tumor site entry is possible for nanocarriers due to the context of leaky vasculature.

As an alternative, they can actively enter the tumor location by using certain ligands. Doxorubicin was encapsulated in apoferritin and then delivered as a pharmaceutical carrier in magnetic nanoparticles for customized cancer treatment. An antibiotic with an antineoplastic action that is an anthracycline is doxorubicin. Using an MRI-based method, doxorubicin was delivered via magnetic particles that were bound by integrin ligands. A magnetic resonance imaging (MRI) approach that targets magnetic particles with integrin ligands was used to control the distribution of doxorubicin53. Two other applications of MRI are MRI-guided cell replacement therapy and MRI-based imaging of cancer-specific gene transfer.

In a liposome-based nanodevice, magnetic particles were used to transport DNA and medicine. For diagnostic reasons, bacteria, viruses, and biomarkers of cancer were found using metallic nanoparticles and microparticles.

## Physical design

For nanoparticles used in heat-induced magnetic field generation or externally controlled hyperthermia, magnetic characteristics are crucial. Biological items can be moved and transported by use of magnetic force. It has been demonstrated that the capacity to apply mechanical stress within cells is advantageous for fate control and molecular cell signaling. These features have been leveraged by applications such as remote control of single-cell operations, medicine release, and sickness treatment. One of the main physical characteristics of magnetic nanoparticles that can be used to modify other characteristics like surface area and magnetism is their size. Numerous researchers have looked into the creation of iron oxide nanoparticles with controlled sizes. For instance, particles smaller than 20 nanometers have been produced via organic-phase synthesis. A seed-mediated mechanism regulated a later growth spurt.(Dumestre et al., 2003). The solvent's boiling point and reaction time are the main variables influencing particle size in the first stage. In order to create a stable system, researchers cover the particles. Surface charge contributes to maintaining particle repulsion, even if the proportion of inert and reactive chemicals on the surface needs to be tuned to maintain the colloidal equilibrium of the nanoparticles. Ho et al. claim that iron oxide can be utilized to produce a wide range of elements with unique chemical and physical characteristics. Gold magnetic nanoparticles, for instance, have the right optical and magnetic characteristics. Higher magnetism can be attained using cobalt and metallic iron magnetic nanoparticles; however, the former needs to be coated to prevent oxidation. Magnetic nanoparticles based on platinum exhibit significant promise as contrast agents for computed tomography (CT) and magnetic resonance imaging (MRI). On the other hand, solid nanoparticles can still be used to store and release medication thanks to porous magnetic nanoparticles, which have the same properties (Murray et al., 2001).

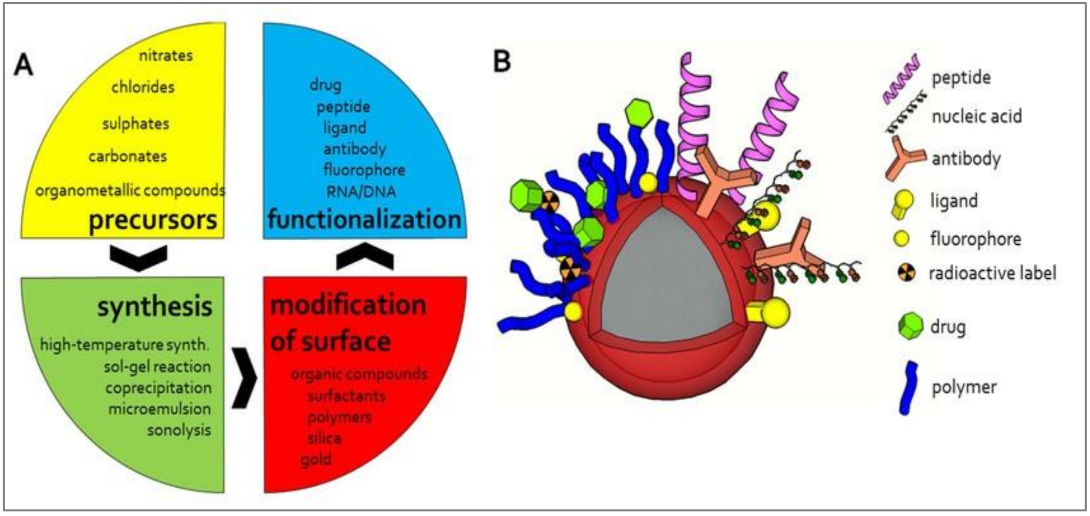

**Figure 9:** The design process plan for magnetic particles (A) and potential alterations and functionalization of magnetic particles(Nam et al., 2008)

### Chemically designed approach

There are two primary approaches have been documented for the functionalization of magnetic particles. In the first, inorganic materials are modified using biomaterials like oligonucleotides and antibodies; in the second, inorganic materials are integrated with additional nanocomponents like quantum dots. The main challenge in methods such as magnetized particle hyperthermia is to achieve a uniform dispersion of nanoparticles and, as a result, a precisely controlled increase in temperature in the tumor tissue. Targeting cancerous cells with specific antibody-conjugated magnetic nanoparticles is one way to achieve this. Magneto-liposomes, particularly those bound to antibodies, can introduce magnetic nanoparticles into tumor cells. Ulbrich et al. proposed a contemporary perspective on the chemical construction of magnetic particles intended for pharmaceutical administration ( Kim et al., 2007). They briefly discussed the two types of chemical surface modifications for particles: covalent and non-covalent. In cancer patients, covalently bonded magnetic nanoparticles with medications can help avoid side effects and treatment resistance. Covalent bonds need to be able to respond to variations in pH, temperature, and even simple enzymatic degradation within the cellular milieu. Researchers have used non-covalent drug conjugation to nanoparticles. It has been asserted that conjugating medications to nanoparticles of magnetic material can effectively transport therapeutics by a combination of coordination chemistry, hydrophobic interaction, and electrostatic contact. Nucleic acids and other biological molecules that connect to magnetic nanoparticles rely on a variety of simultaneous interactions, including hydrophobic, hydrogen bond, and electrostatic interactions. It is crucial to take these factors into account when designing, in particular the potency of individual binding relationships and the total potency of every one of the interactions simultaneously. In order to design and invent novel and desirable functions, an important component in present magnetic nanoparticle research is studying these interactions (Hou, Sun, et al., 2007).

### Characterization Techniques for Magnetic Nanoparticles

Molecular reactivity increases exponentially in nanoscale materials due to their high surface-to-volume ratio, setting them apart from their bulk counterparts. Among these are properties that are chemical, optical, and electrical (Figure 10). The nanoparticles' (NPs') mechanical characteristics might also differ significantly. They are the subject of extensive research because of their intellectual appeal and the technical applications they may have in a range of areas. There are numerous ways to characterize nanoparticles when creating these nanostructures, including mechanical, chemical, and other processes (Table 2). More accurate and reliable methods for characterizing nanomaterials are needed since there are 10 times as many types and amounts being generated now as there were ten years ago. But a classification like this isn't always accurate. This is explained by the fact that nanoscale materials are different from bulk materials in that they are harder to analyze precisely (e.g., too small in size and low quantity in some circumstances following laboratory-scale manufacture) (Klaessig et al., 2011).

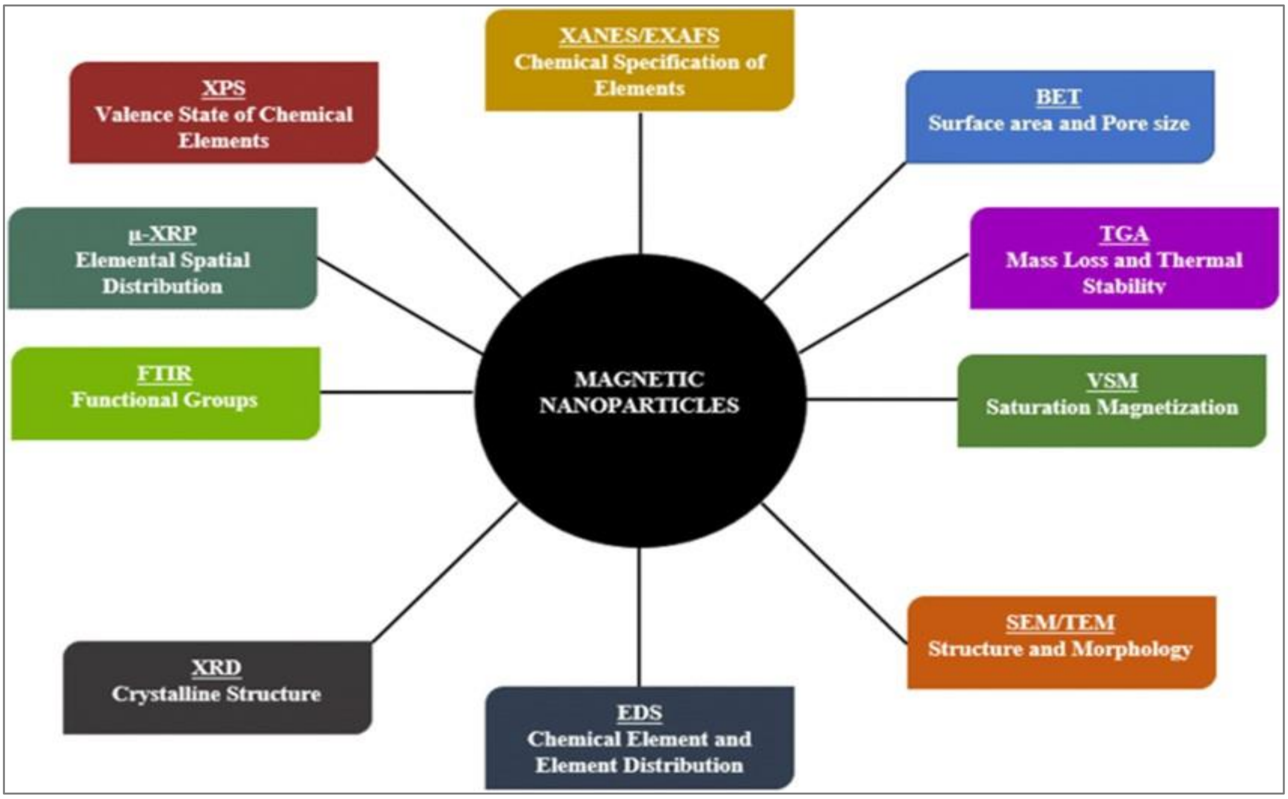

**Figure 10:** The characterization techniques for magnetic nanoparticles (Tiede et al., 2008)

Furthermore, due to the multidisciplinary nature of nanoscience and nanotechnology, not all study groups have accessible access to a wide range of facilities for characterization. In actuality, it is frequently necessary to characterize NPs in a broader sense, necessitating an all-encompassing strategy that supports several points of view. In this instance, it is helpful to understand the drawbacks and advantages of the various methodologies to determine whether, in some circumstances, employing only a few of them will yield sufficient results when examining a particular attribute (such as particle size) (Hassellöv et al., 2008). Researchers are starting to notice that there might be some variations in how analytical characterization techniques applicable to nanomaterials contrasted with other "conventional" (macroscopic) substances as the fields of nanotechnology and nanoscience continue to expand at a rapid pace (Powers et al., 2007). AFM, TEM, HRTEM, and other microscopy-based approaches can provide details on the size, shape, and structure of the nanomaterials' crystals. Certain approaches, like the magnetic methods, can only be used for particular groups of materials. XMCD, SQUID, VSM, and FMR are among the methods employed. More details regarding the optical characteristics, structural makeup, elemental makeup, and other general and more focused physical qualities of the nanoparticle samples can be obtained using a variety of additional techniques. Scattering, X-ray, and spectroscopic technologies are a few of these methods (Stavis et al., 2018).

Size and form are two primary NP features that are investigated. Beyond surface chemistry, measurements can be made of surface area, charge, size distribution, and degree of aggregation. The additional characteristics and applications of the NPs may be impacted by the arrangement, dimensions, and existence of organic ligands on their particle surface. Once the nanoparticles are manufactured, a comprehensive examination of their crystal structure and chemical makeup is also done as a preliminary step. Reliable and precise NP measuring techniques are critical to the commercial use of these materials and industry regulatory compliance (Linsinger et al., 2011). However, the field's multidisciplinary nature, the lack of appropriate standards for calibrating analytical instruments, the challenges associated with sample preparation for analysis, and the interpretation of results present significant obstacles to the examination of nanomaterials. Unresolved concerns in assessing NPs include the analysis of NPs in complicated matrices and the use of online and in situ concentration measurement, especially in scaled-up manufacturing. It's also essential to monitor the trash and effluent from large production (Powers et al., 2006). Sixth, more accurate measurement methods will be needed as the size of the generated nanoparticles grows. As such, it is imperative to accurately define the nanomaterials created through different processes. We consider the surface ligands that affect the physical properties and characterize the nanoparticle's core. Furthermore, we present state-of-the-art in situ operando methods that are used to track the dynamics of nanoparticle creation and investigate the controlled defects that significantly affect the properties of nanoparticles, in addition to what could be called "common" approaches through some recent developments in the field (Gioria et al., 2018).

**Table 2:** Showing techniques used in the characterization of magnetic nanoparticles

| Technique | Main information derived | Reference(s) |
|---|---|---|
| XRD (group: methods based on X-rays) | Crystal arrangement, crystalline particle size, and structure | (Iglesias-Juez et al., 2022) |
| (EXAFS, XANES) XAS | Debye-Waller factors, interatomic distances, the chemical state of the species, and the element-specific X-ray absorption coefficient also apply to non-crystalline NPs. | |
| SAXS | size distribution, growth kinetics, and particle size. | (Hamley, 2021) |
| XPS | Surface-sensitive ligand binding, oxidation states, electronic structure, and elemental composition | (Dahl et al., 2023) |
| FTIR (group: additional methods for main characteristics, composition, and structure) | Ligand binding, surface composition | (Tsagkaris et al., 2023) |
| NMR (all types) | Ligand influence on NP form, atomic composition, electronic core structure, ligand density and organization, and NP size | (Wu et al., 2021) |
| BET | Surface area | (Maitra et al., 2015) |
| TAG | composition of stabilizers and Mass | (Rusly et al., 2024) |
| LEIS | chemical composition of self-assembled monolayers of NPs and Thickness | (Hamoudi & Esaulov, 2016) |
| UV-VIS | hints on NP shape, size, Optical properties, agglomeration state, and concentration | (González et al., 2019) |
| PL spectroscopy | Optical properties–relation to structure features such as composition, size, defects | (Tebyetekerwa et al., 2020) |
| DLS | detection, Hydrodynamic size of agglomerates | (Ross Hallett, 1999) |
| NTA | size distribution and NP size | |
| DCS | NP size and size distribution | |
| ICP-MS | Elemental composition, size, size distribution, NP concentration | (Comfort et al., 2021) |
| SIMS, MALDI, ToF-SIMS | Surface-sensitive chemical data on molecule orientations and structure, surface topography, functional group, and MALDI for NP size | (Talian et al., 2007) |
| H-potential, pH, EPM, DSC, GPC, RMM-MEMS, etc. | | |

*To be continued next page*

*Table 2 Continued*

| Technique | Main information derived | Reference(s) |
|---|---|---|
| SQUID-NanoSQUID (magnetic nanomaterial) | Blocking temperature, magnetization remanence, and saturation | (Russo et al., 2012) |
| VSM | Comparable to ZFC-FC curves and M-H graphs used in SQUID | (Maldonado-Camargo et al., 2017) |
| Mössbauer | Iron oxides can be distinguished by their surface spins, symmetry, magnetic anisotropy energy, oxidation state, magnetic ordering of the Fe atoms, and thermal unblocking. | (Kuzmann et al., 2021) |
| FMR | M values, the magnetic anisotropy constant, the demagnetization field, the NP dimensions, distribution, shape, and crystallographic defect | (Tomczak & Puszkarski, 2020) |
| XMCD | magnetic moments of transition metal ions in ferri-magnetic materials and ferro and Specific element-specific site symmetry. | (Brice-Profeta et al., 2005) |
| Magnetophoretic Magnetic susceptibility, mobility | | |
| Superparamagnetic relaxometry | Finding and locating superparamagnetic NPs, hydrodynamic size distribution, and core characteristics | (Mourdikoudis et al., 2018) |
| TEM (group: microscopy techniques) | The particle growth dynamics, size, shape, aggregating state, size monodispersed, localization, and quantification of NPs in matrices. | (Lin et al., 2014) |
| HRTEM | Details were obtained not just from traditional TEM but also from the crystalline makeup of individual particles. Differentiate between amorphous, polycrystalline, and monocrystalline NPs. Examine flaws | (Clarke et al., 2018) |
| Liquid TEM | Show NP development in real-time, investigate single particle motion, growth mechanisms, and superlattice building. | (Kim et al., 2024) |
| Cryo-TEM | Examine intricate processes of growth and aggregation, which are beneficial for the study of molecular biology and colloidal chemistry in order to prevent the existence of artifacts or damaged specimens. | (Danino, 2012) |
| Electron diffraction | Long-range order parameters, lattice parameters, order-disorder transformation research, and crystal structure | (Chen et al., 2004) |
| STEM | used in conjunction with HAADF and EDX to analyze crystal structure, elemental content, and morphology. Examine the atomic configuration of hetero-interfaces. | (Lu et al., 2020) |
| Aberration-corrected (TEM, STEM) | The atomic structure of nanoparticle clusters resulting from phase segregation, homogeneity, and composition, especially in bimetallic alloys | (Thersleff et al., 2020) |
| EELS (EELS-STEM) | bulk plasmon resonance, the kind and amount of atoms present, their chemical states, and their collective interactions with one another | (Schaffer et al., 2010) |

*To be continued next page*

*Table 2 continued*

| Technique | Main information derived | Reference(s) |
|---|---|---|
| Electron tomography | Detailed 3D particle visualization, images, videos, and quantitative data all the way down to the atomic level | (Baba et al., 2023) |
| SEM-HRSEM, T-SEM-EDX | Morphology, NP dispersion in cell and other matrices, NP lateral dimension accuracy, and speedy element composition analysis | (Mourdikoudis et al., 2018) |
| EBSD | Materials' phase, structure, and crystal orientation are all visible in SEM. Analyze microstructures to find details about grain shape, deformation, texture, and flaws. | (Inkson, 2016) |
| AFM | NP form and size in three dimensions; the extent to which a surface is covered by NPs; the dispersal of NPs in cell and other matrices and supports; the accuracy of NP lateral dimensions; and the expeditious analysis of elemental composition | (Joseph et al., 2023) |
| MFM | conventional AFM imagery combined with data on the magnetic moments of individual nanoparticles. Examine magnetic nanoparticles inside of cells. Separate from non-magnetic nanoparticles | (Abelmann, 2017) |

**X-ray based techniques**

The diffraction of X-rays is one of the techniques used most frequently to describe nanoparticles (NPs). The crystalline structure, phase nature, lattice variables, and crystalline grain size of a material can frequently be ascertained by XRD. The latter parameter is calculated for a given sample using the formula developed by Scherrer and the developing pattern of the greatest signal in the measurement received from XRD analysis. One benefit of using XRD techniques is the production of volume-averaged findings that are statistically representative. Typically, these techniques are applied to powdered materials following the drying of the relevant colloidal solution (Eastlake et al., 2016). By comparing the peak locations and intensities to reference patterns in the data set of the International Centre for Diffraction Data (ICDD, formerly the Joint Committee on Powder Diffraction Standards, JCPDS), one can ascertain the composition of the particles. Apart from instrumental broadening, the size of the particles or crystallites and lattice tensions were the main causes of the XRD peak broadening (Occupational Exposure Sampling for Engineered Nanomaterials., OESEN, 2022).

The size measured by XRD typically exceeds what is referred to as the magnetic size, given that smaller domains exist in particles when all moments are orientated in the identical direction, even in single field particles. In contrast, the size estimated by TEM was larger than the size found by XRD for samples comprising very big particles; in fact, many crystal boundaries are visible on the surface when a particle's size surpasses 50 nm. Ultra-small Au NPs were created by Dai et al. This suggests that these were more developed in the former direction because their XRD measurement showed a significantly more intense peak corresponding to that direction.

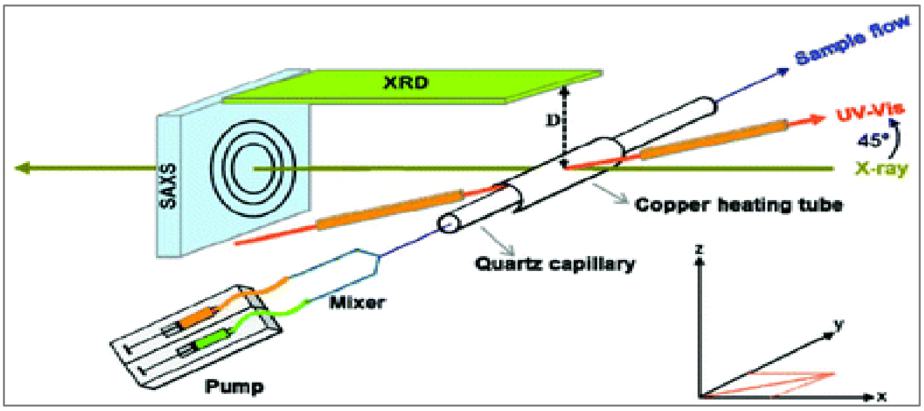

**Figure 11:** Diagrammatic representation of the in situ apparatus used to measure WAXS, SAXS, and UV-Vis in real-time as Au NPs are forming. The apparatus simultaneously measures the UV-Vis, SAXS, and WAXS spectra in the same sample volume (Kaiser & Chalfin, 2017).

The size, shape, and distribution of the particles are usually ascertained using SAXS. Compared to TEM imaging, SAXS data are more statistically average in terms of size values (Figure 11). SAXS was used by Wang et al. to look into how the temperature affects the structure of Pt NPs. At some temperatures, there was a discrepancy between the size ascertained by XRD and the corresponding SAXS result. This is because SAXS is dependent on the size of the electronic density fluctuation zone, whereas XRD is sensitive to the size of the long-range order area. While XRD produces the crystallite size, SAXS provides the real particle size. An integrated technique utilizing QELS (quasi-elastic light scattering), SAXS, and UV-Vis to characterize silver sols in polymer matrices. A monomodal scatterer size distribution was found by SAXS analysis, whereas QELS and UV-Vis created a multimodal particle size distribution. The following methods' ability to differentiate between aggregates or large particles with sizes ranging from 30 to 60 nm may be the cause of this discrepancy (Leibowitz, 2017).

### X-ray-based photoelectron spectroscopy (XPS)

X-ray photoelectron spectroscopy (XPS) is the most popular analytical method for surface chemical characterisation. It is also used to characterize materials at the nanoscale. The photoelectric effect is the basic physical idea at work. The electrical structure, elemental composition, and oxidation states of a material can all be determined quantitatively using XPS, a highly effective method. It can investigate the surface functionalization of nanoparticles in the exchange of ligand interactions, and core/shell formations in addition to functioning in a very high vacuum (Mansfield et al., 2017).

### Fourier transform infrared spectroscopy.

The measurement of the absorbance of electromagnetic energy with wavelengths in the mid-infrared range (4000–400 cm−1) is done using a method called Fourier transform infrared spectroscopy (FTIR). A molecule that absorbs infrared radiation changes its dipole moment, becoming infrared (IR) active. The positions of bands associated with particular functional groups, binding types, and bond strengths are displayed in a recorded spectrum to provide information on molecular interactions and structures (Aublant, 2017). Feliu and colleagues employed a combination of in situ ATR-FTIR and differential electrochemical mass spectroscopy (DEMS) to investigate the effects of Pt nanostructures on the oxidation of ethanol. Using these techniques made it easier to find volatile reaction byproducts and conduct electrochemical adsorbate investigations. They found that the preferential breakdown products were associated with surface features, which was in line with other studies in the same field. COads accumulated on domains and acetaldehyde/acetic acid was produced on a platinum nanoparticle (NP) supported on carbon, with a size range of 3 to 8 nm. DRIFTS and quadrupole mass spectrometry (QMS) were employed to track this catalytic activity. In line with the QMS findings, the FTIR analyses of the adsorbed CO verified the fluctuations in COad and Oad at various times throughout the experiment. We also observed variations in the distribution of CO over a number of Pt surface regions. DRIFTS was considered a valuable instrument for monitoring the surface structure of Pt NPs in situ. The surfactant bonding to FePt NPs produced with oleic acid, and oleylamine was investigated using FTIR in a work published by Shukla et al. As opposed to oleylamine, which demonstrated molecular bonds with FePt molecules while maintaining the NH2 group, the former ligand was observed to establish both monodentate and bidentate bonds with FePt NPs (Yazdani & Pettes, 2018).

## APPLICATIONS OF MAGNETIC NANOPARTICLES

Numerous possible uses have been considered. Given the high cost of production, there is interest in recycling magnetic nanoparticles or using them in highly specialized applications. The quick and simple separation of magnetic nanoparticles, which does away with time-consuming and expensive separation procedures often used in chemistry, gives rise to magnetic chemistry's promise and adaptability. The magnetic nanoparticles can also be sent to the target area by applying a magnetic field. For example, this could enable precision targeting in the battle against cancer (Gilchrist et al., 1957).

### Medical diagnostic and treatment

In an experiment known as magnetic hyperthermia, alternating magnetic fields (AMFs) are used to heat magnetic nanoparticles. This treatment has been investigated for cancer patients. AMFs with an amplitude of 8–16 kAm−1 and a frequency of 100–500 kHz are frequently used to accomplish sufficient heating of magnetic nanoparticles, while considerable research has also been conducted at lower and even as high as 10 MHz. Various chemistries can be used to attach affinity ligands, like as lectins, folic acid, aptamers, and epidermal growth factor (EGF), to the surface of magnetic nanoparticles. This makes it possible to target particular tissues or cells with magnetic nanoparticles. In cancer research, this approach is utilized to target and treat tumors in conjunction with cancer medicines delivered by nanoparticles or magnetic hyperthermia (Colombo et al., 2012). Even with affinity ligands, however, the aggregation of nanoparticles within malignant tumors of all kinds remains suboptimal despite research efforts. After performing a thorough investigation into the transport of nanoparticles to tumors, Willhelm et al. concluded that a solid tumor can only receive a median injection dose of 0.7%. Perhaps the largest impediment to Nano medicine in general is the difficulty of building up sufficient volumes of nanoparticles inside tumors (Vaghari et al., 2016). For a proper distribution of particles throughout the tumor, intravenous injection is usually preferred, while direct injection is employed in certain instances as well. One clear benefit of magnetic nanoparticles is their ability to accumulate in targeted areas through magnetically guided delivery; however, more work needs to be done on this technology before solid tumor delivery can be achieved optimally. Attaching magnetic nanoparticles to cancer cells that are floating freely and enabling their removal from the body is another possible cancer treatment. The therapy has been examined in survival studies after being tested on mice in a lab (Malhotra et al., 2020).

Cancer can be detected with the use of magnetic nanoparticles. Magnetic nanoparticle-containing microfluidic chips allow for the insertion of blood into them. An externally created magnetic field confines these magnetic nanoparticles inside, allowing blood to flow through. The magnetic nanoparticles are coated with antibodies that target proteins or cancer cells). The magnetic nanoparticles can be recovered, and an examination can be performed to search for the presence of the compounds associated with cancer. For the aim of detecting bacteria, iron oxide particles and magnetic nanoparticles that can be coupled with carbohydrates have been used to detect both Gram-positive and Gram-negative bacteria, including Streptococcus suis(Kolosnjaj-Tabi et al., 2016). Specifically, cobalt ferrite, a core-shell magnetic nanoparticle, exhibits antibacterial properties against eukaryotic (like Candida albicans, which causes candida and Candida parapsilosis) as well as prokaryotic (like E. Coli and Staphylococcus aureus) bacteria. It is commonly known that the size of magnetic nanoparticles plays a crucial role in their antibacterial activity; the smaller the particles, the more effective they are. By combining the nanoparticles with oligonucleotides that can either bind to an interesting DNA or RNA sequence and detect it using an aptamer or that can be complementary to the sequence in question, such as pathogenic DNA or the byproducts of DNA amplification reactions when pathogenic DNA is present, additional diagnostic applications can be achieved. This could lead to the discovery of pathogens, such as human-affecting bacteria or viruses, as well as dangerous substances or other substances present in the body (Rivera-Rodriguez & Rinaldi-Ramos, 2021).

## Magnetic immunoassay

Instead of using traditional enzymes, radioisotopes, or fluorescent moieties as labels, magnetic nanobeads are used in magnetic immunoassay (MIA), a unique kind of diagnostic immunoassay. In this assay, the antibody is precisely attached to its antigen, and one of the couple has a magnetically label applied to it. By analyzing the change in the magnetic field that magnetic nanobeads create, a device called a magnetometer or magnetic reader can identify the presence of the beads. The amount of signal the magnetometer measures depends on the quantity of an analyte (virus, toxin, bacteria, cardiac marker, etc.) in the original sample (Monteserín et al., 2021).

## Waste water treatment

Magnetic nanoparticles can be used to clean up contaminated water because of their high surface-to-volume ratio and ease of separation when subjected to a magnetic field. By affixing chelators akin to EDTA to carbon-coated metal nanomagnets, this technique produces a magnetic reagent that expedites the elimination of heavy metals by a factor of three, even from solutions or polluted water at levels as low as micrograms per liter. Regarding the material's environmental impact, due to their remarkable biocompatibility, oxide superparamagnetic nanoparticles like magnetite and maghemite, which are FDA-authorized, can be used to create magnetic Nano beads or nanoparticle clusters with a lot of potential for wastewater treatment. They differ from metallic nanoparticles because of this (Parekh et al., 2020).

## Electrochemical sensing

Using magnetic nanoparticles for electrochemical sensing is the basis of magneto-electrochemical tests. They can be used in two ways: either by increasing the conductivity and affinity of an electrode surface with the analyte or by spreading throughout a sample to collect and pre-concentrate the analyte and manage it by a magnetic field. Coated-magnetic nanoparticles facilitate analyte collection while also allowing MNPs to engage in the sensor's transduction mechanism, an essential aspect of electrochemical sensing. In an effort to replace magnetic supports or any external magnetic field, magnetic electrode shafts or disposable screen-printed electrodes with permanently connected magnets have been used to manipulate MNPs in electrochemical sensing(Bahadur et al., 2017).

## Supported enzymes and peptides

Enzymes, Proteins, and other physiologically and chemically active molecules have been immobilized on magnetic nanoparticles. Because of the proteins' magnetic susceptibility, the immobilization of enzymes on inexpensive, non-toxic, and easily produced iron magnetic nanoparticles (MNP) has shown great promise. This can result in more stable proteins, increased product yield, easier protein purification, and a wide range of applications. They are intriguing as potential solid-phase synthesis supports. Potential applications for this technology include tissue mending, magnetic resonance imaging, drug administration, cellular labeling and separation, biological fluid detoxification, hyperthermia, and magnetofection (Tartaj et al., 2003).

## Random versus site-directed Enzyme Immobilization

Random multipoint attachment of immobilized enzymes on magnetic nanoparticles (MNP) results in a varied protein population with reduced activity because substrate access to the active site is constrained. There are already techniques based on chemical changes that allow MNP to be attached to a protein molecule by a single particular amino acid (such as the N- or C-termini), preventing activity loss brought on by the substrate's unrestricted access to the active site. Furthermore, altering catalytic residues is also avoided by site-directed immobilization. Since both groups lack proteins, one such popular technique uses Alkyne-Azide Click chemistry(Lu et al., 2007).

### Catalyst support

Magnetic nanoparticles have the potential to be useful as supports or catalysts. In chemistry, a catalyst support is the material that a catalyst is bonded to. This material frequently has a huge surface area and is a solid. Surface atoms of heterogeneous catalysts are reactive. Therefore, in order to optimize the surface area of a catalyst, much effort is made to spread it across the support. The support may be inactive or participate in the catalytic processes (Figure 12). Common supports include alumina, silica, and other types of carbon. Immunization of the catalytic core on high surface-to-volume nanoparticles is a potential remedy to this issue. It also provides magnetic nanoparticles with the advantage of easy separation. The combination of magnetic nanoparticles and rhodium catalysis was one early example (Mohammed et al., 2017).

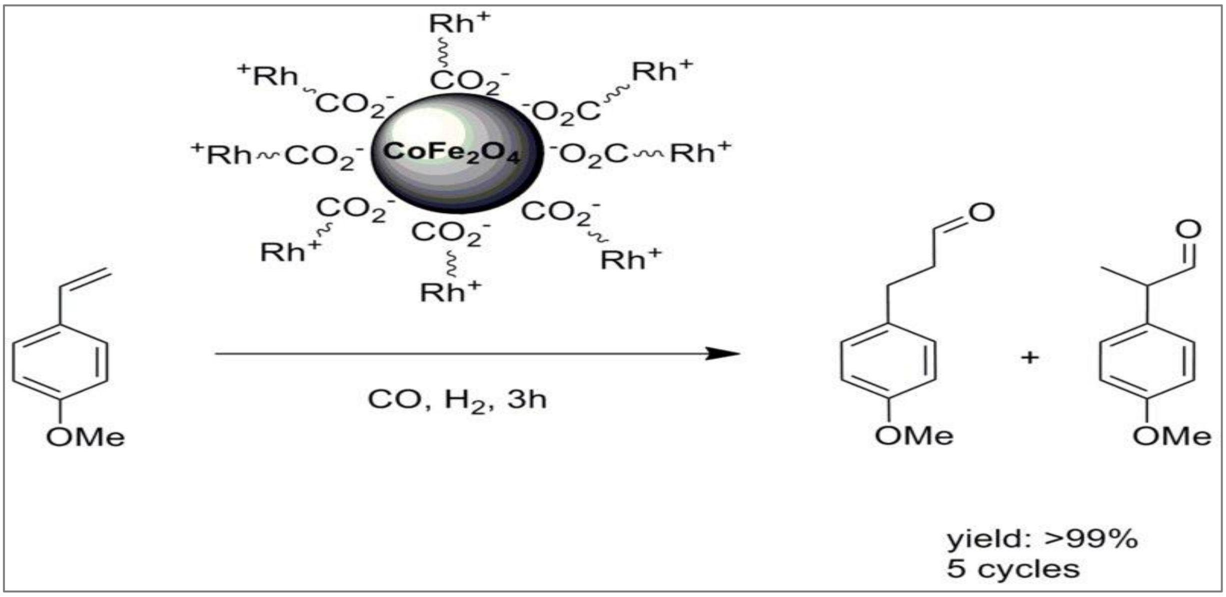

**Figure 12:** In another instance, a diazonium reaction was used to attach the stable radical TEMPO to the cobalt nanoparticles coated with graphene. The subsequent chemo-selective oxidation of both secondary and primary alcohols was carried out using the generated catalyst (Iliasov et al., 2021).

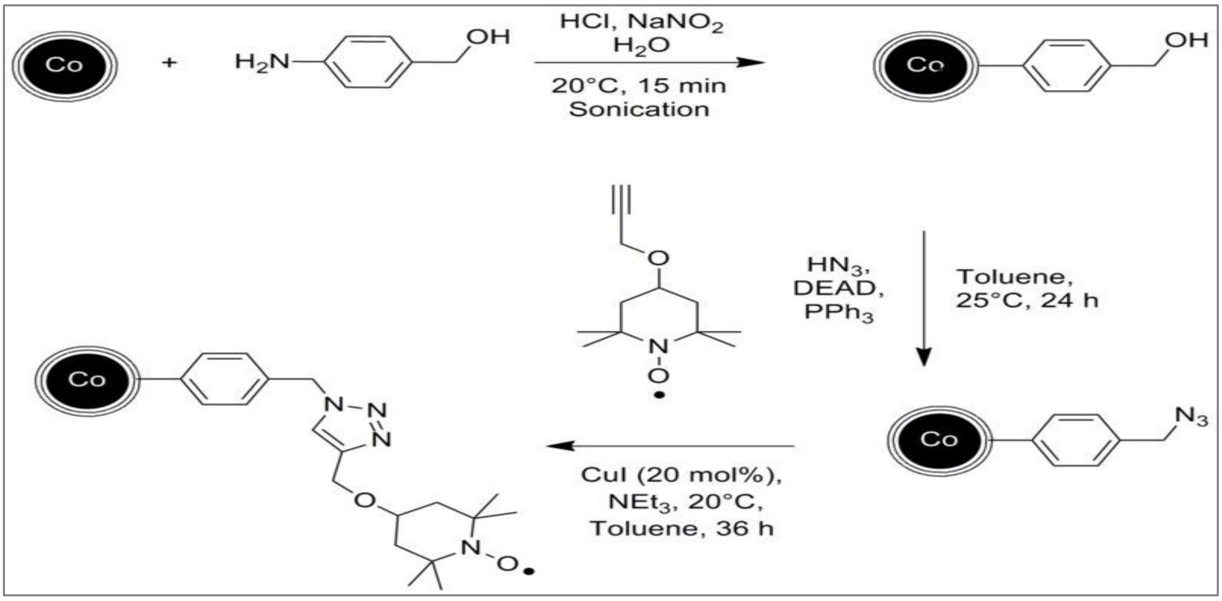

**Figure 13:** A constant flow reactor may be utilized to carry on the catalytic process and guarantee that there is no remaining catalyst in the finished product, as opposed to utilizing a batch reactor.

In that experiment (Figure 13), Because graphene-coated cobalt nanoparticles are more magnetized than Ferrite nanoparticles, a necessary condition for a quick and efficient separation using an external magnetic field, they were used instead of Ferrite nanoparticles (Wong et al., 2018).

### Cancer therapy

After injecting different nanoparticles to induce magnetic fluid hyperthermia, such as iron oxide, magnetite, maghemite, and even gold, a high-frequency magnetic field is delivered to the tumor. These nanoparticles typically generate heat that causes tumors to reach 40–46 °C, which is hot enough to destroy cancer cells. Using magnetic nanoparticles in conjunction with heat (hyperthermia) to cure cancer is a substantial additional potential application. Several studies have shown that magnetic nanoparticles and particle topologies can transport medicinal payloads. Due to the presence of magnetic nanoparticles within liposomes, which are often introduced into lipid bilayers, the most commonly utilized construct is referred to as a "Magneto liposome". A magnetic field that is alternating causes the magnetic nanoparticles to heat up and permeabilize the membrane. This results in the release of the loaded chemical. Even though this therapy method's study is still in its early phases, it has a lot of potential. It is expected that the use of heat and drug release in conjunction will cure cancers more successfully than either method alone (Hoshyar et al., 2016).

### Information storage

The tetragonal stage of the face-centered FePt alloys is suitable for a high level of preservation.

That is a viable option. Nanometers are the smallest possible grain size. Its data density with this material might exceed 1 Terabyte per square inch if the MNPs can be changed at this small scale (Li et al., 2020).

### Magnetic engineering

In genetics, nanoparticles with magnetic properties have a plethora of intriguing applications. Another application is the quick separation of DNA and mRNA. The magnetic bead is affixed to a poly T-tail in one usage. To readily extract mRNA, place a magnet on the tube's side and pour out the liquid. This is because, when combined with mRNA, the mRNA's poly A tail will adhere to the poly T-tail of the bead. Plasmid assembly has also made use of magnetic beads. By sequentially adding genes to an expanding genetic chain and employing nanobeads as an anchor, genetic circuits can be rapidly constructed. It has been demonstrated that this approach, which is substantially quicker than earlier approaches, produces functioning multi-gene complexes through in vitro culture in less than an hour (Janko et al., 2019).

### Physical modeling

A variety of mathematical frameworks describes the movement of magnetic nanoparticle motions. A nanoparticle's magnetism at equilibrium is elucidated by two basic theories: the Stoner-Wohlfarth model and the Langevin function. The magnetization will react uniformly to a magnetic field that vibrates at low amplitudes and high frequencies, corresponding to the Debye/Rosenszweig model (Mylkie et al., 2021).

## CONCLUSION

Magnetic nanoparticles have emerged as a transformative tool in the domains of biotechnology and healthcare because of their inherent unique properties and versatile applications. Recent advancements in the synthesis and design of MNPs have significantly enhanced their functionality, enabling them to serve multiple roles in medical diagnostics and therapeutics. From improving drug delivery to enhancing imaging techniques, MNPs offer a range of benefits that could revolutionize healthcare. Our review highlights the progress made in this field, including innovative methods for synthesizing and functionalizing MNPs. These advancements have prompted the creation of multipurpose nanoparticles that can address complex medical needs, such as targeted drug delivery and real-time imaging. However, despite these promising developments, several challenges remain. Problems associated with the reproducibility of synthesis methods, the consistency of MNP properties, and long-term safety still need to be addressed to fully realize the potential of these nanomaterials. The current limitations underscore the need for continued research and development. Future efforts should focus on standardizing synthesis protocols to ensure the consistency and reliability of MNPs. Overall, the continued evolution of MNP technology holds great promise for advancing medical science and improving patient care. By addressing the current challenges and pursuing innovative research directions, we can further enhance the capabilities of MNPs and unlock their full potential in medicine. As the field progresses, it is crucial to maintain a multidisciplinary approach, integrating insights from chemistry, physics, biology, and engineering to drive the next generation of breakthroughs in nanomedicine.

## REFERENCES

Abelmann, L. (2017). Magnetic Force Microscopy. In *Encyclopedia of Spectroscopy and Spectrometry* (pp. 675–684). Elsevier. **[Crossref]**

Aublant, J. (2017). Standardization of Nanomaterials: Methods and Protocols. In E. Mansfield, D. L. Kaiser, D. Fujita, & M. Van De Voorde (Eds.), *Metrology and Standardization of Nanotechnology* (1st ed., pp. 289–298). Wiley. **[Crossref]**

Baba, N., Hata, S., Saito, H., & Kaneko, K. (2023). Three-dimensional electron tomography and recent expansion of its applications in materials science. *Microscopy*, *72*(2), 111–134. **[Crossref]**

Bahadur, A., Saeed, A., Shoaib, M., Iqbal, S., Bashir, M. I., Waqas, M., Hussain, M. N., & Abbas, N. (2017). Eco-friendly synthesis of magnetite (Fe 3 O 4 ) nanoparticles with tunable size: Dielectric, magnetic, thermal and optical studies. *Materials Chemistry and Physics*, *198*, 229–235. **[Crossref]**

Bossmann, S. H., & Wang, H. (Eds.). (2017). *Magnetic nanomaterials: Applications in catalysis and life sciences*. Royal Society of Chemistry.

Brice-Profeta, S., Arrio, M.-A., Tronc, E., Menguy, N., Letard, I., Cartier Dit Moulin, C., Noguès, M., Chanéac, C., Jolivet, J.-P., & Sainctavit, Ph. (2005). Magnetic order in - nanoparticles: A XMCD study. *Journal of Magnetism and Magnetic Materials*, *288*, 354–365. **[Crossref]**

Brinker, C.J. and Scherer, G.W. (1990) Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing. Academic Press, San Diego.

Carrey, J., Mehdaoui, B., & Respaud, M. (2011). Simple models for dynamic hysteresis loop calculations of magnetic single-domain nanoparticles: Application to magnetic hyperthermia optimization. *Journal of Applied Physics*, *109*(8), 083921. **[Crossref]**

Chaudhary, V., Chen, X., & Ramanujan, R. V. (2019). Iron and manganese based magnetocaloric materials for near room temperature thermal management. *Progress in Materials Science*, *100*, 64–98. **[Crossref]**

Chaudhary, V., & Ramanujan, R. V. (2016). Magnetocaloric Properties of Fe-Ni-Cr Nanoparticles for Active Cooling. *Scientific Reports*, *6*(1), 35156. **[Crossref]**

Chaudhary, V., Wang, Z., Ray, A., Sridhar, I., & Ramanujan, R. V. (2017). Self pumping magnetic cooling. *Journal of Physics D: Applied Physics*, *50*(3), 03LT03. **[Crossref]**

Chen, G., Ni, X., & Nsongo, T. (2004). Lattice parameter dependence on long-range ordered degree during order–disorder transformation. *Intermetallics*, *12*(7–9), 733–739. **[Crossref]**

Chinnasamy, C. N., Huang, J. Y., Lewis, L. H., Latha, B., Vittoria, C., & Harris, V. G. (2008). Direct chemical synthesis of high coercivity air-stable SmCo nanoblades. *Applied Physics Letters*, *93*(3), 032505. **[Crossref]**

Clarke, G., Rogov, A., McCarthy, S., Bonacina, L., Gun'ko, Y., Galez, C., Le Dantec, R., Volkov, Y., Mugnier, Y., & Prina-Mello, A. (2018). Preparation from a revisited wet chemical route of phase-pure, monocrystalline and SHG-efficient BiFeO3 nanoparticles for harmonic bio-imaging. *Scientific Reports*, *8*(1), 10473. **[Crossref]**

Clemons, T. D., Kerr, R. H., & Joos, A. (2019). Multifunctional Magnetic Nanoparticles: Design, Synthesis, and Biomedical Applications. In *Comprehensive Nanoscience and Nanotechnology* (pp. 193–210). Elsevier. **[Crossref]**

Colombo, M., Carregal-Romero, S., Casula, M. F., Gutiérrez, L., Morales, M. P., Böhm, I. B., Heverhagen, J. T., Prosperi, D., & Parak, Wolfgang. J. (2012). Biological applications of magnetic nanoparticles. *Chemical Society Reviews*, *41*(11), 4306. **[Crossref]**

Comfort, N., Cai, K., Bloomquist, T. R., Strait, M. D., Ferrante Jr., A. W., & Baccarelli, A. A. (2021). Nanoparticle Tracking Analysis for the Quantification and Size Determination of Extracellular Vesicles. *Journal of Visualized Experiments*, *169*, 62447. **[Crossref]**

Conley, S., Knies, A., Batten, J., Ash, G., Miner, B., Hwang, Y., et al. (2019) Agreement between Actigraphic and Polysomnographic Measures of Sleep in Adults with and without Chronic Conditions: A Systematic Review and Meta-Analysis. Sleep Medicine Reviews, 46, 151-160. **[Crossref]**

Condé-Green A, Kotamarti VS, Sherman LS, Keith JD, Lee ES, Granick MS, Rameshwar P. Shift toward Mechanical Isolation of Adipose-derived Stromal Vascular Fraction: Review of Upcoming Techniques. Plast Reconstr Surg Glob Open. 2016 Sep 7;4(9):e1017. **[Crossref]**

Dahl, Ø., Sunding, M. F., Killi, V., Svenum, I.-H., Grandcolas, M., Andreassen, M., Nilsen, O., Thøgersen, A., Jensen, I. J. T., & Chatzitakis, A. (2023). Interrogation of the Interfacial Energetics at a Tantalum Nitride/Electrolyte Heterojunction during Photoelectrochemical Water Splitting by *Operando* Ambient Pressure X-ray Photoelectron Spectroscopy. *ACS Catalysis*, *13*(17), 11762–11770. **[Crossref]**

Danino, D. (2012). Cryo-TEM of soft molecular assemblies. *Current Opinion in Colloid & Interface Science*, *17*(6), 316–329. **[Crossref]**

Dumestre, F., Chaudret, B., Amiens, C., Respaud, M., Fejes, P., Renaud, P., & Zurcher, P. (2003). Unprecedented Crystalline Super-Lattices of Monodisperse Cobalt Nanorods. *Angewandte Chemie International Edition*, *42*(42), 5213–5216. **[Crossref]**

Eastlake, A. C., Beaucham, C., Martinez, K. F., Dahm, M. M., Sparks, C., Hodson, L. L., & Geraci, C. L. (2016). Refinement of the Nanoparticle Emission Assessment Technique into the Nanomaterial Exposure Assessment Technique (NEAT 2.0). *Journal of Occupational and Environmental Hygiene*, *13*(9), 708–717. **[Crossref]**

Elaissari, A., Chatterjee, J., Hamoudeh, M., & Fessi, H. (2009). Advances in the Preparation and Biomedical Applications of Magnetic Colloids. In R. Hidalgo-√Álvarez (Ed.), *Structure and Functional Properties of Colloidal Systems* (Vol. 20093872, pp. 315–337). CRC Press. **[Crossref]**

Elliott, D. W., & Zhang, W. (2001). Field Assessment of Nanoscale Bimetallic Particles for Groundwater Treatment. *Environmental Science & Technology*, *35*(24), 4922–4926. **[Crossref]**

Fang, M., Ström, V., Olsson, R. T., Belova, L., & Rao, K. V. (2011). Rapid mixing: A route to synthesize magnetite nanoparticles with high moment. *Applied Physics Letters*, *99*(22), 222501. **[Crossref]**

Ghosh S, et al. (2021) Microbial Nano-Factories: Synthesis and Biomedical Applications. *Front Chem* 9:626834. **[Crossref]**

Gilchrist, R. K., Medal, R., Shorey, W. D., Hanselman, R. C., Parrott, J. C., & Taylor, C. B. (1957). Selective Inductive Heating of Lymph Nodes: *Annals of Surgery*, *146*(4), 596–606. **[Crossref]**

Gioria, S., Caputo, F., Urbán, P., Maguire, C. M., Bremer-Hoffmann, S., Prina-Mello, A., Calzolai, L., & Mehn, D. (2018). Are existing standard methods suitable for the evaluation of nanomedicines: Some case studies. *Nanomedicine*, *13*(5), 539–554. **[Crossref]**

Gleich, B., & Weizenecker, J. (2005). Tomographic imaging using the nonlinear response of magnetic particles. *Nature*, *435*(7046), 1214–1217. **[Crossref]**

González, V., Kharisov, B., & Gómez, I. (2019). Preparation, optical characterization and stability of gold nanoparticles by facile methods. *Revista Mexicana de Física*, *65*(6 Nov-Dec), 690–698. **[Crossref]**

Grass, R. N., Athanassiou, E. K., & Stark, W. J. (2007). Covalently Functionalized Cobalt Nanoparticles as a Platform for Magnetic Separations in Organic Synthesis. *Angewandte Chemie International Edition*, *46*(26), 4909–4912. **[Crossref]**

Grass, R. N., & Stark, W. J. (2006). Gas phase synthesis of fcc-cobalt nanoparticles. *Journal of Materials Chemistry*, *16*(19), 1825. **[Crossref]**

Guerrero, G., Mutin, P. H., & Vioux, A. (2001). Anchoring of Phosphonate and Phosphinate Coupling Molecules on Titania Particles. *Chemistry of Materials*, *13*(11), 4367–4373. **[Crossref]**

Gupta, M., Naqvi, N., Kumar, P. (2017). i AMF – Centralized database of arbuscular mycorrhizal distribution, phylogeny and taxonomy. Journal of Recent Advances in Applied Sciences, 30 (1). 1 - 5 < http://www.jraas.org/ >

Hamley, I. W. (2021). *Small-angle scattering: Theory, instrumentation, data and applications* (First edition). Wiley.

Hamoudi, H., & Esaulov, V. A. (2016). Selfassembly of α,ω-dithiols on surfaces and metal dithiol heterostructures. *Annalen Der Physik*, *528*(3–4), 242–263. **[Crossref]**

Hassellöv, M., Readman, J. W., Ranville, J. F., & Tiede, K. (2008). Nanoparticle analysis and characterization methodologies in environmental risk assessment of engineered nanoparticles. *Ecotoxicology*, *17*(5), 344–361. **[Crossref]**

Heydari, M., Javidi, M., Attar, M. M., Karimi, A., Navidbakhsh, M., Haghpanahi, M., & Amanpour, S. (2015). MAGNETIC FLUID HYPERTHERMIA IN A CYLINDRICAL GEL CONTAINS WATER FLOW. *Journal of Mechanics in Medicine and Biology*, *15*(05), 1550088. **[Crossref]**

Hoshyar, N., Gray, S., Han, H., & Bao, G. (2016). The effect of nanoparticle size on *in vivo* pharmacokinetics and cellular interaction. *Nanomedicine*, *11*(6), 673–692. **[Crossref]**

Hou, Y., Sun, S., Rong, C., & Liu, J. P. (2007). Sm Co 5 ∕ Fe nanocomposites synthesized from reductive annealing of oxide nanoparticles. *Applied Physics Letters*, *91*(15), 153117. **[Crossref]**

Hou, Y., Xu, Z., Peng, S., Rong, C., Liu, J. P., & Sun, S. (2007). A Facile Synthesis of SmCo $_5$ Magnets from Core/Shell Co/Sm $_2$ O $_3$ Nanoparticles. *Advanced Materials*, *19*(20), 3349–3352. **[Crossref]**

Hyeon, T. (2003). Chemical synthesis of magnetic nanoparticles. *Chemical Communications*, *8*, 927–934. **[Crossref]**

Iglesias-Juez, A., Chiarello, G. L., Patience, G. S., & Guerrero-Pérez, M. O. (2022). Experimental methods in chemical engineering: X -ray absorption spectroscopy— XAS , XANES , EXAFS. *The Canadian Journal of Chemical Engineering*, *100*(1), 3–22. **[Crossref]**

Iliasov, A. R., Nizamov, T. R., Naumenko, V. A., Garanina, A. S., Vodopyanov, S. S., Nikitin, A. A., Pershina, A. G., Chernysheva, A. A., Kan, Y., Mogilnikov, P. S., Metelkina, O. N., Schetinin, I. V., Savchenko, A. G., Majouga, A. G., & Abakumov, M. A. (2021). Non-magnetic shell coating of magnetic nanoparticles as key factor of toxicity for cancer cells in a low frequency alternating magnetic field. *Colloids and Surfaces B: Biointerfaces*, *206*, 111931. **[Crossref]**

Inkson, B. J. (2016). Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for materials characterization. In *Materials Characterization Using Nondestructive Evaluation (NDE) Methods* (pp. 17–43). Elsevier. **[Crossref]**

Janko, C., Ratschker, T., Nguyen, K., Zschiesche, L., Tietze, R., Lyer, S., & Alexiou, C. (2019). Functionalized Superparamagnetic Iron Oxide Nanoparticles (SPIONs) as Platform for the Targeted Multimodal Tumor Therapy. *Frontiers in Oncology*, *9*, 59. **[Crossref]**

Javidi, M., Heydari, M., Attar, M. M., Haghpanahi, M., Karimi, A., Navidbakhsh, M., & Amanpour, S. (2015). Cylindrical agar gel with fluid flow subjected to an alternating magnetic field during hyperthermia. *International Journal of Hyperthermia*, *31*(1), 33–39. **[Crossref]**

Johnson, S. H., Johnson, C. L., May, S. J., Hirsch, S., Cole, M. W., & Spanier, J. E. (2010). Co@CoO@Au core-multi-shell nanocrystals. *J. Mater. Chem.*, *20*(3), 439–443. **[Crossref]**

Joseph, T., Kar Mahapatra, D., Esmaeili, A., Piszczyk, Ł., Hasanin, M., Kattali, M., Haponiuk, J., & Thomas, S. (2023). Nanoparticles: Taking a Unique Position in Medicine. *Nanomaterials*, *13*(3), 574. **[Crossref]**

Kaiser, D. L., & Chalfin, K. (2017). Standards from ASTM International Technical Committee E 56 on Nanotechnology. In E. Mansfield, D. L. Kaiser, D. Fujita, & M. Van De Voorde (Eds.), *Metrology and Standardization of Nanotechnology* (1st ed., pp. 269–278). Wiley. **[Crossref]**

Kavre, I., Kostevc, G., Kralj, S., Vilfan, A., & Babič, D. (2014). Fabrication of magneto-responsive microgears based on magnetic nanoparticle embedded PDMS. *RSC Adv.*, *4*(72), 38316–38322. **[Crossref]**

Kim, D., Park, J., An, K., Yang, N.-K., Park, J.-G., & Hyeon, T. (2007). Synthesis of Hollow Iron Nanoframes. *Journal of the American Chemical Society*, *129*(18), 5812–5813. **[Crossref]**

Kim, J., Kang, S., Cheng, F., Wang, Y., Ye, X., & Park, J. (2024). Recent advances in liquid phase transmission electron microscopy of nanoparticle growth and self-assembly. *MRS Bulletin*, *49*(4), 365–376. **[Crossref]**

Klaessig, F., Marrapese, M., & Abe, S. (2011). Current Perspectives in Nanotechnology Terminology and Nomenclature. In V. Murashov & J. Howard (Eds.), *Nanotechnology Standards* (pp. 21–52). Springer New York. **[Crossref]**

Kolosnjaj-Tabi, J., Lartigue, L., Javed, Y., Luciani, N., Pellegrino, T., Wilhelm, C., Alloyeau, D., & Gazeau, F. (2016). Biotransformations of magnetic nanoparticles in the body. *Nano Today*, *11*(3), 280–284. **[Crossref]**

Kralj, S., Makovec, D., Čampelj, S., & Drofenik, M. (2010). Producing ultra-thin silica coatings on iron-oxide nanoparticles to improve their surface reactivity. *Journal of Magnetism and Magnetic Materials*, *322*(13), 1847–1853. **[Crossref]**

Kralj, S., Rojnik, M., Romih, R., Jagodič, M., Kos, J., & Makovec, D. (2012). Effect of surface charge on the cellular uptake of fluorescent magnetic nanoparticles. *Journal of Nanoparticle Research*, *14*(10), 1151. **[Crossref]**

Kuzmann, E., Homonnay, Z., Klencsár, Z., & Szalay, R. (2021). 57Fe Mössbauer Spectroscopy as a Tool for Study of Spin States and Magnetic Interactions in Inorganic Chemistry. *Molecules*, *26*(4), 1062. **[Crossref]**

Leibowitz, M. (2017). International Electrotechnical Commission: Nanotechnology Standards. In E. Mansfield, D. L. Kaiser, D. Fujita, & M. Van De Voorde (Eds.), *Metrology and Standardization of Nanotechnology* (1st ed., pp. 279–288). Wiley. **[Crossref]**

Li, X., Wang, B., Zhou, S., Chen, W., Chen, H., Liang, S., Zheng, L., Yu, H., Chu, R., Wang, M., Chai, Z., & Feng, W. (2020). Surface chemistry governs the sub-organ transfer, clearance and toxicity of functional gold nanoparticles in the liver and kidney. *Journal of Nanobiotechnology*, *18*(1), 45. **[Crossref]**

Lin, P.-C., Lin, S., Wang, P. C., & Sridhar, R. (2014). Techniques for physicochemical characterization of nanomaterials. *Biotechnology Advances*, *32*(4), 711–726. **[Crossref]**

Linsinger, T. P. J., Roebben, G., Solans, C., & Ramsch, R. (2011). Reference materials for measuring the size of nanoparticles. *TrAC Trends in Analytical Chemistry*, *30*(1), 18–27. **[Crossref]**

Liu, H., M. Fu, X. Jin, Y. Shang, D. Shindell, G. Faluvegi, C. Shindell, and K. He, 2016: Health and climate impacts of ocean-going vessels in East Asia. Nat. Clim. Change, 6, no. 11, 1037-1041. **[Crossref]**

Lu, A., Salabas, E. L., & Schüth, F. (2007). Magnetic Nanoparticles: Synthesis, Protection, Functionalization, and Application. *Angewandte Chemie International Edition*, *46*(8), 1222–1244. **[Crossref]**

Lu, A., Schmidt, W., Matoussevitch, N., Bönnemann, H., Spliethoff, B., Tesche, B., Bill, E., Kiefer, W., & Schüth, F. (2004). Nanoengineering of a Magnetically Separable Hydrogenation Catalyst. *Angewandte Chemie International Edition*, *43*(33), 4303–4306. **[Crossref]**

Lu, S., Antonov, S., Li, L., Liu, C., Zhang, X., Zheng, Y., Fraser, H. L., & Feng, Q. (2020). Atomic structure and elemental segregation behavior of creep defects in a Co-Al-W-based single crystal superalloys under high temperature and low stress. *Acta Materialia*, *190*, 16–28. **[Crossref]**

Mahendran, V., & Philip, J. (2012). Nanofluid based optical sensor for rapid visual inspection of defects in ferromagnetic materials. *Applied Physics Letters*, *100*(7), 073104. **[Crossref]**

Maitra, A., Bates, S., Kolvekar, T., Devarajan, P. V., Guzman, J. D., & Bhakta, S. (2015). Repurposing—A ray of hope in tackling extensively drug resistance in tuberculosis. *International Journal of Infectious Diseases*, *32*, 50–55. **[Crossref]**

Maldonado-Camargo, L., Unni, M., & Rinaldi, C. (2017). Magnetic Characterization of Iron Oxide Nanoparticles for Biomedical Applications. In S. H. Petrosko & E. S. Day (Eds.), *Biomedical Nanotechnology* (Vol. 1570, pp. 47–71). Springer New York. **[Crossref]**

Malhotra, N., Lee, J.-S., Liman, R. A. D., Ruallo, J. M. S., Villaflores, O. B., Ger, T.-R., & Hsiao, C.-D. (2020). Potential Toxicity of Iron Oxide Magnetic Nanoparticles: A Review. *Molecules*, *25*(14), 3159. **[Crossref]**

Mansfield, E., Hartshorn, R., & Atkinson, A. (2017). Nanomaterial Recommendations from the International Union of Pure and Applied Chemistry. In E. Mansfield, D. L. Kaiser, D. Fujita, & M. Van De Voorde (Eds.), *Metrology and Standardization of Nanotechnology* (1st ed., pp. 299–306). Wiley. **[Crossref]**

Mehta, A. P., & Pardeshi, C. V. (2023). Multifunctional Magnetic Nanoparticles: An Effective Theranostic Carrier System. In C. V. Pardeshi (Ed.), *Nanomaterial-Based Drug Delivery Systems* (pp.

175–207). Springer International Publishing. **[Crossref]**

Meng, X., Seton, H. C., Lu, L. T., Prior, I. A., Thanh, N. T. K., & Song, B. (2011). Magnetic CoPt nanoparticles as MRI contrast agent for transplanted neural stem cells detection. *Nanoscale*, *3*(3), 977. **[Crossref]**

Mohammed, L., Gomaa, H. G., Ragab, D., & Zhu, J. (2017). Magnetic nanoparticles for environmental and biomedical applications: A review. *Particuology*, *30*, 1–14. **[Crossref]**

Monteserín, M., Larumbe, S., Martínez, A. V., Burgui, S., & Francisco Martín, L. (2021). Recent Advances in the Development of Magnetic Nanoparticles for Biomedical Applications. *Journal of Nanoscience and Nanotechnology*, *21*(5), 2705–2741. **[Crossref]**

Mornet, S., Vasseur, S., Grasset, F., Veverka, P., Goglio, G., Demourgues, A., Portier, J., Pollert, E., & Duguet, E. (2006). Magnetic nanoparticle design for medical applications. *Progress in Solid State Chemistry*, *34*(2–4), 237–247. **[Crossref]**

Mourdikoudis, S., Pallares, R. M., & Thanh, N. T. K. (2018). Characterization techniques for nanoparticles: Comparison and complementarity upon studying nanoparticle properties. *Nanoscale*, *10*(27), 12871–12934. **[Crossref]**

Murray, C. B., Sun, S., Doyle, H., & Betley, T. (2001). Monodisperse 3 *d* Transition-Metal (Co,Ni,Fe) Nanoparticles and Their Assembly intoNanoparticle Superlattices. *MRS Bulletin*, *26*(12), 985–991. **[Crossref]**

Mylkie, K., Nowak, P., Rybczynski, P., & Ziegler-Borowska, M. (2021). Polymer-Coated Magnetite Nanoparticles for Protein Immobilization. *Materials*, *14*(2), 248. **[Crossref]**

Nam, K. M., Shim, J. H., Ki, H., Choi, S., Lee, G., Jang, J. K., Jo, Y., Jung, M., Song, H., & Park, J. T. (2008). Single-Crystalline Hollow Face-Centered-Cubic Cobalt Nanoparticles from Solid Face-Centered-Cubic Cobalt Oxide Nanoparticles. *Angewandte Chemie International Edition*, *47*(49), 9504–9508. **[Crossref]**

Nurettin Sezer, İbrahim Arı, Yusuf Biçer, Muammer Koç, Superparamagnetic nanoarchitectures: Multimodal functionalities and applications, Journal of Magnetism and Magnetic Materials, Volume 538,2021,168300,ISSN 0304-8853. **[Crossref]**.

*Occupational exposure sampling for engineered nanomaterials.* (2022). U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. **[Crossref]**

Panahi, F., Bahrami, F., & Khalafi-Nezhad, A. (2017). Magnetic nanoparticles grafted l-carnosine dipeptide: Remarkable catalytic activity in water at room temperature. *Journal of the Iranian Chemical Society*, *14*(10), 2211–2220. **[Crossref]**

Parekh, K., Nair, J., & Bhardwaj, A. (2020). Biosynthesis of magnetite nanoparticles: An eco-friendly and scalable approach. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, *11*(3), 035014. **[Crossref]**

Philip, J., Mahendran, V., & Felicia, L. J. (2013). A Simple, In-Expensive and Ultrasensitive Magnetic Nanofluid Based Sensor for Detection of Cations, Ethanol and Ammonia. *Journal of Nanofluids*, *2*(2), 112–119. **[Crossref]**

Philip, J., Shima, P. D., & Raj, B. (2008). Nanofluid with tunable thermal properties. *Applied Physics Letters*, *92*(4), 043108. **[Crossref]**

Powers, K. W., Brown, S. C., Krishna, V. B., Wasdo, S. C., Moudgil, B. M., & Roberts, S. M. (2006). Research Strategies for Safety Evaluation of Nanomaterials. Part VI. Characterization of Nanoscale Particles for Toxicological Evaluation. *Toxicological Sciences*, *90*(2), 296–303. **[Crossref]**

Powers, K. W., Palazuelos, M., Moudgil, B. M., & Roberts, S. M. (2007). Characterization of the size, shape, and state of dispersion of nanoparticles for toxicological studies. *Nanotoxicology*, *1*(1), 42–51. **[Crossref]**

Ramaswamy, B., Kulkarni, S. D., Villar, P. S., Smith, R. S., Eberly, C., Araneda, R. C., Depireux, D. A., & Shapiro, B. (2015). Movement of magnetic nanoparticles in brain tissue: Mechanisms and impact on normal neuronal function. *Nanomedicine: Nanotechnology, Biology and Medicine*, *11*(7), 1821–1829. **[Crossref]**

Reeves, D. B. (2017). Nonlinear Nonequilibrium Simulations of Magnetic Nanoparticles. In C. S. S. R. Kumar (Ed.), *Magnetic Characterization Techniques for Nanomaterials* (pp. 121–156). Springer Berlin Heidelberg. **[Crossref]**

Reeves, D. B., & Weaver, J. B. (2012). Simulations of magnetic nanoparticle Brownian motion. *Journal of Applied Physics*, *112*(12), 124311. **[Crossref]**

Reeves, D. B., & Weaver, J. B. (2014). Approaches for Modeling Magnetic Nanoparticle Dynamics. *Critical Reviews in Biomedical Engineering*, *42*(1), 85–93. **[Crossref]**

Rivera-Rodriguez, A., & Rinaldi-Ramos, C. M. (2021). Emerging Biomedical Applications Based on the Response of Magnetic Nanoparticles to Time-Varying Magnetic Fields. *Annual Review of Chemical and Biomolecular Engineering*, *12*(1), 163–185. **[Crossref]**

Ross Hallett, F. (1999). Scattering and Particle Sizing Applications*. In *Encyclopedia of Spectroscopy and Spectrometry* (pp. 2488–2494). Elsevier. **[Crossref]**

Rusly, S. N. A., Jamal, S. H., Samsuri, A., Mohd Noor, S. A., & Abdul Rahim, K. S. (2024). Stabilizer selection and formulation strategies for enhanced stability of single base nitrocellulose propellants: A review. *Energetic Materials Frontiers*, *5*(1), 52–69. **[Crossref]**

Russo, R., Esposito, E., Granata, C., Vettoliere, A., Russo, M., Cannas, C., Peddis, D., & Fiorani, D. (2012).

Magnetic Nanoparticle Characterization Using Nano-SQUID based on Niobium Dayem Bridges. *Physics Procedia*, *36*, 293–299. **[Crossref]**

Sattler MA, Mtasiwa D, Kiama M, Premji Z, Tanner M, Killeen GF, Lengeler C. 2005. Habitat characterization and spatial distribution of *Anopheles* sp. mosquito larvae in Dar es Salaam (Tanzania) during an extended dry period. *Malaria J* 4: 4. **[Crossref]**

Schaffer, B., Grogger, W., Kothleitner, G., & Hofer, F. (2010). Comparison of EFTEM and STEM EELS plasmon imaging of gold nanoparticles in a monochromated TEM. *Ultramicroscopy*, *110*(8), 1087–1093. **[Crossref]**

Schätz, A., Grass, R. N., Kainz, Q., Stark, W. J., & Reiser, O. (2010). Cu(II)−Azabis(oxazoline) Complexes Immobilized on Magnetic Co/C Nanoparticles: Kinetic Resolution of 1,2-Diphenylethane-1,2-diol under Batch and Continuous-Flow Conditions. *Chemistry of Materials*, *22*(2), 305–310. **[Crossref]**

Schätz, A., Grass, R. N., Stark, W. J., & Reiser, O. (2008). TEMPO Supported on Magnetic C/Co-Nanoparticles: A Highly Active and Recyclable Organocatalyst. *Chemistry – A European Journal*, *14*(27), 8262–8266. **[Crossref]**

Schätz, A., Reiser, O., & Stark, W. J. (2010). Nanoparticles as Semi-Heterogeneous Catalyst Supports. *Chemistry – A European Journal*, *16*(30), 8950–8967. **[Crossref]**

Schneider-Futschik, E. K., & Reyes-Ortega, F. (2021). Advantages and Disadvantages of Using Magnetic Nanoparticles for the Treatment of Complicated Ocular Disorders. *Pharmaceutics*, *13*(8), 1157. **[Crossref]**

Seo, W. S., Lee, J. H., Sun, X., Suzuki, Y., Mann, D., Liu, Z., Terashima, M., Yang, P. C., McConnell, M. V., Nishimura, D. G., & Dai, H. (2006). FeCo/graphitic-shell nanocrystals as advanced magnetic-resonance-imaging and near-infrared agents. *Nature Materials*, *5*(12), 971–976. **[Crossref]**

Shankar, S.S., et al. (2004) Rapid Synthesis of Au, Ag, and Bimetallic Au Core-Ag Shell Nanoparticles Using Neem (Azadirachta indica) Leaf Broth. Journal of Colloid and Interface Science, 275, 496-502. **[Crossref]**

Sharifi, I., Shokrollahi, H., & Amiri, S. (2012). Ferrite-based magnetic nanofluids used in hyperthermia applications. *Journal of Magnetism and Magnetic Materials*, *324*(6), 903–915. **[Crossref]**

Stavis, S. M., Fagan, J. A., Stopa, M., & Liddle, J. A. (2018). Nanoparticle Manufacturing – Heterogeneity through Processes to Products. *ACS Applied Nano Materials*, *1*(9), 4358–4385. **[Crossref]**

Stiufuc, G. F., & Stiufuc, R. I. (2024). Magnetic Nanoparticles: Synthesis, Characterization, and Their Use in Biomedical Field. *Applied Sciences*, *14*(4), 1623. **[Crossref]**

Suji Choi, Sang Ihn Han, Dokyoon Kim, Taeghwan Hyeon, Dae-Hyeong Kim (2019) High-performance stretchable conductive nanocomposites: materials, processes, and device applications. Royal Society of Chemistry. **[Crossref]**

Tadic, M., Kralj, S., Jagodic, M., Hanzel, D., & Makovec, D. (2014). Magnetic properties of novel superparamagnetic iron oxide nanoclusters and their peculiarity under annealing treatment. *Applied Surface Science*, *322*, 255–264. **[Crossref]**

Talian, I., Orinák, A., Preisler, J., Heile, A., Onofrejová, L., Kaniansky, D., & Arlinghaus, H. F. (2007). Comparative TOF-SIMS and MALDI TOF-MS analysis on different chromatographic planar substrates. *Journal of Separation Science*, *30*(16), 2570–2582. **[Crossref]**

Tartaj, P., Morales, M. A. D. P., Veintemillas-Verdaguer, S., Gonz lez-Carre O, T., & Serna, C. J. (2003). The preparation of magnetic nanoparticles for applications in biomedicine. *Journal of Physics D: Applied Physics*, *36*(13), R182–R197. **[Crossref]**

Tebyetekerwa, M., Zhang, J., Xu, Z., Truong, T. N., Yin, Z., Lu, Y., Ramakrishna, S., Macdonald, D., & Nguyen, H. T. (2020). Mechanisms and Applications of Steady-State Photoluminescence Spectroscopy in Two-Dimensional Transition-Metal Dichalcogenides. *ACS Nano*, *14*(11), 14579–14604. **[Crossref]**

Thersleff, T., Budnyk, S., Drangai, L., & Slabon, A. (2020). Dissecting complex nanoparticle heterostructures via multimodal data fusion with aberration-corrected STEM spectroscopy. *Ultramicroscopy*, *219*, 113116. **[Crossref]**

Tiede, K., Boxall, A. B. A., Tear, S. P., Lewis, J., David, H., & Hassellöv, M. (2008). Detection and characterization of engineered nanoparticles in food and the environment. *Food Additives & Contaminants: Part A*, *25*(7), 795–821. **[Crossref]**

Tomczak, P., & Puszkarski, H. (2020). Interpretation of ferromagnetic resonance experimental results by cross-validation of solutions of the Smit-Beljers equation. *Journal of Magnetism and Magnetic Materials*, *507*, 166824. **[Crossref]**

Tsagkaris, A. S., Bechynska, K., Ntakoulas, D. D., Pasias, I. N., Weller, P., Proestos, C., & Hajslova, J. (2023). Investigating the impact of spectral data pre-processing to assess honey botanical origin through Fourier transform infrared spectroscopy (FTIR). *Journal of Food Composition and Analysis*, *119*, 105276. **[Crossref]**

Vaghari, H., Jafarizadeh-Malmiri, H., Mohammadlou, M., Berenjian, A., Anarjan, N., Jafari, N., & Nasiri, S. (2016). Application of magnetic nanoparticles in smart enzyme immobilization. *Biotechnology Letters*, *38*(2), 223–233. **[Crossref]**

Van Dijk, T., Bakker, M. S., Holtrop, F., Nieger, M., Slootweg, J. C., & Lammertsma, K. (2015). Base-Stabilized Nitrilium Ions as Convenient Imine

Synthons. *Organic Letters*, *17*(6), 1461–1464. **[Crossref]**

Wang J, et al. (2015) Identifying a Rab effector on the macroautophagy pathway. *Methods Mol Biol* 1298:117-25. **[Crossref]**

Wang, C., Hou, Y., Kim, J., & Sun, S. (2007). A General Strategy for Synthesizing FePt Nanowires and Nanorods. *Angewandte Chemie International Edition*, *46*(33), 6333–6335. **[Crossref]**

Weizenecker, J., Gleich, B., Rahmer, J., Dahnke, H., & Borgert, J. (2009). Three-dimensional real-time *in vivo* magnetic particle imaging. *Physics in Medicine and Biology*, *54*(5), L1–L10. **[Crossref]**

Wong, D. W., Gan, W. L., Teo, Y. K., & Lew, W. S. (2018). Interplay of cell death signaling pathways mediated by alternating magnetic field gradient. *Cell Death Discovery*, *4*(1), 49. **[Crossref]**

Wu, B., Majumdar, R. D., Lysak, D. H., Ghosh Biswas, R., Tabatabaei-Anaraki, M., Jenne, A., You, X., Soong, R., Lane, D., Helm, P. A., Codina, A., Decker, V., Simpson, M. J., & Simpson, A. J. (2021). Towards real-time kinetic monitoring of wastewater treatment: A case study of sunlight and ozone treatment of unconcentrated wastewater using flow NMR. *Chemical Engineering Journal*, *405*, 126696. **[Crossref]**

Yazdani, S., & Pettes, M. T. (2018). Nanoscale self-assembly of thermoelectric materials: A review of chemistry-based approaches. *Nanotechnology*, *29*(43), 432001. **[Crossref]**

Yoon, T.-J., Lee, W., Oh, Y.-S., & Lee, J.-K. (2003). Magnetic nanoparticles as a catalyst vehicle for simple and easy recyclingElectronic supplementary information (ESI) available: XRD and FT-IR data, as well as the detailed experimental conditions for the catalytic hydroformylation reactions. See http://www.rsc.org/suppdata/nj/b2/b209391j/. *New Journal of Chemistry*, *27*(2), 227–229. **[Crossref]**

Zhang, X., Reeves, D. B., Perreard, I. M., Kett, W. C., Griswold, K. E., Gimi, B., & Weaver, J. B. (2013). Molecular sensing with magnetic nanoparticles using magnetic spectroscopy of nanoparticle Brownian motion. *Biosensors and Bioelectronics*, *50*, 441–446. **[Crossref]**