A Review Study of Magnetic Nano-Particles Synthesis, Characterization Methods and Applications

Manoj Kumar[a], and Genius Walia[b]

Department of Physics, University College of Basic Sciences & Humanities Guru Kashi University, Bathinda, Punjab, India.

[a] manojjt977@gmail.com
[b] waliagenius@gmail.com

Abstract

Magnetic nanoparticles (MNPs) have drawn a lot of interest due to their special qualities, which include large surface area, super para magnetism, and ease of functionalization. These qualities make MNPs perfect for use in electronics, biomedicine, and environmental remediation. This article delivers a critical and nuanced overview, integrating diverse perspectives to advance a deeper understanding of MNP synthesis, characterization, and applications. Typical synthesis methods are covered, such as sol-gel, hydrothermal, thermal decomposition, and co-precipitation. This paper also covers important characterization methods for evaluating the structural and magnetic properties of MNPs, including vibrating sample magnetometry (VSM), X-ray diffraction (XRD), and transmission electron microscopy (TEM). The many uses of MNPs in areas such as environmental pollution control, bio-sensing, and biomedicine are also covered. In addition to offering mechanistic insight into the synthesis, functionalization, and use of MNPs, this thorough analysis also describes the limitations and future possibilities.

Keywords: Magnetic nanoparticles, Synthesis, Characterization, Applications.
Received 27 January 2025; First Review 23 February 2025; Accepted 24 March 2025.

*** Address of correspondence**
Manoj Kumar
Department of Physics, University College of Basic Sciences & Humanities Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India.
Email: manojjt977@gmail.com

How to cite this article
Manoj Kumar, and Genius Walia, A Review Study of Magnetic Nano-Particles Synthesis, Characterization Methods and Applications, J. Cond. Matt. 2025; 03 (02): 21-26.

Available from:
https://doi.org/10.61343/jcm.v3i02.61

Introduction

The science of manipulating or miniaturizing matter at the atomic and molecular levels and dealing with matter at the scale of one billionth of a meter (1 nm = 10^{-9} m), is known as nanotechnology. In general, the nanoparticle size ranges from 1nm to 100 nm [1]. The prefix "nano" is used to denote "one billionth" of something. Richard Phillips Feynman has been introduced first of all the idea of nanotechnology in the meeting of American Physical Society in December 1959 with his well-known speech, "There's plenty of room at the bottom" [2].

Magnetic nanoparticles (MNPs) are those nanoparticles which shows unique magnetic properties. These nanoparticles have size range from 1 to 200 nanometres and are prepared by the magnetic materials such as nickel, cobalt, iron etc. Today's theoretical foundation for the manufacture and use of magnetic nanoparticles (MNPs) is largely based on Néel's discoveries about the magnetic behaviour of tiny particles. His contributions to solid-state physics and magnetism won him the 1970 Nobel Prize in Physics. Due to unique properties MNPs are used widely in many applications such as biomedicine, data storage and environmental remediation.

In recent years, nanoparticles of magnetic nature have gained numerous attention due to their special qualities and uses. In this study the synthesis, characterization and applications of magnetic nano particles are briefly explained.

Synthesis Methods

Different synthesis methods are utilized to get magnetic nano particles of suitable size, morphology, stability and biocompatibility. All these methods are categorised into three different kinds: -

1. Chemical synthesis methods

2. Physical synthesis methods

3. Biological synthesis methods

Following figure (1) shows a pictorial representation of MNPs synthesis using chemical, physical and biological synthesis methods.

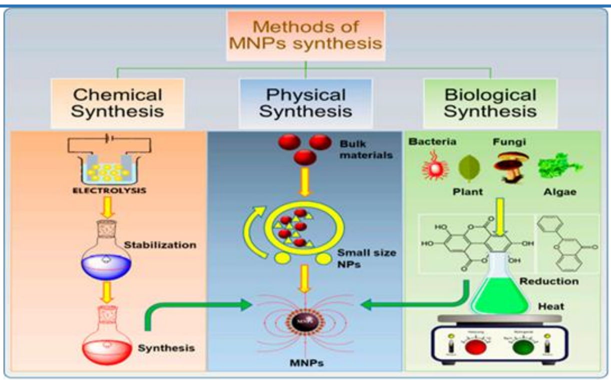

Figure 1: Shows chemical, physical and biological synthesis methods of synthesising magnetic nanoparticles [3].

1. Chemical Synthesis Methods

There are several bottom-up approaches to chemical synthesis for magnetic nano particles. The following are few popular methods typically used to synthesize magnetic nano particles.

1.1 Coprecipitation Synthesis Method

Coprecipitation is the mostly used method for preparing MNPs having controlled size and required magnetic properties [4]. With this method, a base is combined with an inert environment at ambient temperature to combine the Fe (II) ion and Fe (III) aqueous salt solution. Cost-effective, large quantities production and mild condition operation are the advantages of this method. Limited control over particle size and shape, aggregation of prepared nanoparticles and impurities are the disadvantages of coprecipitation method.

Following figure (2) represents the coprecipitation synthesis method for preparation of Fe_3O_4 nano-particles.

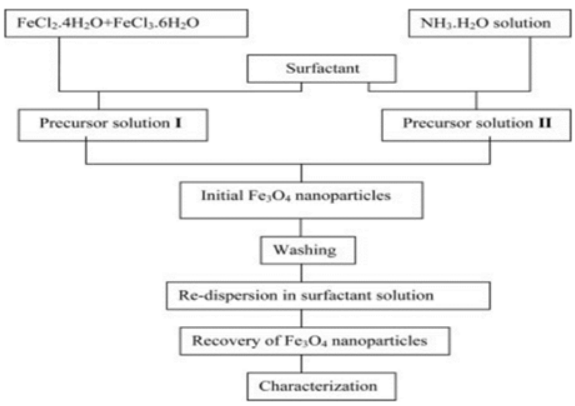

Figure 2: shows the coprecipitation method for preparation of Fe_3O_4 magnetic nano-particles [5].

1.2 Thermal Decomposition Synthesis Method

The thermal decomposition synthesis method is commonly used for synthesis of iron oxide magnetic nanoparticles, particularly Fe_3O_4 and Fe_2O_3, which have various applications. By break down iron precursors with the help of heated natural surfactants, magnetic iron oxide nanoparticle samples with excellent crystallinity and size control have been produced [6]. The iron precursor is dissolved in a suitable solvent with a stabilizing agent such as oleic acid or oleylamine.

This forms a homogeneous solution or suspension. Then the solution is heated under controlled conditions to a specific temperature range, typically between 200°C to 400°C. At high temperatures, the iron precursor undergoes decomposition and release components such as water and organic ligands (if present) and desired iron oxide MNPs formed [7]. This technique has been accounted for as one of the most mind-blowing techniques to create MNPs of uniform size and homogeneous shape in large scale [8]. Disadvantage of this technique are environmental unfriendly synthesis and costly in nature.

1.3 Micro-emulsion Synthesis Method

Hydrophilic and lipophilic phases, which include surfactants and co-surfactants are constituents of micro-emulsions. This fluid is transparent and isotropic and is made up of water, oil, and amphiphile. This method includes mixing of oil and a surfactant to water while stirring them with magnetic stirrer between 100 to 20¬0C.

There are three kinds of micro-emulsions: - a) The fluid stage of oil in water (O/W), which contains some oil drops, b) Water in oil (W/O), wherein water droplets are present but oil is the dominating phase, c) In this type there is equal quantity of oil and water are used. For example, in the micro-emulsion of W/O type, a surfactant was applied to water droplets in organic solvent for shrinking the size of the MNPs [9-10]. This method yields size and shape MNPs, also suitable for coating nanoparticles with surfactants. But low yield, high cost and toxic organic solvent requirement are the disadvantages of micro-emulsion method.

1.4 Hydrothermal Synthesis Method

Various wet-chemical technologies are used in the hydrothermal method to crystallize material in an airtight vessel from an aqueous solution at high temperatures (between 130°C and 250°C) and high vapour pressures of range 0.3 and 4 MPa [11]. The amount to which minerals are soluble in water affects the crystallisation process. This method was used to create uniformly sized particles of several magnetic nanomaterials [12].

Zheng and others used the hydrothermal technique for producing Fe3O4 nanoparticles with the use of Aerosol-OT (AOT) as surfactant [13]. Advantages of this method are pure nanoparticles synthesis, good control over morphology and size and environment friendly also. Time consumption, special equipment requirement are the disadvantages of this method.

1.5 Sol-Gel Synthesis Method

This process produces gels at room temperature by hydrolysing and polycondensing metal alkoxides. Water or another solvent is used to dissolve metallic salts in order to create sol [14]. Because of Van der Waals interactions between the particles, which become increased as the temperature is increased and the mixture is stirred. In the end, gel is produced after the mixture is heated till the solvent has vaporized and the solution is dried out [15-16]. By using the sol-gel method Akbar and others have effectively manufactured α-Fe_2O_3 nanoparticles, and have investigated their magnetic properties [17]. Low processing temperature, high purity and homogeneity and fine nanoparticles production are the advantages of this method. Disadvantages of this method are long processing time for synthesis and high cost of instrument.

2. **Physical Synthesis Methods**

There are two types of physical methods which are bottom-up and top-down. The present study will cover three physical processes: wire explosion, laser evaporation, and ball milling.

2.1 Ball Milling Method/Mechanical Synthesis Method

High-energy impact grinding, or mechanical milling, can be done in a variety of mills, usually planetary and shaker mills, using balls inside of containers. The components of planetary mills are several cylindrical containers positioned on a rotating platform as shown in following figure (3). Each of the two horizontal rotations around the container axis and the base centre are included in the planetary movements. Shaker mills are often more efficient, but planetary mills offer greater versatility for producing samples in larger quantities. It is an easy-to-understand interaction that produces fine-finished particles by mechanically crushing coarse-finished particles [18-19]. Benjamin and colleagues created this method for the first time in 1970, and it creates homogenous composite particles with a consistent, closely spaced interior structure [20].

Figure 3: contains pictures of planetary and shaker mills.

2.2 Laser Evaporation Synthesis Method

This bottom-up technique involves condensation to synthesize nanoparticles from fluid or vaporous stages [21]. It is also used to manufacture iron oxide MNPs [22]. The raw materials used in this process are selected as coarse finished particles, which are vaporized through with the help of laser light. It is positioned at the base of a cell that has been lowered in a fluid arrangement and identified by laser radiation. A beam of laser light is used for irradiating the substance in the liquid solution. The material's vapours cooled to the gaseous stage, which causes a rapid accumulation and nucleation that results to nanoparticles formation [23].

2.3 Wire Explosion Synthesis Method

The modern physiochemical method of wire explosion produces MNPs in a safe and hygienic manner. This method is really helpful because it eliminates the necessity for retreating results or separating nanoparticles from the arrangement. Iron oxide MNPs were recently designed utilizing this technique to remove arsenic from water [24]. It protects the environment and uses the least amount of energy to create nano powders that are less polluting [25].

3. **Biological Synthesis Method**

It is renowned method which is used for producing MNPs in green synthesis way, involves microorganisms and plants [26]. This technique produces MNPs that are bio-resorbable and which are widely used in industry of biomedical. This approach has the advantages as efficiency, sustainability, and also environment friendly. While the nanoparticles are poorly dispersed is its drawback [27]. Scientists currently have a lot of interest in developing nanoparticles from plant tissue, concentrates, exudates, and other plant parts [28]. Researchers may have different viewpoints on the method chosen depending on their findings and intended usage. Because of this, there isn't only one method that is thought to be the most effective for producing MNPs. There are drawbacks to each strategy, and the choice is influenced by a variety of factors as size of prepared nanoparticles, their yield, their shape, morphology and experiment's expense.

Characterization Techniques

Characterizing the synthesized magnetic nanoparticles is crucial for understanding their properties and potential applications. Following are few commonly used characterization techniques.

1. **X-ray Diffraction (XRD) Technique**

• **Purpose:** this technique is used to determine the structural information of synthesized nanoparticles and purity of phase of the nanoparticles.

• **Description:** The diffraction pattern tells information about the crystal lattice parameters and the size of the crystallites.

2. **Transmission Electron Microscopy (TEM)**

• **Purpose:** this is used to determine the size, shape, and morphology of the synthesized nanoparticles.

• **Description:** High-resolution TEM (HRTEM) can results lattice fringes, providing insight into the crystallinity of the nanoparticles.

3. **Atomic Force Microscopy (AFM)**

• **Purpose:** AFM is used to determine three-dimensional surface topology, also provide information about particle size & aggregation.

4. **Fourier Transform Infrared Spectroscopy (FTIR)**

• **Purpose:** FTIR is used to identify the surface functional groups and bonding interactions on the nanoparticles.

• **Description:** This information is essential for understanding the surface chemistry and potential functionalization of the nanoparticles.

5. **Vibrating Sample Magnetometry (VSM)**

• **Purpose:** To measure the magnetic properties of the nanoparticles.

• **Description:** Properties measured include saturation magnetization, coercivity, and remanence. These are critical for applications in magnetic storage, imaging, and hyperthermia.

6. **Thermogravimetric Analysis (TGA)**

• **Purpose:** TGA is used to determine thermal stability of prepared MNPs by measuring weight loss with respect to temperature.

The characterization techniques are used according to the desired application purposes. Following Table-1 shows the comparative study of all above discussed techniques with their purposes, advantages and limitations

Table 1: Comparative study of magnetic nanoparticle characterization techniques.

Characterization Technique	Purpose	Advantages	Limitations
X-ray Diffraction (XRD)	Structural analysis, phase identification	Non-destructive, provides crystal structure information	Limited for amorphous materials, requires pure samples
Transmission Electron Microscopy (TEM)	Morphology and size analysis	High-resolution imaging, nanoscale analysis	Expensive, requires complex sample preparation
Atomic Force Microscopy (AFM)	Surface topography and mechanical properties	High spatial resolution, non-destructive, works in ambient conditions	Small scan area, slow scanning speed, possible tip-sample interaction artifacts
Fourier Transform Infrared Spectroscopy (FTIR)	Surface chemistry and functional group analysis	Quick analysis, useful for organic coatings	Limited to functional group detection, not quantitative
Vibrating Sample Magnetometry (VSM)	Magnetic property evaluation	Provides precise magnetic measurements	Requires a uniform sample
Thermogravimetric Analysis (TGA)	Thermal stability and composition	Quantifies organic coatings and thermal stability	Cannot analyse individual nanoparticle properties

Application of MNPs

The MNPs in last few years shows their importance on account of their outstanding results in different fields due to their unique properties. The use and applications of MNPs in a few prominent domains, including biomedicine, bio-detecting, climate, farming, and catalysis, have been compiled in this overview. The following is a brief overview of MNP's significant uses in these fields-

1. **Biomedicine**

Magnetic resonance imaging is improved because of ability of MNPs to interact with external fields and vary the magnetic fields in the surrounding area. Energy dissipation, translation and rotation caused by the many types of force and torque that the external applied magnetic field produces and generates at dipoles. There are numerous applications for such phenomena, such as separation of cells, biomarker development, and magnetic medication delivery, biomedical imaging, the detection of bacteria for theranostics, the induction of drug release, and hyperthermia.

2. **Bio-sensing**

MNPs-based sensors have been used in many industries with outstanding results, including food industry, laboratory, medical diagnostics, and environmental observing [29-30]. The biomedical sector has anticipated a broad range of applications for MNP-based biosensors because of its sensitivity, compact size, and exciting non-invasive detecting feature [31].

3. **Environment**

Because the release of hazardous, chemicals and compounds, degradation and contamination are becoming serious environmental problems. Wastewater, drinking water, ocean, and groundwater all contain various organic contaminants that could have major negative effects on human health [32-33]. It could be necessary to use some more effective methods to improve water quality. Nanotechnology is now being recognized as one of the better and more reliable substitutes for ordinary treatments. Purification of water and air has been reported to use nanomaterials, carbon, and metal oxide [34].

4. Agriculture

Numerous studies have been done demonstrating the effective use of metallic nanoparticles for improving soil quality, germination of seeds, and plant protection [35-36]. Iron oxide magnetic nanoparticles are used as soil nourishment to enhance production with very few losses [37].

5. Energy Storage

Data storage, electrochemical storage, and thermal storage are only a few of the energy storage systems that use MNPs, especially those made of pure metallic elements, because of their large surface area and magnetic features, which improve the efficiency of these systems [38].

6. Catalysis

MNPs have important benefits in the realm of catalysis because of their magnetic characteristics, which make separation and reusability simple. They have been successfully used in a number of catalytic processes, such as photo-oxidation and hydrogenation reactions [39].

Conclusion

The production of magnetic nanoparticles is a difficult process influenced by various parameters. Understanding and optimizing these parameters is crucial for producing nanoparticles with the desired properties for specific applications. This chapter provides a comprehensive summary of different synthesis methods, characterization techniques, laying the foundation for further research and development in this exciting field.

References

1. S Horikoshi and N Serpone, Microwaves in Nanoparticle Synthesis 1stedn (Berlin: Wiley) 2013.
2. R P Feynman, "*There's plenty of room at the bottom*", Engineering and Science 23, pages 22-36, 1960.
3. A Ali, T Shah, R Ullah, P Zhou, M Guo, M Ovais, Z Tan and Y Rui, "*Review on Recent Progress in Magnetic Nanoparticles: Synthesis, Characterization, and Diverse Applications*", Front. Chem.9:629054, 2021.
4. S K Vashist, *"Magnetic Nanoparticles-Based Biomedical and Bioanalytical Applications"*, Journal of Nanomedicine & Nanotechnology 04(02) e130, 2013.
5. J Sun, S Zhou, P Hou, Y Yang, J Weng, X Li and M Li, *"Synthesis and characterization of biocompatible Fe_3O_4 nanoparticles"*, Journal of Biomedical Materials Research Part AVolume 80A, Issue 2 p. 333-341, 2007.
6. TK Indira and PK Lakshmi, *"Magnetic nanoparticles - A review"*, International Journal of Pharmaceutical Sciences and Nanotechnology 3, pages 1035–1042, 2010.
7. Y W Jun, J W Seo and J Cheon, *"Nano scaling laws of magnetic nanoparticles and their applicability's in biomedical sciences"*, Accounts of Chemical Research, 41(02), pages 179-189, 2008.
8. J Kudr, Y Haddad, L Richtera, Z Heger, M Cernak, V Adam and O Zitka, *"Magnetic Nanoparticles: From Design and Synthesis to Real World Applications"*, Nanomaterials (Basel), 7(9), 243, 2017.
9. J A L Pérez, M A L Quintela, J Mira, J Rivas and S W Charles, *"Advances in the Preparation of Magnetic Nanoparticles by the Microemulsion Method"*, The Journal of Physical Chemistry B, 101 (41), pages 8045-8047, 1997.
10. J Mosayebi, M Kiyasatfar and S Laurent, Synthesis, *"Functionalization, and Design of Magnetic Nanoparticles for Theranostic Applications"*, Advanced Healthcare Materials, 6(23), 2017.
11. W Wu, Q He and C Jiang C, *"Magnetic Iron Oxide Nanoparticles: Synthesis and Surface Functionalization Strategies"*, Nanoscale Research Letters. 3, pages 397–415, 2008.
12. X Wang, J Zhuang, Q Peng and Y Li, *"A general strategy for nanocrystal synthesis"*, Nature 437(7055), 121-4, 2005.
13. Y Zheng, C Yao, B Feng and Y Wang, *"Synthesis and magnetic properties of Fe_3O_4 nanoparticles"*. Materials Research Bulletin. 41(3), 2006.
14. S A M K Ansari, E Ficiarà, F A Ruffinatti, I Stura, M Argenziano, O Abollino, R Cavalli, C Guiot and F D'Agata, *"Magnetic Iron Oxide Nanoparticles: Synthesis, Characterization and Functionalization for Biomedical Applications in the Central Nervous System"*, Materials, 12(3), 2019.

15. S Hasany, I Ahmed, J Rajan and A Rehman, *"Systematic Review of the Preparation Techniques of Iron Oxide Magnetic Nanoparticles"*, Nanoscience & Nanotechnology. 2, pages 148-158, 2012.
16. M T Mohammed and S Mohammed, *"Synthesis and characterization of nanocoating's derived by sol–gel onto a new surgical titanium surface"*, Materials Research Express, 6(7), 2019.
17. S Akbar, S K Hasanain, N Azmat and M Nadeem, *"Synthesis of Fe_2O_3 nanoparticles by new Sol-Gel method and their structural and magnetic characterizations"*, arXiv preprint condensed matter/0408480, 2004.
18. H J Fecht, E Hellstern, Z Fu and W L Johnson, "Nanocrystalline Metals Prepared by High-Energy Ball Milling", Metallurgical and Materials Transactions A, 21, pages 2333-2337, 1990.
19. M S El-Eskandarany, *"Mechanical Alloying for Fabrication of Advanced Engineering Materials"*, William Andrew Publishing/Noyes, New York, 2001.
20. J S Benjamin, *"Dispersion strengthened superalloys by mechanical alloying, Metallurgical Transactions"*, 1, pages 2943-2951, 1970.
21. P Biehl, M Von der Lühe, S Dutz and FH Schacher, *"Synthesis, Characterization, and Applications of Magnetic Nanoparticles Featuring Polyzwitterionic Coatings"*, Polymers (Basel), 10(1), 91, 2018.
22. D N Shin, Y Matsuda and E R Bernstein, *"On the iron oxide neutral cluster distribution in the gas phase. II. Detection through 118 nm single photon ionization"*, The Journal of Chemical Physics, 120(9), pages 4157–4164, 2004.
23. H Kurland, J Grabow, G Staupendahl, W Andrä, S Dutz and M E Bellemann, *"Magnetic iron oxide nanopowders produced by CO_2 laser evaporation"*, Journal of Magnetism and Magnetic Materials, 311, 73-77, 2007.
24. K Song, W Kim, C Y Suh, D Shin, K S Ko, and K Ha, *"Magnetic Iron Oxide Nanoparticles Prepared by Electrical Wire Explosion for Arsenic Removal"*, Powder Technology, 246, pages 572-574, 2013.
25. Y A Kotov, *"Electric Explosion of Wires as a Method for Preparation of Nanopowders"*, Journal of Nanoparticle Research. 5, pages 539-550, 2003.
26. R Verma, S Pathak, A K Srivastava, S Prawer and S Tomljenovic-Hanic, *"ZnO Nanomaterials: Green Synthesis, Toxicity Evaluation and New Insights in Biomedical Applications"*, Journal of Alloys and Compounds. 876 160175, 2021.
27. A Komeili, *"Molecular Mechanisms of Compartmentalization and Biomineralization in Magnetotactic Bacteria"*, FEMS Microbiology Reviews. 36, pages 232-255, 2012.
28. S Gul, S B Khan, I U Rehman, M A Khan and M Khan, *"A Comprehensive Review of Magnetic Nanomaterials Modern Day Theranostics"*, Frontiers in Materials. 6, 179, 2019.
29. J B Haun, T J Yoon, H Lee and R Weissleder, *"Magnetic Nanoparticle Biosensors"*, WIREs Nanomedicine and Nanobiotechnology. 2, pages 291-304, 2010.
30. T A P Rocha-Santos, *"Sensors and Biosensors Based on Magnetic Nanoparticles"*, TrAC Trends in Analytical Chemistry. 62, pages 28-36, 2014.
31. G Chen, I Roy, C Yang and P N Prasad, *"Nanochemistry and Nanomedicine for Nanoparticle-Based Diagnostics and Therapy"*, Chemical Reviews. 116, pages 2826-2885, 2016.
32. Y Jin, F Liu, C Shan, M Tong and Y Hou, *"Efficient Bacterial Capture with Amino Acid Modified Magnetic Nanoparticles"*, Water Research. 50, pages124-134, 2014.
33. J Govan, *"Recent Advances in Magnetic Nanoparticles and Nanocomposites for the Remediation of Water Resources"*, Magnetochemistry 6, 49, 2020.
34. R Baby, B Saifullah and M Z Hussein, *"Carbon Nanomaterials for the Treatment of Heavy Metal-Contaminated Water and Environmental Remediation"*, Nanoscale Research Letters. 14, 341, 2019.
35. Y S El-Temsah, A Sevcu, K Bobcikova, M Cernik and E J Joner, *"DDT Degradation Efficiency and Ecotoxicological Effects of Two Types of NanoSized Zero-Valent Iron (nZVI) in Water and Soil"*, Chemosphere 144, pages 2221-2228, 2016.
36. M Rui, C Ma, Y Hao, J Guo, Y Rui, X Tang, Q Zhao, X Fan, Z Zhang, T Hou and S Zhu, *"Iron Oxide Nanoparticles as a Potential Iron Fertilizer for Peanut (Arachis hypogaea)"*, Frontiers in Plant Science. 7, 815, 2016.
37. S Mishra, C Keswani, P Abhilash, L F Fraceto and H B Singh, *"Integrated Approach of Agri-Nanotechnology: Challenges and Future Trends"*, Frontiers in Plant Science. 8, 471, 2017.
38. N Suresh Kumar, R P Suvarna, K C B Naidu and B V S Reddy, *"Magnetic nanoparticles for high energy storage applications, Fundamentals and industrial applications of magnetic nanoparticles"*, Woodhead Publishing, pages 601–618, 2022.
39. J Govan and Y K Gun'ko, *"Recent Advances in the Application of Magnetic Nanoparticles as a Support for Homogeneous Catalysts"*, Nanomaterials, 4(2), pages 222 -241, 2014.